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# Societal transformations 2026 – 2045

100 anticipated radical technologies,  
20 regimes

The first AI-assisted Radical  
Technology Inquiry

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# Arvoisa lukija,

käsissäsi on raportti, jonka on tarkoitus olla muutakin kuin katsaus uusiin teknologioihin. Sen tehtävänä on auttaa pysähtymään sen äärelle, miten nopeasti ympäröivä maailma muuttuu ja miksi tuota muutosta on syytä tarkastella vakavasti jo ennen kuin sen seuraukset näkyvät kaikkialla arjessamme. Juuri tästä syystä radikaalien teknologioiden ennakointi (RTI) on ollut eduskunnan tulevaisuusvaliokunnalle tärkeää työtä jo pitkään. Olemme halunneet ymmärtää ajoissa, mitkä teknologiat voivat muuttaa yhteiskunnan toimintaa syvästi, missä järjestyksessä muutokset voivat edetä ja millaisiin kysymyksiin päätöksenteon pitäisi osata vastata ennen kuin on liian myöhäistä.

Tässä raportissa jatkuu työ, jota on tehty RTI-menetelmällä jo vuodesta 2013 lähtien. Perusajatus on ollut alusta asti kunnianhimoinen: emme tyydy luettelemaan kiinnostavia teknologioita, vaan pyrimme rakentamaan niistä kokonaiskuvan, joka on hyödyllinen lainsäätäjille, tutkijoille, yrityksille, opettajille, viranomaisille ja kansalaisille. Tulevaisuutta ei voi hallita, jos sitä ei ensin pyri hahmottamaan. Siksi tässäkin raportissa on lähdetty liikkeelle samasta kunnianhimoisesta tavoitteesta kuin aiemmin: tunnistetaan sata sellaista eri kypsyysvaiheissa olevaa radikaalia teknologiaa, joiden vaikutukset voivat ulottua laajasti yhteiskunnan eri toimintoihin, ja tarkastellaan niitä 20 arvonluontiverkoston kautta.

Tällä kertaa työssä on kuitenkin mukana myös jotakin olennaisesti uutta. Generatiivinen tekoäly on tullut mukaan tutkimusprosessiin tavalla, joka olisi vielä muutama vuosi sitten tuntunut epärealistiselta. On ollut tärkeää nähdä käytännössä, miten tekoäly voi auttaa laajojen aineistojen läpikäynnissä, teknologiakokonaisuuksien jäsentämisessä, lähdepohjaisessa kuvaustyössä ja vaikutusten ennakoinnissa.

Samalla on ollut aivan yhtä tärkeää nähdä sen rajat. Tekoäly ei korvaa harkintaa, vastuuta eikä tutkimuksellista arviointia. Siksi pidämme tämän raportin ehkä tärkeimpänä metodologisena opetuksena sitä, että hyvä ennakointi voi vahvistua tekoälyn avulla, mutta sitä ei voi ulkoistaa tekoälylle.

Yksi tämän hankkeen näkyvimmistä uusista tuloksista on RTI-GPT eli tekoälyavustaja, joka on perehdytetty raportin aineistoon. Sitä voi pitää keskustelevana oppaana, joka johdattaa kiinnostuneet raportin ja sen noin 2 000-sivuisen liiteaineiston äärelle: lukijan ei tarvitse itse etsiä oikeaa kohtaa pitkästä PDF:stä, vaan hän voi kysyä omin sanoin, mitä aineisto kertoo esimerkiksi jostakin teknologiasta, toimialasta, yrityksestä, säädöshankkeesta tai yhteiskunnallisesta ilmiöstä. Tekoälyavustaja voi muodostua raporttikokonaisuuden käytetyimmäksi käyttöliittymäksi, jopa suositummaksi kuin varsinainen PDF-raportti. Tämä on merkittävä muutos siinä, miten ennakointitietoa voidaan käyttää. Vaikka raportin tietopohja ei päivity automaattisesti, RTI-GPT tekee raportin aineistosta vuorovaikutteisen, sillä se voi vastata käyttäjän kysymyksiin ja käyttäjän pyynnöstä myös verrata raportin tuloksia annettuun aineistoon tai internetlähteeseen. Varsinainen raportti ei kykene keskustelemaan analyysiin, mutta RTI-GPT kykenee.

Kun radikaalien teknologioiden ennakointi käynnistyi vuonna 2012, tutkijoille esitettiin toive, että kehitettävä menetelmä saisi joskus sykkivän sydämen ja pystyisi päivittymään automaattisesti. Silloin ajatus oli enemmän suunta kuin todellinen mahdollisuus. Nyt olemme lähempänä sitä kuin tuolloin osattiin kuvitella. Menetelmä voi vahvistua, nopeutua ja tulla elävämmäksi, mutta se tarvitsee edelleen ihmisiä, jotka ymmärtävät, mitä kysyä, mitä epäillä ja mihin johtopäätöksiin kannattaa lopulta sitoutua.

Tulevaisuusvaliokunta julkaisi ennen tätä nyt käsillä olevaa julkaisua RTI-raportin humanoidiroboteista. Se oli eräänlainen menetelmällinen välivaihe: siinä RTI-ajattelutapaa ei sovellettu sataan teknologiaan, vaan poikkeuksellisen syvälle yhteen nopeasti kehittyvään teknologiaperheeseen. Samalla testattiin käytännössä, miten tekoäly voi auttaa jäsentämään teknologian yhteiskunnallisia vaikutuksia, mahdollisuuksia ja riskejä. Nyt vuonna 2025 pilotoitu tekoälyavusteinen työskentelytapa on laajennettu takaisin koko RTI-rungon tasolle tarkastelemaan sataa teknologiaa, 20:tä arvonluontiverkostoa ja koko yhteiskunnallista muutосkenttää.

RTI-työn yhteydessä on katsottu myös taaksepäin ja kysytty yksinkertainen, mutta tärkeä kysymys: etenivätkö aiemmissa ennakoinneissa korkeimmalle nostetut teknologiat todella muita nopeammin? Vastaus näyttää olevan ”kyllä”.

Ensimmäisistä, vuoden 2013 RTI-ennakointituloksista tehtiin vuonna 2016 väliarvio. Silloin todettiin, että vaikuttavimmiksi ennakoitujen teknologioiden yläneljännes oli kehittynyt kolmessa vuodessa nopeammin kuin seuraavaksi ylin neljännes, joka taas oli kehittynyt kolmatta nopeammin, ja niin edelleen.

Vuoden 2018 ennakkoinnista ei tehty vastaavaa virallista väliarviota, mutta tätä esipuhetta varten toteutettiin tekoälyavusteinen tarkastelu siitä, miten nuo kahdeksan vuotta sitten arvioitut teknologiat olivat kypsyneet ja kehittyneet ja miten niiden merkitys oli kasvanut tähän mennessä. Tarkastelussa ei arvioitu teknologioiden nykyistä tasoa, vaan niiden etenemistä eli sitä, kuinka nopeasti ne olivat vuoden 2018 jälkeen parantuneet kyvyiltään, lähestyneet markkinavalmiutta, yleistyneet käytössä tai kasvaneet yhteiskunnallisessa merkityksessään. Jokaisen sadan teknologian etenemisnopeutta kuvattiin asteikolla 0–10, ja näitä arvoja verrattiin vuoden 2018 alkuperäiseen luokitukseen, jossa neljä tähteä tarkoitti vaikuttavimmaksi ennakoitua 25 teknologian ryhmää, kolme tähteä seuraavaksi vahvinta 25 teknologian ryhmää ja niin edelleen.

Tekoälyavusteinen tarkastelu otti lähtökohdaksi vuoden 2018 raportin teknologiakuvaukset. Sitä tuettiin valikoiduilla ajantasaisilla verkkolähteillä niillä alueilla, joilla kehitys oli ollut erityisen nopeaa tai epävarmaa. Tulos oli samansuuntainen kuin vuoden 2016 väliarviossa: vuonna 2018 vaikuttavimmaksi ennakoitu neljännes oli kehittynyt vuoteen 2026 mennessä toista neljänneestä voimallisemmin, ja myös muut neljännekset etenivät odotetussa järjestyksessä. Kansankielisesti sanottuna vuosina 2013 ja 2018 kärki ei siis ollut vain lista kiinnostavista ideoista, vaan se osui molemmilla kerroilla hyvin niihin teknologioihin, jotka todella lähtivät kovimpaan juoksuun. Tämä antaa hyvän perusteen olettaa, että myös tämän raportin kärkijoukko, erityisesti vaikuttavimmaksi arvioitu 25 teknologian ryhmä, sisältää todennäköisesti ne kohteet, joiden etenemistä kannattaa seurata kaikkein tarkimmin.

Raporttia voi lukea kahdella tavalla. Yksi lukija haluaa ehkä aloittaa teknologioista: siitä, mitä uusia läpimurtoja on näkyvissä, miten nopeasti ne voivat kypsyä ja miksi juuri ne on nostettu mukaan sadan joukkoon (tulosten yhteenveto 2, täydelliset tulokset liitteessä 2). Toinen lukija taas haluaa ehkä aloittaa yhteiskunnasta: siitä, miten liikenne, oppiminen, terveys, työn organisointi, vallan rakenteet tai tiedon hankkiminen voivat muuttua tulevina vuosina (tulosten yhteenveto 1, täydelliset tulokset liitteessä 3). Molemmat lukutavat ovat perusteltuja. Juuri siksi RTI-menetelmä on rakennettu kahden näkökulman varaan: teknologioita ei ymmärretä ilman yhteiskuntaa, eikä yhteiskunnallista muutosta voi ymmärtää ilman teknologioita.

Ennen kaikkea raportin tulokset pakottavat katsomaan laajempaa kuvaa eikä vain yksittäisiä innovaatioita. Usein teknologiakeskustelu typistyy siihen, mikä uusi sovellus, laite tai järjestelmä näyttää kiinnostavalta juuri nyt. Tämä raportti pyrkii kysymään vaikeamman, mutta tärkeämmän kysymyksen: mitä tapahtuu, kun useat teknologiat kypsyvät samanaikaisesti, kytkeytyvät toisiinsa ja alkavat muuttaa yhteiskunnan perusrakenteita, työnjakoa, osaamistarpeita, valtasuhteita ja turvallisuuden ehtoja? Juuri tällaisen kokonaiskuvan vuoksi raportti on hyödyllinen. Se auttaa näkemään, missä uudet mahdollisuudet avautuvat, missä kehityksen pullonkaulat sijaitsevat ja missä riskit voivat kasvaa huomaamatta liian suuriksi.

Toivomme, että tätä raporttia luetaan uteliaasti, mutta myös vastuullisesti. Ennakkoinnin tarkoitus ei ole antaa lopullisia vastauksia, vaan auttaa kysymään oikeita kysymyksiä ajoissa. Jos tämä raportti ja sitä täydentävä RTI-GPT tukevat parempaa

keskustelua, parempaa valmistautumista ja viisaampaa päätöksentekoa, ne ovat täyttäneet tehtävänsä. Tulevaisuus ei synny itsestään. Sitä rakennetaan valinnoilla, ja juuri siksi meidän on pyrittävä ymmärtämään mahdollisimman hyvin, millaisten teknologisten murrosten keskellä nuo valinnat tehdään.

”Valitaan suunta.”

#### **TULEVAISUUSVALIOKUNNAN TEKNOLOGIAN ENNAKOINTI -OHJAUSRYHMÄ,**

Ville Vähämäki pj. (ps)

Timo Harakka (sd.)

Ville Kaunisto (kok.)

Sheikki Laakso (ps.)

Sinuhe Wallinheimo (kok.)

# Dear reader,

You are reading a report that is intended to be more than a review of new technologies. Its purpose is to help us pause and consider how rapidly the world around us is changing, and why that change should be examined seriously even before its consequences become visible everywhere in our everyday lives. This is precisely why the foresight of radical technologies has long been important work for the Committee for the Future of the Parliament of Finland. We have wanted to understand in good time which technologies may profoundly change the way society functions, in what order these changes may unfold, and what kinds of questions decision-making should be able to answer before it is too late.

This report continues the development of the so called Radical Technology Inquirer method (RTI) that has been carried out since 2013. From the outset, the basic idea behind the work has been ambitious: we do not merely list interesting technologies, but seek to build an overall picture of them that is useful for legislators, researchers, companies, teachers, authorities and citizens. The future cannot be governed unless one first tries to grasp it. That is why this report, too, starts from the same ambitious objective as before: to identify one hundred anticipated radical technologies whose impacts may extend widely across different functions of society, and to examine them through twenty value-creation networks.

This time, however, the work includes something essentially new. Generative artificial intelligence has become part of the research process in a way that would have seemed unrealistic only a few years ago. It has been important to see in practice where AI can help in reviewing extensive bodies of material, structuring technological clusters, producing source-based descriptions and anticipating impacts. At the

same time, it has been just as important to see its limits. AI does not replace judgement, responsibility or research-based assessment. For this reason, perhaps the most important methodological lesson of this report is that good foresight can be strengthened with the help of AI, but it cannot be outsourced to AI.

One of the most visible new outcomes of this project is RTI-GPT, an AI assistant trained on the material of the report. It can be thought of as a conversational guide to the report and its approximately 2,000 pages of appendix material: the reader does not need to search for the right section in a long PDF, but can ask in their own words what the material says about, for example, a technology, sector, company, legislative initiative or societal phenomenon. It may become the most widely used interface to the report, even ahead of the actual PDF report. This is a significant change in how foresight knowledge can be used. RTI-GPT makes the report's knowledge base interactive: it can answer users' questions and, at the user's request, also examine material provided by the user or a source indicated on the internet in relation to the report's foresight results. The actual report does not provide this kind of conversational analysis, but RTI-GPT makes it possible.

When this work began in 2012, the researchers were presented with the hope that the method might one day acquire a beating heart and be able to update its foresight results automatically. At that time, the idea was more of a direction than a real possibility. Now we are closer to it than we were then able to imagine. The method can become stronger, faster and more alive, but it still needs people who understand what to ask, what to question and which conclusions are ultimately worth committing to.

The present publication was preceded by the Committee for the Future's RTI report on humanoid robots, published in 2025. It was a kind of methodological intermediate stage: in it, the full RTI approach was not applied to one hundred technologies, but exceptionally deeply to one rapidly developing technology family. At the same time, the report tested in practice how AI can help analyse the societal impacts, opportunities and risks of a technology. That experiment has now been expanded back to the level of the full RTI framework: an examination of one hundred technologies, twenty value-creation networks and the entire field of societal change.

In connection with the RTI work, we have also looked back and asked a simple but important question: did the technologies ranked highest in earlier foresight exercises really advance faster than the others? The answer appears to be yes.

An interim assessment of the first RTI foresight results from 2013 was carried out in 2016. At that time, it was found that the top quartile of technologies anticipated in 2013 to have the greatest impact had developed over four years faster than the next highest quartile, which in turn had developed faster than the third quartile, and so on.



No corresponding official interim assessment has been carried out for the 2018 foresight exercise, but for this foreword an AI-assisted review was conducted of how the technologies assessed eight years ago have developed, matured and grown in significance up to the present day. The review did not assess the current level of the technologies, but rather their rate of progress: how quickly they have improved in capability since 2018, approached market readiness, become more widely adopted or grown in societal significance. Each of the one hundred technologies was given an assessment of this rate of progress on a scale from 0 to 10, and these assessments were compared with the original 2018 classification, in which four stars referred to the group of 25 technologies anticipated to have the greatest impact, three stars to the next strongest group of 25 technologies, and so on.

The AI-assisted review was based on the technology descriptions in the 2018 report and supported with selected up-to-date online sources in areas where development has been particularly rapid or uncertain. Its result was similar to that of the 2016 interim assessment: by 2026, the quartile anticipated in 2018 to have the greatest impact had developed more strongly than the second quartile, and the other quartiles also progressed in the expected order. In plain language, the leading technologies identified in 2013 and 2018 were not merely lists of interesting ideas; on both occasions, they successfully identified the technologies that truly set off at the fastest pace. This provides good grounds to assume that the leading group in this report as well, especially the group of 25 technologies assessed as having the greatest impact, is likely to contain the development paths whose progress should be monitored most closely.

The report can be read in two ways. One reader may wish to begin with the technologies: what new breakthroughs are visible, how quickly they may mature, and why these particular technologies have been included among the one hundred. This is covered in Summary of Results 2, with the complete results in Appendix 2. Another reader may wish to begin with society: how transport, learning, health, the organisation of work, structures of power or the acquisition of knowledge may change in the coming years. This is covered in Summary of Results 1, with the complete results in Appendix 3. Both ways of reading are justified. This is precisely why the RTI method is built on two perspectives: technologies cannot be understood without society, and societal change cannot be understood without technologies.

The significance of the results lies above all in the fact that they force us to look beyond individual innovations and consider the broader picture. Technology discussions are often reduced to which new application, device or system happens to seem interesting at the moment. This report seeks to ask a more difficult but more important question: what happens when several technologies mature simultaneously, connect with one another and begin to transform the basic structures of society, the division of labour, competence needs, power relations and the conditions of security? This kind of overall picture makes the report useful. It helps us see where new opportunities are opening up, where the bottlenecks of development are and where risks may grow unnoticed until they become too large.

We hope that this report will be read with curiosity, but also with responsibility. The purpose of foresight is not to provide final answers, but to help ask the right questions in time. If this report and the accompanying RTI-GPT support better discussion, better preparedness and wiser decision-making, they will have fulfilled their purpose. The future does not emerge on its own. It is built through choices, and that is precisely why we must strive to understand as well as possible the kinds of technological transformations amid which those choices are made.

“Let us choose a direction.”

#### **THE TECHNOLOGY FORESIGHT STEERING GROUP OF THE COMMITTEE FOR THE FUTURE**

Ville Vähämäki, Chairman (Finns Party)

Timo Harakka (Social Democratic Party of Finland)

Ville Kaunisto (National Coalition Party)

Sheikki Laakso (Finns Party)

Sinuhe Wallinheimo (National Coalition Party)

# Introduction

The pace of technological development has grown unusually fast, uneven, and difficult to interpret. Technical breakthroughs, commercial scaling, regulatory reactions, and geopolitical tensions now interact in ways that can alter everyday life in a relatively short period of time. For this reason, the societal significance of radical technologies should not be assessed only through their technical novelty or market prospects. Their importance lies equally in their capacity to reorganize infrastructures, institutions, power relations, work, and everyday practices. In some cases, such reorganization may open new possibilities for productivity, health, accessibility, or sustainability. In other cases, it may intensify concentration of power, insecurity, exclusion, or conflict. From a foresight perspective, the issue is therefore not whether technological change will be consequential, but how its consequences will be distributed, governed, and interpreted.

Recent years have made this particularly visible. Large-scale disruptions have shown how rapidly sociotechnical change can reshape ordinary life, public authority, international dependencies, and the boundaries between resilience and vulnerability. Broad technological and sociotechnical trajectories can help explain why major disruptions may emerge faster, spread wider, and affect daily life more deeply than societies often anticipate. It is in this sense that the present report is situated between two competing horizons: one in which technological development supports broader flourishing, and another in which the same developments deepen fragility, asymmetry, and coercion. The future remains open, and the stakes of technological foresight are high.

## What was the task

The task of the present report was to produce an updated foresight summary of anticipated radical technologies and their wider societal implications by applying and refining the Radical Technology Inquirer (RTI) methodology. In substantive terms, the report identifies and organizes one hundred anticipated radical technologies (ARTs) into twelve technology groups and examines their possible implications across twenty global value-producing networks (GVNs). In methodological terms, the report continues to renew RTI with the help of generative AI. The present exercise therefore has a dual purpose. First, it provides an updated picture of the technological developments most likely to shape future societal transformations. Second, it examines how far AI can support a full RTI-style foresight process when used under explicit analytical constraints.

For that reason, the report is not only a summary of technological developments. It is also an attempt to update the practical conditions under which technology foresight can be carried out. The question is not merely which technologies matter, but how such technologies can be identified, described, evidenced, and related systematically to societal transformation in a research environment where both the speed of technological change and the availability of generative AI have increased substantially.

## How the task was carried out

The work was carried out as a continuation of the RTI method rather than a wholly new foresight framework. The underlying idea remained the same as in earlier RTI reports: anticipated radical technologies were identified and described, and their significance was then assessed in relation to broad societal value-producing networks. However, the route by which the present report arrived at its final technology, and the impact set differed from earlier rounds. In the 2018 RTI report (Linturi & Kuusi 2018), the source base and technology baskets were built through extensive crowdsourcing and expert-supported processing. To assess the compatibility of generative AI with the RTI method, a pilot study was carried out in 2025 (Björkroth et al. 2025). In the pilot, the foundational work on just one ART, humanoid robots, was conducted manually by researchers and then extended with AI-assisted analysis. At that stage, AI proved useful in societal impact analysis. In the present study, the newly launched research features of generative AI enabled its use also in the earlier phases of the process: in identifying candidate domains for the full range of 100 ARTs, in generating and refining prospect ARTs, in expanding the descriptions of those technologies, in producing evidence dossiers, and in supporting ART-by-GVN impact analysis. In practical terms, an AI-assisted “full iteration” of RTI only became viable quite recently, when Deep Research-type model functions became available. Earlier generative AI tools could support selected phases of the process, as seen in the 2025 pilot, but not yet the source-grounded and sufficiently systematic handling of a full-spectrum RTI round at this scale. Despite the extensive use of AI,

the process in this present remained researcher-led in all decisive respects, with the research team curating candidate technologies, checking evidence dossiers, and interpreting and refining the resulting analyses. The report should therefore be understood as an AI-assisted RTI process, not an automatically generated outlook.

The present report also differs from the 2025 pilot in one further respect. Whereas the pilot investigated in depth one anticipated radical technology and its implications across the value creation networks, the current report returns to a broader system-level horizon. It therefore asks not only which individual technologies may become significant, but also how several technological developments may advance and mature in parallel, reinforcing or counteracting one another, and alter the conditions under which societies produce value, exercise power, and interpret risk.

## How to read the results

The results of this report should be read as structured foresight, not as prediction. The report does not claim that all listed technologies will mature exactly as described, nor that each identified impact will materialize in a linear way. Rather, the purpose is to identify plausible directions of change, clarify where transformation pressures may be accumulating, and make visible the kinds of societal effects that may otherwise remain unnoticed until they are already well underway. The report is therefore best read as an analytical map of emerging possibilities, tensions, and dependencies. Its value lies less in point prediction than in systematic comparability across technologies and societal domains.

The twelve technology groups should be understood as organizing devices that make a broad set of anticipated radical technologies easier to interpret. They do not imply that technological change proceeds neatly inside group boundaries. On the contrary, many of the most important future effects are likely to arise precisely through combinations across groups, for example between sensing, AI, robotics, energy systems, standards, and digital platforms. Similarly, the twenty value-producing networks should not be read as isolated sectors. They are analytical models of broad societal functions, and their purpose is to show how technological change may shift the dominant and challenger regimes through which value is created. Many technologies therefore appear significant not only because of their direct use, but because of their institutional, economic, political, or cultural spillovers across several networks at once.

For this reason, the results should be read not only as a comparison of individual technologies, but as a structured estimate of their combined societal reach and plausibility. In RTI-methodology, the total significance of an anticipated radical technology is based on the sum of its impacts across all twenty value-producing networks, weighted by its maturity. The highest-ranking technologies are therefore not simply those that seem most dramatic in one field, but those whose effects spread across several networks and whose maturity makes those effects plausible within the assessment horizon. The ranking follows this logic because technologies with

broad horizontal effects often change society most deeply: by cutting across several domains at once, they can generate entirely new verticals, meaning new sectors, markets, and institutional arrangements. High total scores thus reflect breadth, intensity, and practical readiness. Lower scores, by contrast, may reflect narrower applicability or earlier maturity rather than lack of significance as such.

This report can be approached from two complementary directions. A reader primarily interested in broader societal change may begin with the twenty global value-producing networks (GVNs), where the emphasis is on how technological development may reshape the dominant and challenger regimes through which value is created in society (Summary of results 1). A reader primarily interested in technological change may begin with the twelve technology groups and the one hundred anticipated radical technologies (ARTs) organized under them (Summary of results 2).

The ART sections present 100 anticipated radical technologies as bottleneck-oriented technology bundles. Their purpose is not only to describe individual technologies, but to identify the kinds of capability shifts that may remove important technical, economic, institutional, or operational constraints across several domains at once. Organizing the ARTs into technology groups aims to help the reader see broader patterns and connections between related ARTs, while the individual ART entries in attachments provide a more specific picture of what each technology bundle consists of and why it matters.

The GVN sections approach the same material from the opposite direction. Instead of starting from technologies, they start from broad societal functions such as transport, logistics, health care, acquiring information, or power structures. Their purpose is to describe plausible transformations in the way value is created, organized, and contested in these domains, and to show how different anticipated radical technologies may contribute to those transformations.

## How to use the Appendices

The main research material is contained in the appendix section of this report. The first attachment summarizes the anticipated impact of the 100 ARTs on 20 GVNs in a table form. In Attachment 2, each anticipated radical technology (ART) is presented in detail, together with source references, a maturity assessment, and its expected fields of impact. Attachment 3 displays the anticipated societal impacts of the ARTs on GVNs, starting from the passenger transport GVN and ending in power structures GVN. The ART descriptions that were used as reference when gathering the evidence for ARTs can be found from Attachment 4. The GVN descriptions that were used as reference when anticipating the societal impacts of ARTs can be found from Attachment 5. Scoring criteria for ART maturity and ART/GVN impact are included in Attachment 6.

The appendix material has been designed first and foremost to be read by AI systems. Any interested reader can, of course, also consult it directly for details, reasoning, and source references. The most convenient and intended way to use the material, however, is to make it available to an AI system. Due to the length and structure of the material, to be useful, generative AI needs understanding of the knowledge architecture of the report – a map helping it to know what kind of information can be found and where it can be found. This places requirements on the AI. It needs capability to use the supplied instructions and act accordingly. Several contemporary AI systems are widely available, each with their own user interfaces. ChatGPT with its Custom GPT feature is the most common.

To enable such use with customized AI, the research material structure has been standardized so that related content can be located without having to read the entire appendix section from beginning to end. The AI-oriented appendix package is available at <https://www.eduskunta.fi/en/members-and-parliamentary-bodies/committees/committee-for-the-future/radical-technology-inquirer-rti> and it includes a Readme.txt file that provides an illustrative guide to using the material with ChatGPT, the service most used in Finland. In principle, the package enables the user to build their own RTI-GPT with any AI model of their choice. It should be kept in mind, however, that the quality of answers differs by the model even when the database and GPT instructions are identical.

## Introducing the Radical Technology Inquirer GPT (RTI-GPT)

Even though such development work was not originally planned, one of the report's authors, Risto Linturi, created and shared an example of how the full research dataset behind this report can be explored via customized RTI-GPT. The readers are encouraged to try this with a free ChatGPT account either by opening this link, [RTI-GPT \(FIN\)](#) for a Finnish language version, [RTI-GPT \(ENG\)](#) for an English language version, or by selecting the Custom GPT called **Radical Technology Inquirer –GPT (Fin)** or **Radical Technology Inquirer –GPT (Eng)** within ChatGPT. Use requires logging in ChatGPT. ChatGPT was chosen as a platform for the model experiment because it enabled (at least in spring 2026), free sharing of links to user-created customized GPTs. It should be noted that at the time of publication, free registered use enables just the basic thinking mode of RTI-GPT, which is sufficient for exploring the content of the report. More in-depth insights can be generated, however, by using extended thinking mode. Detailed instructions for using this RTI-GPT can be obtained simply by asking it from RTI-GPT itself. Questions or requests may concern any area of life, technology, or society. The answers produced by RTI-GPT are based primarily on the research material provided to it. For that reason, its answers are most precise and least open to interpretation when the user refers to the GVN and ART names used in the report, although this is not required.

The questions can be very broad. For example, both the Summary of results 1 (GVN) and Summary of results 2 (ART) in this summary report were each produced with a single RTI-GPT prompt. Questions may also refer to external sources. One may, for example, ask for an account of the most likely transformation of passenger transport and request that the system read the Finnish online legal database Finlex to identify the main legislative barriers and bottlenecks affecting that transformation. It is also possible to ask RTI-GPT to study company websites, professional groups, or schools of thought and ask for an assessment of how they are likely to fare in the future. Such possibility to cross reference external sources from the perspective of RTI seems to yield useful answers that it was included in RTI-GPT despite the drawback that RTI-GPT may then also allow low quality material to influence its answers if user is not careful in formulation their queries. To help the user to understand the nature of RTI-GPT and to formulate relevant prompts, RTI-GPT is instructed to clearly indicate what part of its response is based on its database, what comes from the user-appointed sources and what it found from the internet. As with all GPTs, it is better to start a new discussion when changing the topic.

It should be remembered, however, that RTI-GPT is a language model and that it interprets foresight material in its own way. The future is not easy to predict, unless one is speaking of the orbits of planets and stars. Foresight is therefore inherently uncertain, and AI will certainly make mistakes in it as even the most experienced humans do. Even so, an AI equipped with a systematic framework and a broad research base of this kind is clearly of great interest and can generate many fresh perspectives worthy of consideration.



# Summary of results 1: anticipated transformations in 20 global value-producing networks

This is a summary from the results in Attachment 3: Anticipated GVN Impacts of ARTs and Attachment 5: GVN descriptions used in ART impact assessment. The summary describes and evaluates the potential transformation of each global value-producing network used to describe societal functions in the RTI-methodology. Key technologies anticipated to drive the transformation are listed. Further extensively detailed analysis how each ART may impact each GVN can be found in Attachment 3.

The impact scores mentioned in the ART lists are logarithmic (possible values are 0, 1, 3, 5, 10 or 20). For more detailed impact score criteria, see Attachment 6.

This summary was created by using the RTI-GPT.

# GVN 1 – Passenger Transport

## KEY CONCLUSION

The core transformation in GVN 1 is a shift from ownership-based mobility toward networked, service-based and partly autonomous mobility solutions. The change is not only technical: it also affects urban structure, the logic of ownership, and who coordinates traffic. The strongest challenger-regime dynamic emerges when vehicles, infrastructure, connectivity, payment and AI-based control increasingly operate as one system rather than as separate layers. The key uncertainty is whether the result will be a more efficient shared mobility regime or an even more tightly controlled platform regime.

## UNDERLYING LOGIC OF THE GVN

GVN 1 is organized around moving people from one place to another safely, efficiently, comfortably, freely and at reasonable cost. The current dominant regime rests on private car use, the infrastructure that supports it, and schedule-based public transport. Its strength lies in flexibility and the deep cultural, spatial and economic embedding of private cars, but the model also creates underutilized assets, large parking needs, emissions, and exclusion of those who cannot drive. The challenger regime rests on autonomous vehicles, Mobility as a Service models, shared mobility, electric solutions and more precise digital infrastructure. This suggests that the pressure for change is directed not only at vehicles but at the entire logic of mobility: how trips are bought, combined, allocated and coordinated. The central conflict is therefore not simply car versus bus, but privately controlled mobility versus service-based and increasingly system-coordinated mobility.

## ANTICIPATED DIRECTION OF TRANSFORMATION

The likely direction is toward higher utilization rates, service-based models, and continuous coordination. The main benefits are efficiency, safety, lower costs, lower emissions, and better accessibility. This points to passenger transport moving away from one person controlling one vehicle at a time toward systems that allocate capacity, routing and responsibility far more dynamically.

The change may also be discontinuous in places. Once usable autonomy, reliable connectivity and interoperable control infrastructure converge with mature regulation, part of today's ownership and parking logic may lose its foundation quickly. What remains uncertain is how quickly consumers accept the loss of direct control, how cities redistribute street and parking space, and whether public transport is strengthened or weakened in the transition.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate. Many drivers — electrification, persistent connectivity, platforms and AI-assisted coordination — have already moved from pilot projects into practice, but legal liability, safety requirements and inherited infrastructure slow the broader shift.

- 2026–2045: fast and potentially discontinuous. If autonomy, reliable oversight, and service-based coordination become established, the shift may accelerate clearly between 2026 and 2045 because both the cost structure and the use of space will change at the same time.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 05.029 Self-Driving Vehicles — impact score in GVN 1: 20 — shifts decision and control capacity from the human driver to the system; in this GVN it strengthens service-based mobility, automation, and networked control.
- ART 01.001 Global Broadband Connectivity — impact score in GVN 1: 10 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens service-based mobility, automation, and networked control.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 1: 10 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens service-based mobility, automation, and networked control.
- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 1: 10 — enables coordinated action among many machines, software systems and actors; in this GVN it strengthens service-based mobility, automation, and networked control.

## **GVN SUMMARY**

GVN 1 is strategically important because it brings together infrastructure, energy, data, regulation, and everyday accessibility. The change seems to advance first in layers and then potentially by leaps if service-based and autonomous logic starts to outcompete the ownership-based model. The greatest uncertainty is whether safety, liability, and social acceptance can be resolved in a sufficiently credible way.

## **GVN 2 – Logistics**

### **KEY CONCLUSION**

The core transformation in GVN 2 is the shift from linear supply chains to continuously visible, software-directed, and partly autonomous networks of goods flows. The change is structural because it simultaneously affects transport, storage, packaging, distribution, and the role of the consumer. The strongest drivers are collaborative AI coordination, autonomous transport solutions, persistent connectivity and traceability. The direction of change is toward faster, more granular and more home-linked logistics.

### **UNDERLYING LOGIC OF THE GVN**

GVN 2 is organized around moving goods, materials, equipment, animals and waste from one place to another easily, accurately, flexibly and cost-effectively. The current dominant regime is built around industry- and trade-centered logistics, shared transport infrastructure, containerization, large shipment sizes, and the consumer's

own pickup work. This favors large actors, standardized packaging, and deeply established distribution channels.

The challenger regime is based on smart robotization, autonomous vehicles and drones, individually identifiable packaging, digital platforms, cloud services, and shared smart lockers. This suggests that the change in logistics is not only a transport shift but also a shift in information, traceability, and exception management.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The likely direction is toward real-time synchronized goods flows, smaller shipment sizes, more automated sorting and a more direct link between manufacturer, distributor and end user. The main benefits are smoother distribution, better availability in sparsely populated areas, less waste, and stronger competition. This suggests that a competitive advantage in logistics is shifting increasingly toward the ability to see and steer the whole network rather than simply manage a single transport leg.

The change may move faster than in many other GVN areas because logistics immediately reward solutions that improve efficiency and precision. It remains unclear how far labor-market effects, cybersecurity risks, and the governance of urban space will limit large-scale deployment, even though they clearly appear as constraints.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: moderate but accelerating. Recent years have strengthened platforms, visibility, and automation, but the reordering of the whole network has been uneven and concentrated among large actors.
- 2026–2045: fast. By 2045, logistics appears likely to benefit especially strongly from multi-agent coordination, autonomy and traceability, so the change may spread rapidly across the whole chain.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 2: 20 — enables coordinated action among many machines, software systems and actors; in this GVN it strengthens a real-time coordinated and visible logistics network.
- ART 05.029 Self-Driving Vehicles — impact score in GVN 2: 20 — shifts decision and control capacity from the human driver to the system; in this GVN it strengthens a real-time coordinated and visible logistics network.
- ART 12.093 Global Supply Chain Traceability Networks — impact score in GVN 2: 20 — makes the origin of materials, components and supply chains more auditable; in this GVN it strengthens a real-time coordinated and visible logistics network.
- ART 01.001 Global Broadband Connectivity — impact score in GVN 2: 10 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens a real-time coordinated and visible logistics network.

## **GVN SUMMARY**

GVN 2 is strategically important because it acts as the backbone of material and informational movement across other networks. The change looks set to accelerate as visibility, traceability and automation converge. The greatest uncertainty is whether work, responsibility and safety change in a controlled way or whether logistical efficiency is achieved at the cost of new vulnerabilities.

## **GVN 3 – Manufacturing of Goods**

### **KEY CONCLUSION**

The core transformation in GVN 3 is the shift from centralized mass production toward more flexible, partly distributed and digitally directed manufacturing. The change is above all a change in production structure: design, manufacturing, standardization, and distribution are being reconnected in new ways. The strongest drivers are agile factories, humanoid robots, manufacturing-specific standardization, and collaborative AI coordination. The direction is not a full departure from economies of scale, but a new combination of scale and customization.

### **UNDERLYING LOGIC OF THE GVN**

GVN 3 is organized around producing physical goods and equipment in ways that are functional, high-quality, cost-effective, and suited to user needs. The current dominant regime rests on large industrial facilities, global centralization, subcontracting chains, mass production, and hierarchical distribution. It is supported by norm-based governance, risk aversion, and the separation of design from production.

The challenger regime is built on robotization, digital manufacturing, 3D printing, AI-assisted design, flexible lines, and digital manufacturing chains. This suggests that the core of the change is not only a new machine base, but also production moving closer to use, maintenance, and rapid iteration.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward production in which variation, short runs, and local adaptation are economically feasible more often than before. The main benefits are lower inventory and logistics needs, easier repair, more local employment, and less vulnerability to global disruption. On this basis, manufacturing is gradually shifting from pure volume optimization toward responsiveness and model-based control.

The change is likely to be uneven. Large and safety-critical manufacturing environments will remain heavily standardized for a long time, while the production of smaller series, spare parts, and configurable products may change quickly. It remains unclear how far intellectual property rights, liability issues, and quality assurance will ultimately limit genuinely distributed manufacturing.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate. Digital design, robotics and software-defined production control have strengthened clearly, but the traditional logic of scale and quality remains strong.
- 2026–2045: moderate but accelerating. By 2045, the shift is likely to deepen because flexible automation, certified interoperability, and the modularity of production reinforce one another.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 06.039 Reconfigurable & Agile Factories — impact score in GVN 3: 20 — makes production more rapidly reconfigurable; in this GVN it strengthens flexible, digital and partly distributed manufacturing.
- ART 12.100 Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure — impact score in GVN 3: 20 — standardizes production quality, testing and certification practices; in this GVN it strengthens flexible, digital and partly distributed manufacturing.
- ART 05.031 Humanoid and General-Purpose Robots — impact score in GVN 3: 20 — brings general-purpose robotics into environments designed for humans; in this GVN it strengthens flexible, digital and partly distributed manufacturing.
- ART 06.038 Digital Twin & Simulation-Driven Production — impact score in GVN 3: 10 — turns the state of production and infrastructure into something that can be continuously simulated and optimized; in this GVN it strengthens flexible, digital and partly distributed manufacturing.

## GVN SUMMARY

GVN 3 is strategically important because it determines how quickly society can turn design into physical production. The change is likely to advance in layers: first in information-intensive and high-value segments, and later more broadly. The greatest uncertainty is how strongly quality, liability, and IP issues ultimately slow decentralization.

## GVN 4 – Sustenance

### KEY CONCLUSION

The core transformation in GVN 4 is the shift from standardized food production based on long chains toward a more personalized, local, and biotechnologically diversified food system. The change matters because it simultaneously affects health, sustainability, security of supply, and everyday habits. The strongest drivers are cellular agriculture, synthetic biology, traceability and automated coordination, but consumer behavior remains the decisive bottleneck. The direction is clear, but the pace depends on acceptance and changes in distribution channels.

## UNDERLYING LOGIC OF THE GVN

GVN 4 is organized around securing the supply of energy, nutrients, and trace elements for humans and pets. The current dominant regime rests on traditional agriculture, animal production, industrial processing, distribution channels dominated by retail chains, and strong regulation and control. The values of this system emphasize economies of scale, safety, and the preservation of existing structures.

The challenger regime is built around indoor farming, urban production, biotechnological food production, insect protein, robot kitchens, and new methods that extend shelf life. This suggests that the food system is beginning to split: one part continues to industrialize, while another moves closer to the consumer and to individual needs.

## ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward food that is more measurable, more tailored, and logistically more flexible than before. The main benefits are improving public health, lower environmental burden, greater crisis resilience, and new business opportunities. This suggests that the food system may shift away from pure volume logistics toward demand-driven, partly localized, and biologically programmable production.

Technological potential is likely to advance faster than habits and regulation. Challenger-regime solutions may mature quickly in laboratories and limited applications, but the broader shift depends on whether new proteins, gene editing, and automated preparation are accepted as part of everyday food. It remains unclear how quickly major distributors will adopt these models or how sharply consumer perceptions will change.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: slow but strengthening. Many solutions have recently moved from experiments to visible alternatives, but the basic structure of the system still rests heavily on traditional agriculture and retail.
- 2026–2045: moderate but accelerating. By 2045, the shift may strengthen clearly if the benefits for health, sustainability and security of supply begin to outweigh the cultural inertia of traditional food models.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 09.069 Cellular Agriculture & Cultured Meat — impact score in GVN 4: 20 — detaches part of food production from traditional agricultural logic; in this GVN it strengthens a personalized, increasingly local, and more biotechnological food system.
- ART 09.071 Synthetic Biology & Designer Microbes — impact score in GVN 4: 10 — opens the door to biologically designed production and process solutions; in this GVN it strengthens a personalized, increasingly local, and more biotechnological food system.

- ART 12.093 Global Supply Chain Traceability Networks — impact score in GVN 4: 10 — makes the origin of materials, components and supply chains more auditable; in this GVN it strengthens a personalized, increasingly local, and more biotechnological food system.
- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 4: 10 — enables coordinated action among many machines, software systems and actors; in this GVN it strengthens a personalized, increasingly local, and more biotechnological food system.

## **GVN SUMMARY**

GVN 4 is strategically important because it connects biology, logistics, consumer behavior and crisis resilience. Change appears likely, but uneven. The greatest uncertainty is how quickly acceptance, regulation, and distribution networks adapt to the technological potential.

## **GVN 5 – Energy Supply**

### **KEY CONCLUSION**

The core transformation in GVN 5 is the shift from a centralized and production-heavy energy system toward decentralized, storable, and software-directed energy production and use. The change is clearly structural because it simultaneously affects production, storage, demand flexibility, grids, and fuel production. The strongest drivers are microgrids, storage, and power-to-X solutions, supported by interoperability and multi-actor control. This is one of the fastest-reorganizing GVN areas.

### **UNDERLYING LOGIC OF THE GVN**

GVN 5 is organized around producing, refining, storing, and distributing energy in forms suited to demand. The current dominant regime is based on centralized fossil fuel and nuclear generation, distribution grids, regulated markets, and little interest in storage. Behind it is the need to secure cheap energy, maintain regional price uniformity, and regulation that slows the pace of change.

The challenger regime is built on renewable energy, batteries, synthetic fuels, local production, fuel cells, and new kinds of energy infrastructures. This suggests that energy is increasingly becoming a problem of coordination and control rather than production alone: what matters is not only how much energy is produced, but who can store it, sell it, time it, and use it flexibly.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a modular energy economy in which production, storage, consumption, and transport are linked into a single controllable whole. The main benefits are lower costs, less dependence on centralized infrastructure,



better security of supply, and environmental gains. This suggests that the value of energy is shifting increasingly toward the ability to combine decentralized resources into a reliable system.

In this GVN in particular, technical and institutional change may begin to reinforce one another. The more renewables, storage, and local control solutions are adopted, the harder it becomes for the old model to retain its position. It remains unclear how quickly political resistance, sunk costs, and investment uncertainty will ease in different regions.

### **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: moderate but accelerating. Renewables, storage and local control have already changed the logic of energy, even though the centralized system remains strong.
- 2026–2045: fast. By 2045, decentralization, storage and synthetic fuels appear strong enough to reshape both the technical and institutional structure quickly.

### **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 08.066 Resilient microgrids — impact score in GVN 5: 20 — decentralizes energy management into local, resilient nodes; in this GVN it strengthens decentralized, storable and software-directed energy.
- ART 08.060 Grid-Scale Energy Storage — impact score in GVN 5: 20 — smooths variation in the power system and enables more flexible usage models; in this GVN it strengthens decentralized, storable and software-directed energy.
- ART 08.062 Green Hydrogen & Power-to-X — impact score in GVN 5: 20 — turns electricity into storable and transportable fuels; in this GVN it strengthens decentralized, storable and software-directed energy.
- ART 12.091 Universal IoT Interoperability Standards — impact score in GVN 5: 10 — lowers the friction of interoperability across device and system ecosystems; in this GVN it strengthens decentralized, storable and software-directed energy.

### **GVN SUMMARY**

GVN 5 is strategically important because nearly all other networks depend on the energy it provides. The change looks accelerating and cumulative. The greatest uncertainty is how quickly political and regulatory structures adapt to the logic of decentralized energy.

## GVN 6 – Materials

### KEY CONCLUSION

The core transformation in GVN 6 is the shift in the materials economy toward lighter, cleaner, more circular and functionally smarter materials. The change is important but more indirect than in many service GVNs, because it proceeds through the performance and resource structure of other networks. The strongest drivers are circularity, materials traceability, manufacturing standards, and new processes. The direction is clear, but the heavy legacy of process industry makes progress gradual.

### UNDERLYING LOGIC OF THE GVN

GVN 6 is organized around producing and refining materials so that they support other production, withstand use and remain economically available. The current dominant regime is based on traditional industrial materials, mass production, global supply chains, and capital-intensive processes. The system is sustained by stability, predictability, and strong existing industrial investments.

The challenger regime emphasizes new lightweight and efficient materials, nano-technology, bio-based solutions, lower-temperature processes, 3D printing, and more efficient recycling. This suggests that materials are gradually shifting from passive raw inputs to infrastructure elements that determine system performance.

### ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward a material system in which origin, reuse, functionality, and the energy efficiency of processes matter more than before. The main benefits are a stronger circular economy, lower environmental burden, and the enabling of new processes. This suggests that the competitiveness of materials is judged less by price alone and more by full lifecycle and system effect.

The change is likely to advance first in applications where a new material brings an immediate performance or regulatory benefit. It remains unclear how quickly old material standards, capital-intensive plants, and global sourcing logic will make room for genuinely new material paradigms.

### ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: slow but strengthening. Many material trends have strengthened, but heavy processes, long approval cycles, and industrial inertia keep the shift slow for now.
- 2026–2045: moderate. By 2045, circularity, traceability, and new standards in production may reinforce the change, but the whole material system will not transform quickly.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 06.040 Circular & Sustainable Manufacturing — impact score in GVN 6: 20 — shifts manufacturing toward circularity, repairability, and material efficiency; in this GVN it strengthens a circular and performance-oriented materials economy.
- ART 12.100 Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure — impact score in GVN 6: 20 — standardizes production quality, testing and certification practices; in this GVN it strengthens a circular and performance-oriented materials economy.
- ART 12.093 Global Supply Chain Traceability Networks — impact score in GVN 6: 10 — makes the origin of materials, components, and supply chains more auditable; in this GVN it strengthens a circular and performance-oriented materials economy.
- ART 06.039 Reconfigurable & Agile Factories — impact score in GVN 6: 10 — makes production more rapidly reconfigurable; in this GVN it strengthens a circular and performance-oriented materials economy.

## **GVN SUMMARY**

GVN 6 is strategically important because it defines the resource and cost base of other networks. The change is likely, but structurally heavy. The greatest uncertainty is whether a complementary logic of new materials emerges or a genuinely replacement-oriented industrial logic.

## **GVN 7 – Built Environment**

### **KEY CONCLUSION**

The core transformation in GVN 7 is the shift in the built environment from a slowly changing background to a programmatically maintained, measurable, and partly autonomy-adaptive system. The change is structural, but slower than in many digital GVNs because the built environment is slow, regulated, and long-lived. The strongest drivers are supportive infrastructure for autonomy, construction and maintenance robotics, and digital design. The direction is toward an environment that no longer only reacts to use but begins to anticipate and steer it.

### **UNDERLYING LOGIC OF THE GVN**

GVN 7 is organized around providing people and activities with a usable, safe and fit-for-purpose built environment. The current dominant regime rests on traditional construction methods, tight norm-based governance, centralized decision-making, and design driven by cost and location. Construction and maintenance are still only lightly automated and strongly directed by authorities and professional structures.

The challenger regime emphasizes construction and maintenance robotics, changing mobility solutions, new materials, and advanced building automation. This suggests that the built environment is beginning to shift from a structure that passively supports use to an active service layer that carries energy, data, logistics, and automated movement.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward an environment in which automation and sensing are interwoven with design, use, and maintenance. The main benefits are efficiency, easier maintenance, new material solutions, and changing space requirements. This suggests that the built environment is adapting more to moving machines, flexible services, and continuous use of data than to fixed solutions built for a single purpose.

The change is likely to concentrate first in environments where automation brings direct savings or safety benefits: logistics properties, new districts, maintenance-critical sites, and corridors for autonomous traffic. It remains unclear how quickly norms, investment cycles, and local decision-making will allow for a broader system-level shift.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: slow. In the logic of this GVN, the built environment is a slow variable: new technologies are visible, but broad structural change is still proceeding slowly.
- 2026–2045: moderate but accelerating. By 2045, the support needs of automation, changes in energy solutions, and the digitalization of maintenance may accelerate the change significantly.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 05.034 Supportive Infrastructure for Autonomy — impact score in GVN 7: 20 — builds the physical and digital support layer required by autonomy; in this GVN it strengthens a built environment that supports automation and is guided by data.
- ART 05.029 Self-Driving Vehicles — impact score in GVN 7: 20 — shifts decision and control capacity from the human driver to the system; in this GVN it strengthens a built environment that supports automation and is guided by data.
- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 7: 10 — enables coordinated action among many machines, software systems and actors; in this GVN it strengthens a built environment that supports automation and is guided by data.
- ART 04.022 Immersive Augmented & Virtual Reality — impact score in GVN 7: 10 — brings experiential and simulated environments into everyday activity; in this GVN it strengthens a built environment that supports automation and is guided by data.

## **GVN SUMMARY**

GVN 7 is strategically important because it locks in the operating possibilities of other networks for a long time. The change appears slow but cumulative. The greatest uncertainty is how much of the new logic can be built on top of the old environment and how much it requires entirely new areas and standards.

## **GVN 8 – Exchange**

### **KEY CONCLUSION**

The core transformation in GVN 8 is the shift in exchange from physical, bank- and organization-centered structures toward digital, platform-mediated and programmatically linked markets. The change is structural because it simultaneously affects payment, marketplaces, trust, taxation, and the responsibility of the consumer. The strongest drivers are global connectivity, interoperable payment rails, AI-assisted coordination and trustworthy digital regulation. The direction is toward exchange that is more continuous, more borderless, and more granularly priced.

### **UNDERLYING LOGIC OF THE GVN**

GVN 8 is organized around enabling the exchange of goods, services and rights easily, safely and efficiently. The current dominant regime is built on physical points of sale, bank-centered payment systems, hierarchical organizations, and control mechanisms anchored in stability. It is underpinned by the value placed on security, auditability, and familiar roles.

The challenger regime is based on e-commerce, global platforms, automation, the sharing economy, cryptocurrencies, and new digital service environments. This suggests that exchange is shifting away from individual organizations toward a structure dominated by protocols, payment layers, and data-driven marketplaces.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward lower-friction exchange in which payment, contracting, logistics, and the customer interface merge into a single programmable chain. The main benefits are ease, greater comparability for consumers, and the emergence of new market forms, but also changes in regulation, the tax base, and user responsibility. This suggests that the basic unit of exchange is no longer the individual purchase event, but an increasingly continuous relationship between the user, data, and the service platform.

The interoperability of payment and regulation will determine whether exchange becomes genuinely more open or only more tightly controlled by new platform intermediaries. It remains unclear how much of the traditional retail and banking structure will remain as a durable anchor, even though the pressure for change is clear.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: fast. E-commerce, digital platforms and new forms of payment have already changed exchange rapidly between 2018 and 2026.
- 2026–2045: moderate but accelerating. The next phase depends on how far interoperability in payment, identity and regulation actually extends; if it succeeds, the acceleration could be strong.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 12.095 Interoperable Digital Currency Payment Networks — impact score in GVN 8: 20 — connects payment and settlement across different systems; in this GVN it strengthens digital, continuous, and cross-border exchange.
- ART 01.001 Global Broadband Connectivity — impact score in GVN 8: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens digital, continuous, and cross-border exchange.
- ART 12.096 Machine-Readable Regulation (Rules as Code) — impact score in GVN 8: 5 — turns the interpretation of rules into something that can be implemented programmatically; in this GVN it strengthens digital, continuous, and cross-border exchange.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 8: 10 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens digital, continuous, and cross-border exchange.

## GVN SUMMARY

GVN 8 is strategically important because it determines how value changes hands across other networks. The transformation is already underway and is likely to deepen further. The greatest uncertainty is whether friction in exchange falls for everyone or whether power merely shifts to new digital gatekeepers.

## GVN 9 – Remote Impact

### KEY CONCLUSION

The core transformation in GVN 9 is the erosion of physical presence as a privileged condition for influence, work, interaction and control across many areas. The change is partly discontinuous because the same technical infrastructure can both democratize participation and concentrate influence. The strongest drivers are global connectivity, satellite-based connectivity, immersive interfaces, and robots that extend remote impact into the physical world. The direction is toward a society in which distance is less and less a decisive barrier, while problems of authenticity and control grow.

### UNDERLYING LOGIC OF THE GVN

GVN 9 is organized around enabling influence over other people, spaces and processes from a distance. The current dominant regime rests on physical presence,

organized communication channels, bureaucracy, and the special status of face-to-face influence. Friction related to distance has acted as a constraint on administration, work, and social interaction alike.

The challenger regime is built on global IT platforms, new channels of influence, remotely controlled robots and avatars, machine perception, VR/AR environments, and synthetic media. This suggests that remote impact will not remain a matter of communication only but will increasingly extend into physical environments and decision-making.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a model in which influence, coordination, guidance, oversight, and participation can increasingly take place without a shared location. The main benefits are accessibility, efficiency, and the emergence of new operating models, but the material also highlights misuse, manipulation, and technological unreliability. This suggests that remote impact is becoming a normal societal mode of action rather than an exceptional solution.

Remote impact is likely to deepen quickly where it can be linked to strong authentication, a high-quality sense of presence and reliable remote-action capability. It remains unclear how quickly people and institutions will learn to distinguish authentic, manipulated, and automatically generated forms of remote influence from one another.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: fast. The technical basis for remote impact has strengthened rapidly, especially in communication, platforms and hybrid work.
- 2026–2045: fast and potentially discontinuous. If robots, immersion, and synthetic media connect seamlessly to the communications infrastructure, the expansion of remote impact may accelerate strongly by 2045.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 01.001 Global Broadband Connectivity — impact score in GVN 9: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens the normalization of remote impact alongside physical presence.
- ART 10.079 Satellite Mega-Constellations & Space Internet — impact score in GVN 9: 10 — extends connectivity, positioning and visibility into areas where terrestrial infrastructure is weak; in this GVN it strengthens the normalization of remote impact alongside physical presence.
- ART 04.022 Immersive Augmented & Virtual Reality — impact score in GVN 9: 10 — brings experiential and simulated environments into everyday activity; in this GVN it strengthens the normalization of remote impact alongside physical presence.

- ART 05.031 Humanoid and General-Purpose Robots — impact score in GVN 9: 20 — brings general-purpose robotics into environments designed for humans; in this GVN it strengthens the normalization of remote impact alongside physical presence.

## **GVN SUMMARY**

GVN 9 is strategically important because it changes the meaning of distance across many other networks. The shift is already visible and may deepen rapidly. The greatest uncertainty concerns whether authenticity, trust and controllability can be preserved when remote impact becomes ubiquitous.

## **GVN 10 – Automation of Work**

### **KEY CONCLUSION**

The core transformation in GVN 10 is the automation of work moving from individual machines toward broad, coordinated, and partly human-independent task networks. The change is structural because it affects the organization of work, the tax base, professional identities, and what is regarded as human work in the first place. The strongest drivers are collaborative multi-agent AI, trustworthy AI, general-purpose robots, edge-based perception, and supportive infrastructure for autonomy. This is one of the fastest and broadest shifts across the whole economy.

### **UNDERLYING LOGIC OF THE GVN**

GVN 10 is organized around producing work outputs efficiently, safely and appropriately. The current dominant regime is based on repetitive automation, human-operated machines, the centrality of human skills, and the view that machines complement rather than broadly replace human labor. The system is sustained by professional identities, the need for control, and fear of autonomous machines.

The challenger regime centers on advanced autonomous machines, AI and machine learning, mobile robotics, 3D printing, sharing logic, and 24/7 service readiness. This suggests that work automation no longer means the mechanization of a single work step, but entire task chains in which humans remain in roles of supervision, exception handling, and goal setting.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward production and service environments in which more tasks can be launched, monitored, and corrected programmatically. The main benefits are productivity, availability, and lower costs, but at the same time liability, ethics, and tax-based issues become more acute. This suggests that work automation will spread gradually to almost all environments in which tasks can be described, sensed, and turned into machine decision or execution chains.



The change is likely to accelerate as trustworthy AI and physically general-purpose robotics move closer together. It remains unclear when the adaptation of human trust, responsibility structures and occupational systems will begin to follow technological possibility rather than slow it down.

### **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: moderate but accelerating. The basic layers of automation have strengthened quickly, but the broad deployment of human-independent task networks is still incomplete.
- 2026–2045: fast. By 2045, the technological drivers appear mature enough to reshape the structure of work widely, if institutional barriers do not halt the process.

### **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 10: 20 — enables coordinated action among many machines, software systems, and actors; in this GVN it strengthens the shift of work toward machine-produced performance.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 10: 20 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens the shift of work toward machine-produced performance.
- ART 05.031 Humanoid and General-Purpose Robots — impact score in GVN 10: 20 — brings general-purpose robotics into environments designed for humans; in this GVN it strengthens the shift of work toward machine-produced performance.
- ART 05.034 Supportive Infrastructure for Autonomy — impact score in GVN 10: 20 — builds the physical and digital support layer required by autonomy; in this GVN it strengthens the shift of work toward machine-produced performance.

### **GVN SUMMARY**

GVN 10 is strategically important because it directly reshapes work, taxation, and skill demand. The change appears to be accelerating and broad-based. The greatest uncertainty is how society handles the transformation of responsibility, livelihood, and the meaning of work.

## **GVN 11 – Work and Income**

### **KEY CONCLUSION**

The core transformation in GVN 11 is the detachment of work, earning, and economic agency from the exclusive model of wage labor and hierarchical organization. The change may be discontinuous because the same technologies that free work from place and institutions can also concentrate market power in new platforms.

The strongest drivers are connectivity, general-purpose robotics, AutoML, trustworthy AI, and digital learning networks. This is not only a labor-market change, but a reorganization of welfare, taxation, and social status.

## **UNDERLYING LOGIC OF THE GVN**

GVN 11 is organized around giving people the possibility to earn a livelihood, save resources, and influence their own well-being and the position of those close to them. The current dominant regime rests on specialized wage labor, large production structures, a strong role for ownership and capital, and the taxation of work. It is underpinned by the value placed on security, stability, hierarchies, and familiar roles.

The challenger regime emphasizes AI and robotization, the platform economy, crowdsourcing, small-scale self-sufficiency, remote work and self-direction. This suggests that the relationship between work and income is fragmenting: some income still arises in organizations, some on platforms, some through self-service and self-provisioning, and some through entirely new digital niches.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a diversification of work in which stable employment does not disappear entirely, but ceases to be the only socially legitimate form of livelihood. The main benefits are more meaningful work, greater self-direction, and lower transaction costs, but at the same time the erosion of the tax base, social-security challenges, and the psychological attachment to wage labor come to the fore. This suggests that the adaptive capacity of institutions is the real bottleneck of the transition.

If tools, connectivity and automated production resources truly democratize, part of the value of work may shift back to small actors and local networks. It remains unclear to what extent platforms, property rights, and algorithmic control capture this potential into a new dependency relationship.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: moderate. Remote work, platforms, and AI have already changed forms of earning, but the institutional core of wage labor remains strong.
- 2026–2045: fast and potentially discontinuous. By 2045, the combined effect of automation, the democratization of tools, and learning networks may rapidly alter the relationship between work and income if institutions begin to adapt.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 01.001 Global Broadband Connectivity — impact score in GVN 11: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens the dispersion of earning and work into forms beyond wage labor.

- ART 05.031 Humanoid and General-Purpose Robots — impact score in GVN 11: 20 — brings general-purpose robotics into environments designed for humans; in this GVN it strengthens the dispersion of earning and work into forms beyond wage labor.
- ART 03.018 Automated Machine Learning (AutoML) — impact score in GVN 11: 20 — lowers the threshold for using advanced analytics and optimization tools; in this GVN it strengthens the dispersion of earning and work into forms beyond wage labor.
- ART 11.089 Digital Learning Networks and Skill Credentialing — impact score in GVN 11: 10 — turns learning, the collection of evidence and qualifications into portable networks; in this GVN it strengthens the dispersion of earning and work into forms beyond wage labor.

## GVN SUMMARY

GVN 11 is strategically important because it defines the future logic of livelihood, taxation, and social position. The change may accelerate sharply if technological and institutional drivers align at the same time. The greatest uncertainty is whether the outcome is broader agency or a new and even less concealed dependency on platforms.

## GVN 12 – Health Care

### KEY CONCLUSION

The core transformation in GVN 12 is the shift from centralized health care built around population-level standards toward personalized, continuous, and partly user-managed health maintenance. The change is structural, but not necessarily institutionally revolutionary, because old systems will remain in parallel for a long time. The strongest drivers are trustworthy AI, precision medicine, connectivity, edge diagnostics, and an interoperable device ecosystem. The direction is toward health as a service and the continuous management of data flows, rather than the episodic care visit.

### UNDERLYING LOGIC OF THE GVN

GVN 12 is organized around enabling a healthy life for as long as possible and around preventing and treating disease. The current dominant regime rests on centralized and bureaucratic health-care systems, general recommendations, tight professional regulation, and institutional trust. It is underpinned by the values of equality, population health, and controlled pharmaceutical and care chains.

The challenger regime emphasizes personalized medicine, self-diagnostics, wearables, AI, genomics, biohacking, and innovations aimed at extending life. This suggests that health is beginning to split in two: some care remains strongly institutional, but an increasing share of measurement, prevention and choice moves closer to the user.

## ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward a system in which health is produced more continuously through data, analytics and individualized interventions. The main benefits are better targeting, greater individuality, and more anticipatory care, but misinformation, cybersecurity, self-diagnosis errors, and conflicts with professionals also come to the fore. This suggests that the legitimacy of health care will increasingly depend on its ability to combine personalization with reliability.

The change is likely to accelerate where data can be linked to clear benefits without shifting responsibility entirely onto the individual. It remains unclear how much inequality will grow if personalized health solutions are first more accessible to those with greater purchasing power or stronger digital skills.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate but accelerating. Wearables, AI and the use of genomic information have strengthened rapidly, but the basic system remains strongly institutional.
- 2026–2045: fast. By 2045, the combined effect of data, diagnostics and trustworthy AI may shift the center of gravity of health care decisively toward personalized and continuous care.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 09.073 Precision Medicine & Genomic Diagnostics — impact score in GVN 12: 20 — targets diagnostics and treatment to the individual biological profile; in this GVN it strengthens personalized and continuous health management.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 12: 20 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens personalized and continuous health management.
- ART 01.003 Edge AI for Sensor Data — impact score in GVN 12: 10 — brings sensing and decision-making close to the actual situation; in this GVN it strengthens personalized and continuous health management.
- ART 12.091 Universal IoT Interoperability Standards — impact score in GVN 12: 10 — lowers the friction of interoperability across device and system ecosystems; in this GVN it strengthens personalized and continuous health management.

## GVN SUMMARY

GVN 12 is strategically important because it directly affects quality of life, the cost structure of care, and the functional capacity of the population. The change appears accelerating but layered. The greatest uncertainty is how personalization, reliability, and equality can be kept within the same system.

## GVN 13 – Redressing Disabilities

### KEY CONCLUSION

The core transformation in GVN 13 is the shift from a model centered on protection and simple compensation toward an approach that actively expands functional capacity and augments it technologically. The change is structural but uneven, because the integration of assistance, rehabilitation, and autonomy-enhancing technologies is progressing at different speeds. The strongest drivers are advanced prosthetics and exoskeletons, trustworthy AI, edge-based sensor interpretation, robotics, and autonomous mobility. The direction is toward solutions in which barriers are removed both from the environment and from limitations in the user's own functional capacity at the same time.

### UNDERLYING LOGIC OF THE GVN

GVN 13 is organized around correcting or compensating for the harms caused by disability, functional limitations, or reduced capacity. The current dominant regime is based on institutional and home care, simple assistive devices, limited use of new technology, and strong guidance. Behind it are paternalism, protection and basic accessibility solutions.

The challenger regime centers on robotics, AI, artificial organs and implants, advanced assistive devices, personal AI assistants, and community-based forms of support. This suggests that the redressing of disability is shifting from compensation alone toward the active expansion of functional capacity and stronger self-reliance.

### ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward solutions in which physical support, cognitive assistance and environmental intelligence are linked together. The main benefits are greater independence, inclusion, and active aging, but the material also raises concerns on cybersecurity, data security, the risks of experimental solutions, and the challenge of rapid change. This suggests that the technical potential is strong, but the scale of the effects will be determined by acceptability and usability.

Environmental accessibility and personal technology are likely to function as mutually reinforcing layers rather than alternatives. It remains unclear how much advanced solutions can be funded through the public service system and how much of the change will remain market-driven.

### ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate. Assistive technology and AI have developed visibly, but broad transformation of the service structure is still incomplete.
- 2026–2045: moderate but accelerating. By 2045, technological capability may advance greatly, but the scale of the effects will depend on funding, safety and legal acceptability.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 04.024 Advanced Prosthetics & Exoskeletons — impact score in GVN 13: 20 — expands physical capacity through advanced assistive devices; in this GVN it strengthens the technological expansion and compensation of functional capacity.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 13: 10 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens the technological expansion and compensation of functional capacity.
- ART 05.029 Self-Driving Vehicles — impact score in GVN 13: 10 — shifts decision and control capacity from the human driver to the system; in this GVN it strengthens the technological expansion and compensation of functional capacity.
- ART 01.001 Global Broadband Connectivity — impact score in GVN 13: 10 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens the technological expansion and compensation of functional capacity.

## **GVN SUMMARY**

GVN 13 is strategically important because it directly concerns autonomy, participation and equality. The change appears realistic but layered. The greatest uncertainty is whether advanced solutions become broadly available or remain the benefit of a narrow user group.

# **GVN 14 – Acquiring Information**

## **KEY CONCLUSION**

The core transformation in GVN 14 is the shift in information acquisition from authorized sources and publishing organizations toward a decentralized, machine-mediated environment exposed to an authenticity crisis. The change is rapid and partly discontinuous because the availability, interpretation, and verifiability of information are changing at the same time. The strongest drivers are communications infrastructure, content-authenticity solutions, trustworthy AI, edge-based sensing, and satellite-based visibility. The direction is toward an information environment in which the volume of information grows, but the legitimacy of information becomes a more contested question.

## **UNDERLYING LOGIC OF THE GVN**

GVN 14 is organized around enabling the acquisition of information about events, conditions, and meanings in the world. The current dominant regime rests on organized information gathering, media publishing, limited observation, and officially certified sources. It is underpinned by belief in authorities, dependence on established sources, and the entertainmentization of information.

The challenger regime emphasizes digital platforms, search engines, AI, more advanced measuring devices, crowdsourcing, and machine interpretation. This suggests that information acquisition is increasingly becoming a question of who gets to produce observations, how they are filtered, and under what conditions they are regarded as authentic.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward near-continuous information acquisition in which the user can receive both primary data and preinterpreted views of the same issue. The main benefits are broader availability and stronger local usefulness, but bubbles, external interference, the difficulty of interpretation, and fake sources are also brought forward strongly. This suggests that competitive advantage in information acquisition is shifting increasingly toward verifiability and the quality of interpretation.

Greater technical visibility does not automatically produce greater shared understanding. On the contrary, the more data and interpretation machines are provided, the more important content authenticity, source comparison, and trustworthy AI become. It remains unclear what new institutional balance will emerge between legacy media, platforms and users.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: fast. The technical and organizational basis of information acquisition has already changed extremely quickly between 2018 and 2026.
- 2026–2045: fast and potentially discontinuous. By 2045, the combination of authenticity infrastructure, AI interpretation, and distributed sensing may alter the entire logic of information acquisition at once across multiple sectors.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 01.001 Global Broadband Connectivity — impact score in GVN 14: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens the decentralization of information acquisition and the new need for verifiability.
- ART 12.098 Content Authenticity Infrastructure — impact score in GVN 14: 20 — makes the origin and integrity of content more verifiable; in this GVN it strengthens the decentralization of information acquisition and the new need for verifiability.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 14: 10 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens the decentralization of information acquisition and the new need for verifiability.
- ART 01.003 Edge AI for Sensor Data — impact score in GVN 14: 10 — brings sensing and decision-making close to the actual situation; in this GVN it strengthens the decentralization of information acquisition and the new need for verifiability.

## **GVN SUMMARY**

GVN 14 is strategically important because it directly affects what is regarded as true and usable information. The change appears extremely fast. The greatest uncertainty is whether abundant information produces more shared visibility or a deeper crisis of trust.

## **GVN 15 – Proficiency and its Proof**

### **KEY CONCLUSION**

The core transformation in GVN 15 is the shift from degree- and institution-centered validation of competence toward continuous, evidence-based, and technologically supported credential building. The change is structural because it simultaneously affects learning, labor markets, certification, and the role of educational organizations. The strongest drivers are digital learning networks, trustworthy AI, immersive training, content authenticity, and the portability of personal data. The direction is toward competence that is increasingly demonstrated through practical evidence rather than through a single formal gatekeeper.

### **UNDERLYING LOGIC OF THE GVN**

GVN 15 is organized around enabling the acquisition of proficiency and its credible verification. The current dominant regime rests on traditional educational institutions, official assessment, siloed teaching, and recognition centered on titles and degrees. It is underpinned by the strong role of authorities and institutional quality assurance.

The challenger regime emphasizes online learning, simulations, gamification, VR/AR, competence-based credentials, and learning to learn. This suggests that the value of competence is shifting increasingly toward performance, evidence, and continuous updating rather than formal educational pathways alone.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a system in which learning is distributed across many environments while verification simultaneously becomes technically more precise. The main benefits are more direct feedback, stronger motivation, and more individualized progression, but the material also raises the readiness of teachers, quality assurance, and unequal access. This suggests that the transition succeeds only when new learning modes and credible verification develop together.

The relationship between labor markets and education is likely to change substantially. If competence can be demonstrated more precisely, the significance of the traditional degree monopoly also declines. It remains unclear how far employers, authorities, and professional communities are willing to give up older marks of quality.



## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate but accelerating. Online learning, simulations, and the use of competence data have strengthened quickly, but the formal logic of degrees remains strong.
- 2026–2045: fast. By 2045, evidence-based credentialing and digital learning may rapidly reshape the logic of qualification if employers and institutions begin to trust new forms of proof.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 11.089 Digital Learning Networks and Skill Credentialing — impact score in GVN 15: 20 — links learning, evidence collection, and qualifications into portable networks; in this GVN it strengthens evidence-based and continuously updated validation of competence.
- ART 04.022 Immersive Augmented & Virtual Reality — impact score in GVN 15: 10 — brings experiential and simulated environments into everyday activity; in this GVN it strengthens evidence-based and continuously updated validation of competence.
- ART 12.098 Content Authenticity Infrastructure — impact score in GVN 15: 10 — makes the origin and integrity of content more verifiable; in this GVN it strengthens evidence-based and continuously updated validation of competence.
- ART 12.094 Personal Data Portability & Trust Frameworks — impact score in GVN 15: 10 — gives the user a portable way to manage identity, rights and profile data; in this GVN it strengthens evidence-based and continuously updated validation of competence.

## GVN SUMMARY

GVN 15 is strategically important because it affects how capability is recognized and how people gain access to new roles. The change appears to be accelerating, but it depends on institutional acceptance. The greatest uncertainty is whether a genuinely open competence system emerges or a new certification monopoly.

## GVN 16 – Producing Experiences

### KEY CONCLUSION

The core transformation in GVN 16 is the shift from passive consumption toward participatory, immersive, and continuously networked experiences. The change is partly discontinuous because technology simultaneously changes content production, distribution, forms of participation, and the economic logic of experiences. The strongest drivers are global connectivity, XR, AI's ability to interpret human intent, and edge-based interpretation of sensory data. The direction is toward experiences that are less tied to place, more co-produced, and more precisely personalized.

## UNDERLYING LOGIC OF THE GVN

GVN 16 is organized around producing experiences, art, entertainment, and meaningful forms of participation. The current dominant regime rests on traditional art and entertainment forms, the producer–consumer relationship, institutions, and the authenticity of physical presence. It is underpinned by passive consumption, the preservation of tradition, and established production and distribution channels.

The challenger regime emphasizes digitalization, VR/AR, AI, robotics, interactivity and the democratization of experiences. This suggests that experience production is shifting away from the control of a few institutions toward an environment in which audiences, technology and distribution platforms shape content together.

## ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward experiences that are at once personalized, shared and multisensory. The main benefits are greater creativity, stronger sociality, and new forms of experience with ethical or mission-driven emphasis, but addiction, manipulation and social alienation are also raised as risks. This suggests that competitive advantage in the experience economy is shifting from content alone toward the ability to manage the form of participation and the intensity of the social experience.

Experience production is one of the GVNs in which technological change quickly becomes visible in everyday practice. It remains unclear how durable the value of authentic physical presence will be and to what extent institutions can preserve their position in the new experience economy.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: fast. Connectivity, platforms and digital participation have already changed the production of experiences rapidly between 2018 and 2026.
- 2026–2045: fast and potentially discontinuous. By 2045, the combination of XR, AI and intent interpretation may alter the entire logic of the experience economy very quickly.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 01.001 Global Broadband Connectivity — impact score in GVN 16: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens immersive, participatory, and personalized experiences.
- ART 04.022 Immersive Augmented & Virtual Reality — impact score in GVN 16: 20 — brings experiential and simulated environments into everyday activity; in this GVN it strengthens immersive, participatory, and personalized experiences.
- ART 04.026 AI Understanding of Human Intent & Context — impact score in GVN 16: 20 — interprets human intent, context and needs more effectively than before; in this GVN it strengthens immersive, participatory, and personalized experiences.

- ART 01.003 Edge AI for Sensor Data — impact score in GVN 16: 10 — brings sensing and decision-making close to the actual situation; in this GVN it strengthens immersive, participatory, and personalized experiences.

## **GVN SUMMARY**

GVN 16 is strategically important because it is tied to culture, social relations and the production of meaning. The change appears fast and self-reinforcing. The greatest uncertainty is whether the new experience infrastructure expands participation or increases the risks of manipulation and dependency.

# **GVN 17 – Safety and Security**

## **KEY CONCLUSION**

The core transformation in GVN 17 is the shift from a centralized, reactive and authority-driven safety model toward decentralized, anticipatory, and data-driven production of safety and security. The change is structural, but it contains a strong tension between safety, privacy, and trust. The strongest drivers are trustworthy AI, edge-based sensing, and interoperable IoT standards, supported by connectivity and multi-actor coordination. The direction is toward safety produced as a continuous interaction among the environment, the user and systems.

## **UNDERLYING LOGIC OF THE GVN**

GVN 17 is organized around protecting people, environments, and systems from threats, risks, and harm. The current dominant regime rests on centralized authorities, periodic inspections, reactive measures, and hierarchical control. It is underpinned by normativity, trust in institutions, and the expectation that society produces safety mainly from the top down.

The challenger regime emphasizes decentralized safety solutions, advanced technologies, personal diagnostics, crowdsourcing, and the growing risk awareness of individuals. This suggests that safety is becoming a continuously measurable and locally produced characteristic rather than merely an institutional service.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a system in which hazard detection, interpretation, and first response move partly closer to the user, devices, and the network edge. The main benefits are anticipation, participation, and individualized preparedness, but privacy issues, the erosion of trust, and the risk of shifting too much responsibility onto the individual are also highlighted. This suggests that improved safety may go hand in hand with a new layer of surveillance.

The legitimacy of the safety system is likely to depend increasingly on whether data-driven approaches can be made transparent and proportionate. It remains unclear how far people will accept continuous monitoring in exchange for a stronger sense of safety.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: moderate. The technological drivers have strengthened clearly, but in the logic of the material, the institutional structure of safety changes more slowly than the technical layer.
- 2026–2045: moderate but accelerating. By 2045, anticipatory and networked safety may strengthen significantly if interoperability and trustworthy AI mature sufficiently.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 03.017 Trustworthy AI Systems — impact score in GVN 17: 20 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens anticipatory and decentralized safety.
- ART 01.003 Edge AI for Sensor Data — impact score in GVN 17: 20 — brings sensing and decision-making close to the actual situation; in this GVN it strengthens anticipatory and decentralized safety.
- ART 12.091 Universal IoT Interoperability Standards — impact score in GVN 17: 20 — lowers the friction of interoperability across device and system ecosystems; in this GVN it strengthens anticipatory and decentralized safety.
- ART 03.019 Collaborative Multi-Agent AI — impact score in GVN 17: 10 — enables coordinated action among many machines, software systems and actors; in this GVN it strengthens anticipatory and decentralized safety.

## GVN SUMMARY

GVN 17 is strategically important because it defines the basis of risk management across many other networks. The change appears medium-paced but steadily strengthening. The greatest uncertainty is the point at which anticipation begins to resemble continuous control and starts to erode trust.

# GVN 18 – Collaboration and Trust

## KEY CONCLUSION

The core transformation in GVN 18 is the shift of trust from personal relationships, hierarchies, and national institutions toward networked, transparent, and technically mediated trust mechanisms. The change is structural, but its success depends on whether the new trust is produced in a genuinely open way or merely through new kinds of gatekeepers. The strongest drivers are global connectivity, decentralized trust networks, trustworthy AI, privacy-preserving learning, and machine-readable regulation. The direction is toward cooperation that can be built more broadly than before without a pre-existing institutional bond.

## UNDERLYING LOGIC OF THE GVN

GVN 18 is organized around enabling cooperation and the building of trust between individuals, communities, and organizations. The current dominant regime is based

on hierarchical trust, cultural norms, public oversight, and the legal system. In addition, national boundaries and the protection of privacy have been key conditions of trust.

The challenger regime emphasizes digital platforms, peer-trust mechanisms, reputation, transparency, blockchain, crowdfunding, and crowdsourcing. This suggests that trust is increasingly becoming a verifiable, measurable, and portable property rather than something grounded only in institutional membership.

## **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a system in which cooperation can be launched among a wider range of actors more quickly than before, provided that identity, data rights, reputation, and the interpretation of rules are interoperable. The main benefits are openness, stronger community, and greater globality, but fraud, regulatory conflicts, and the slow pace of trust-building are also highlighted. This suggests that technical infrastructure can reduce friction, but cannot remove the social cost of building trust.

New trust mechanisms may also change how power is distributed: who can prove, verify, certify, and regulate the terms of cooperation. It remains unclear whether genuinely decentralized trust systems will emerge or whether much of the new trust infrastructure will end up under the control of a few platforms.

## **ESTIMATED PACE OF TRANSFORMATION**

- 2018–2026: moderate. Digital solutions for collaboration and trust have strengthened, but institutional trust has not quickly lost its position.
- 2026–2045: moderate but accelerating. By 2045, the combined effect of data rights, decentralized verification and machine-readable regulation may accelerate the shift clearly.

## **MOST INFLUENTIAL ARTS FOR THIS GVN**

- ART 01.001 Global Broadband Connectivity — impact score in GVN 18: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens networked and technically verifiable trust-building.
- ART 11.083 Decentralized Trust Networks (Web3 & Blockchain) — impact score in GVN 18: 20 — creates technical mechanisms for decentralized verification and transaction trust; in this GVN it strengthens networked and technically verifiable trust-building.
- ART 03.017 Trustworthy AI Systems — impact score in GVN 18: 10 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens networked and technically verifiable trust-building.
- ART 12.096 Machine-Readable Regulation (Rules as Code) — impact score in GVN 18: 10 — turns the interpretation of rules into something that can be implemented programmatically; in this GVN it strengthens networked and technically verifiable trust-building.

## **GVN SUMMARY**

GVN 18 is strategically important because many other networks do not scale without functional trust. The change appears credible but socially demanding. The greatest uncertainty is whether the new trust infrastructure replaces the old one or is built on top of it as a new layer of control.

## **GVN 19 – Existential Meaning**

### **KEY CONCLUSION**

The core transformation in GVN 19 is the shift in the sources of meaning from work, status, and local peer groups toward networks, experiences, communities, and new technological forms of self-expression. The change is slower and more cultural than in many other GVNs, but its effects may be deep. The strongest drivers are connectivity, immersive experiences, trustworthy AI, general-purpose robots, and portable identity. The direction is toward a situation in which meaning is less and less built around a single assumed life path.

### **UNDERLYING LOGIC OF THE GVN**

GVN 19 is organized around giving people the experience that life is purposeful, valuable, and socially recognized. The current dominant regime rests on identity built around work and profession, hierarchical divisions of labor, status competition, and traditional forms of voluntary work. Behind it are the desire for stability, the need for acceptance and fear of change.

The challenger regime emphasizes digitalization, robotization, the gamification of work, local and online communities, VR/AR, and global sharing platforms. This suggests that the production of meaning is gradually detaching from an exclusive hierarchy of work and status and spreading across multiple parallel communities and experiences.

### **ANTICIPATED DIRECTION OF TRANSFORMATION**

The anticipated direction is toward a fragmented but more diverse environment of meaning. The main benefits are new forms of self-expression, global participation, and new communities, but the material also highlights difficult transitions, unrealistic expectations, and the risk of negative influences. This suggests that the new infrastructure of meaning may increase agency, but may also expose people to more unstable comparison and identity pressure than before.

The shift is likely to accelerate if work is automated and experiential and community-based alternatives gain greater cultural legitimacy. It remains unclear whether a new stable structure of meaning will emerge or whether the outcome will be continuous competition for attention, participation and visibility.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: slow but strengthening. In the logic of the material, cultural change proceeds more slowly than technical change, even though platforms and networks have already changed the sources of meaning.
- 2026–2045: moderate. By 2045, automation, networked communities and immersive experiences may reinforce the shift significantly, but cultural adoption is likely to remain relatively slow.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 04.022 Immersive Augmented & Virtual Reality — impact score in GVN 19: 20 — brings experiential and simulated environments into everyday activity; in this GVN it strengthens the shift of meaning toward networks, experiences, and self-expression.
- ART 01.001 Global Broadband Connectivity — impact score in GVN 19: 20 — builds a near-ubiquitous connectivity layer; in this GVN it strengthens the shift of meaning toward networks, experiences, and self-expression.
- ART 12.094 Personal Data Portability & Trust Frameworks — impact score in GVN 19: 10 — gives the user a portable way to manage identity, rights and profile data; in this GVN it strengthens the shift of meaning toward networks, experiences, and self-expression.
- ART 05.031 Humanoid and General-Purpose Robots — impact score in GVN 19: 10 — brings general-purpose robotics into environments designed for humans; in this GVN it strengthens the shift of meaning toward networks, experiences, and self-expression.

## GVN SUMMARY

GVN 19 is strategically important because it concerns life direction, identity, and social recognition. The change appears slow but far-reaching. The greatest uncertainty is whether the old structure of meaning is sustainably replaced or merely dispersed without a new shared foundation.

## GVN 20 – Power Structures

### KEY CONCLUSION

The core transformation in GVN 20 is the shift of power from hierarchical structures tied to geography and organizational position toward networks, protocols, comparable services and partly programmatically enforced governance. The change is clearly structural and may be discontinuous in some areas, because power can move quickly to whoever controls the coding and implementation of rules. The strongest drivers are trustworthy AI, rules as code, platform interoperability and decentralized governance. The direction is toward governance in which power does not disappear, but changes form.

## UNDERLYING LOGIC OF THE GVN

GVN 20 is organized around optimizing shared decision-making in organizations and society. The current dominant regime is built on hierarchical organizations, geographically based public authority, the structural influence of elites, and a broad machinery of legislation and oversight. Behind it are conservatism, traditional decision-making, and an emphasis on stability.

The challenger regime emphasizes digitalization, automation, decentralized and subject-based governance, platform communities, a new boundary between markets and hierarchies, and the use of AI and crowdsourcing. This suggests that the core of power is shifting toward the ability to define rule interfaces, comparability, and verifiable execution.

## ANTICIPATED DIRECTION OF TRANSFORMATION

The anticipated direction is toward governance in which rules can be published, compared, simulated, and enforced more dynamically than before. The main benefits are better decision quality, subsidiarity, democratization, and more flexible control, but the material also highlights costs, complexity, inequality, and resistance from administrative tradition. This suggests that the decentralization of power does not automatically mean an equalization of power.

In this GVN in particular, the compatibility of technology and institutions will decide everything. If regulation, trust, and algorithmic enforcement can be connected credibly, change may accelerate quickly. It remains unclear whether the outcome will be more open governance models or new kinds of technocratic gatekeepers.

## ESTIMATED PACE OF TRANSFORMATION

- 2018–2026: slow but strengthening. In the logic of the material, power structures change slowly, even though digitalization has already opened up new alternatives and new pressures.
- 2026–2045: moderate but accelerating. By 2045, the machine-readability of rules, decentralized governance and platform models may speed up the change if legitimacy can be preserved.

## MOST INFLUENTIAL ARTS FOR THIS GVN

- ART 03.017 Trustworthy AI Systems — impact score in GVN 20: 20 — makes the use of AI more auditable and institutionally acceptable; in this GVN it strengthens the shift of power and governance from hierarchies toward code and networks.
- ART 12.096 Machine-Readable Regulation (Rules as Code) — impact score in GVN 20: 20 — turns the interpretation of rules into something that can be implemented programmatically; in this GVN it strengthens the shift of power and governance from hierarchies toward code and networks.



- ART 11.084 Platform Cooperatives & Fair Work — impact score in GVN 20: 20 — offers an alternative to investor-driven platforms as community-owned networks; in this GVN it strengthens the shift of power and governance from hierarchies toward code and networks.
- ART 11.088 Scalable Decentralized Governance — impact score in GVN 20: 20 — makes decentralized decision-making by large groups more feasible; in this GVN it strengthens the shift of power and governance from hierarchies toward code and networks.

## GVN SUMMARY

GVN 20 is strategically important because it defines the rules of the game for other networks. The change will probably advance slowly at first, but may accelerate as new forms of governance prove their practicality. The greatest uncertainty is whether power actually broadens or only shifts into new technological forms of mediation.

# Summary of results 2: 12 technology groups, 100 anticipated radical technologies

This is a summary of the anticipated radical technology breakthroughs. The ARTs form twelve broad technology groups whose expected development is introduced here. Each group is complemented with a list of ARTs belonging to it.

The maturity levels mentioned in the ART lists vary in the range from 1 to 7 (for full maturity criteria, see Attachment 6):

1. Scientific principle has been theoretically proven
2. Scientific principle has been measured in laboratory
3. Functional laboratory prototype exists
4. Proof-of-Concept: Prototype does useful work
5. Competing production prototypes are being developed
6. Products are delivered to customers
7. Competing products are increasingly delivered to customers

The ART lists also mention total impact score for each ART. This anticipated impact varies from 16 (ART 10.081: Closed-loop life support systems) to 1440 (ART 01.001: Global broadband connectivity). For complete ranking of all 100 ARTs, see Attachment 1. ART total impact scores are calculated by summing up an ARTs potential

maximum impact in each GVN by year 2045 and multiplying it by the maturity. Detailed principles on how ART impact in a GVN is evaluated, see Attachment 6.

All the 100 ARTs are described in detail in Attachment 2 in terms of how each ART is anticipated to solve a certain technological bottleneck and what is its potential and maturity. Also, the evidence of each ART's current development status is presented. Further, the impact of each ART within each GVN is analysed in Attachment 3. In this summary, the development is described jointly for each different technology group. This summary was created by using the RTI-GPT.

## Group 1 – Sensing, Measurement & Connectivity

### KEY CONCLUSION

Group 1 brings together technologies that turn sensing, measurement, and connectivity into infrastructural capabilities rather than isolated devices. The group matters because almost all later automation, AI, and platform solutions depend on data being generated reliably, moving to the right place, and remaining usable even under disruption. The group is mostly enabling, but already directly transformative in some areas: broadband connectivity, edge computing, and privacy-preserving sensing are moving from early adoption into broader basic infrastructure. At the same time, some subtracks, such as integrated sensing and communication (ISAC) and parts of quantum sensing, are still clearly in the development phase.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is turning the physical world into something that can be continuously measured, interpreted, and networked. It addresses bottlenecks related to slow observation, breaks in data transfer, the limits of centralized computing, and the fact that in many environments, signals are too weak, noisy, or delayed for safe automation. When sensing, communication, and local decision-making are combined, they create the basis for real-time coordination, remote operation, safety, and operational reliability.

The strongest impact appears where large numbers of distributed objects must be kept visible and controllable at the same time: transport, logistics, energy, the built environment, remote operations, and automated services. The group also determines how much power shifts toward networks, sensors, and the actors that control them. Its significance is therefore not only technical but institutional: it affects what can be monitored, verified, optimized and automated, and on what terms.

### DEVELOPMENT OUTLOOK

The most mature subtracks are currently global broadband connectivity, edge AI for sensor data, and privacy-preserving sensing. These already have functioning services, clear commercial use cases and multiple investing actors. Quantum and high-precision sensing, as well as quantum-resilient communication, are beyond

pure research, but adoption is still selective. Integrated sensing and communication appears promising, but it is still more of an emerging architectural direction than a mature market.

The next phase is likely to arise not from a single breakthrough but from layering: connectivity, sensors, local AI, security and privacy gradually merging into a single operational infrastructure. This also increases dependence on telecom networks, specialized chips, standards and cybersecurity. What remains unclear is which actors will ultimately control this infrastructure layer, how quickly costs will fall and to what extent regulation begins to limit continuous sensing in public environments.

## **ARTS IN THE GROUP**

- ART 01.001 Global Broadband Connectivity — maturity: 6 — total impact score: 1440
- ART 01.002 Ultra-Low Latency Networks — maturity: 5 — total impact score: 505
- ART 01.003 Edge AI for Sensor Data — maturity: 6 — total impact score: 966
- ART 01.004 Quantum & High-Precision Sensing — maturity: 5 — total impact score: 240
- ART 01.005 Micro/Nano Sensor Networks — maturity: 5 — total impact score: 480
- ART 01.006 Privacy-Preserving Pervasive Sensing — maturity: 6 — total impact score: 696
- ART 01.007 Quantum-Resilient and Secure Communication Networks — maturity: 5 — total impact score: 345
- ART 01.008 Integrated Sensing and Communication (ISAC) — maturity: 4 — total impact score: 336

## **GROUP SUMMARY**

The strength of Group 1 lies in providing an operational layer of sensing and connectivity for almost all other technology groups. The greatest uncertainties concern security, privacy, energy efficiency and whether the resulting infrastructure model remains open or becomes highly concentrated. Strategically, the group is important precisely because it often remains invisible to the end user, yet it defines the practical scope within which automation, remote operation and data-driven services can function at all.

## Group 2 – Computing Hardware & Non-Von-Neumann Paradigms

### KEY CONCLUSION

Group 2 brings together technologies that reshape the physical basis of computing: new transistors, memory, photonics, quantum computing, and memory-centric paradigms. The group is highly significant because it affects the energy, speed, and cost at which later AI, sensing, and simulation systems can operate. It is above all enabling rather than already widely and directly transformative. At the same time, it is internally uneven: some solutions are approaching commercial use, while others are still in the research and prototype phase.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the attempt to break through the limits of the current computing architecture. It addresses bottlenecks related to the energy cost of moving data, the slowing of transistor scaling, thermal load, latency in memory hierarchies, and the fact that many future applications require more computation closer to the sensor and with far smaller power budgets than current platforms allow.

The strongest impact is indirect: the group does not usually transform an industry on its own, but it changes the economic and technical feasibility of other technologies. If computing becomes substantially more energy-efficient, denser or more distributed, the effects appear in edge computing, digital twins, autonomy, photonic information processing, and sensor networks. Its strategic importance is therefore greater than its immediate visibility in the market.

### DEVELOPMENT OUTLOOK

The most mature subtracks are compute-in-memory and neuromorphic chips, next-generation memory and storage, and early specialized uses of photonic computing. These already have working prototypes, some delivered products or clear industrial development paths. New transistor materials and molecular computing are clearly in earlier development phase: their principles and laboratory-scale implementations have been demonstrated, but industrial scale, reliability and the software ecosystem remain open questions.

The group is likely to advance asymmetrically. Instead of one unified new computing paradigm, the market will probably see several parallel specialized solutions: in-memory computing for certain AI workloads, photonics for bandwidth-intensive tasks, new memory technologies between storage and fast cache, and quantum computing for limited optimization and simulation problems. What remains unclear is when these become an invisible new baseline for users, or how quickly they displace the currently dominating CMOS-based solutions at scale.

## ARTS IN THE GROUP

- ART 02.009 Compute-in-Memory & Neuromorphic Chips — maturity: 5  
— total impact score: 405
- ART 02.010 Novel transistor technologies and materials beyond silicon CMOS — maturity: 3 — total impact score: 144
- ART 02.011 Quantum Computing Platforms — maturity: 5  
— total impact score: 170
- ART 02.012 Photonic and Optical Computing — maturity: 5  
— total impact score: 200
- ART 02.013 Next-Gen Memory & Storage — maturity: 5  
— total impact score: 240
- ART 02.014 Molecular Computing — maturity: 3 — total impact score: 18

## GROUP SUMMARY

The strength of Group 2 lies in its potential to remove the energy, thermal and latency bottlenecks that many other radical technologies run into. The greatest uncertainties concern manufacturability, software, standardization, and which sub-tracks will find a sufficiently large market. Strategically, the group matters because it will determine the long-term performance and cost structure of the entire digital infrastructure.

## Group 3 – Artificial Intelligence & Learning Systems

### KEY CONCLUSION

Group 3 describes the evolution of AI toward more coordinated, reliable, and autonomous operation. The group is important because it no longer concerns only the accuracy of individual models, but also how machine learning can be linked to decision-making, collaboration, privacy, automation, and scientific discovery. Some parts of the group are already directly transformative: multi-agent AI, federated learning, AutoML and trustworthy AI are moving into practical deployment. Causal reasoning and autonomous scientific discovery are still more emerging capabilities than established infrastructure.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the shift of AI from pattern recognition toward more systematic collaboration, causal understanding, safe deployment, and scalable learning. It addresses bottlenecks related to fragmented data, the difficulty of maintaining models, reliability, coordination, and the fact that complex environments require many agents acting together rather than predictions from one model alone.

The strongest impact appears where decisions must be made quickly, in distributed form and with justification: network control, autonomy, logistics, production, platform economies, and research. At the same time, the group changes organizational power relations by moving more judgment and optimization into software stacks, data integration, and safety assurance. This makes it a change in operating logic, not just a group of tools.

## DEVELOPMENT OUTLOOK

The most mature subtracks are collaborative multi-agent AI, federated and privacy-preserving learning, AutoML, and several trustworthy AI practices. These already have production use, functioning software libraries, pilots or growing standardization. Causal learning and reasoning is clearly useful, but still only mid-stage in terms of the full promise. AI-driven autonomous scientific discovery has moved well beyond prototypes, toward concrete use cases, but not yet into broad research infrastructure.

The next phase is likely to develop along two converging directions. The first is operational: multiple agents, automated model building, and privacy-compatible learning become part of everyday processes. The second is epistemic: models must produce results that are better justified, auditable, and resistant to intervention errors. What remains unclear is when reliability and causal requirements become real market thresholds, or to what extent autonomous AI-driven discovery begins to replace human-led research processes.

## ARTS IN THE GROUP

- ART 03.015 Causal Learning & Reasoning — maturity: 4 — total impact score: 512
- ART 03.016 Federated & Privacy-Preserving Learning — maturity: 6 — total impact score: 726
- ART 03.017 Trustworthy AI Systems — maturity: 5 — total impact score: 1065
- ART 03.018 Automated Machine Learning (AutoML) — maturity: 6 — total impact score: 636
- ART 03.019 Collaborative Multi-Agent AI — maturity: 6 — total impact score: 1080
- ART 03.020 Quantum-Accelerated AI Systems — maturity: 5 — total impact score: 120
- ART 03.021 AI-Driven Autonomous Scientific Discovery — maturity: 5 — total impact score: 330

## GROUP SUMMARY

The strength of Group 3 lies in its ability to turn AI from an isolated analytics function into a layer for coordinating and governing action. The greatest uncertainties concern explainability, safety, data governance, and how much decision-making

organizations are willing to transfer to agent systems. Strategically, the group is important because it affects productivity, risk management, and the governing logic of the digital economy at the same time.

## **Group 4 – Human-Machine Interaction & Augmentation**

### **KEY CONCLUSION**

Group 4 brings together technologies that reshape the interface between humans and systems. Its significance lies in making digital environments more immediate, natural and individualized, but also in deepening surveillance, interpretation, and dependence on neuro- or behavioral data. The group is highly heterogeneous: XR and advanced prosthetics are already relatively mature, while brain-to-brain interfaces and memory prostheses are still at a much earlier development stage. Overall, the group is more enabling and human-centered than directly transformative at the level of whole systems.

### **SIGNIFICANCE OF THE TECHNOLOGY AREA**

The common denominator of the group is the deepening of the interface. Its technologies aim to reduce friction between human perception, intention and movement and the digital system. They address bottlenecks related to remote or clumsy interaction, difficult-to-interpret context, limits in physical capability, and the fact that today's keyboard, screen, and touch paradigms are no longer sufficient for all use cases.

The strongest impact appears in training, remote operation, healthcare, industrial support, accessibility, and new consumer interfaces. At the same time, the group changes what can be inferred or measured about a person during use: intent, attention, memory function, and neural response can become part of the system's input. This creates both major potential and significant ethical and regulatory tensions.

### **DEVELOPMENT OUTLOOK**

The most mature subtracks are immersive AR/VR and advanced prosthetics and exoskeletons. These already have products, competition, and growing adoption. Brain-computer interfaces have moved from the laboratory stage to clinical or early commercial paths, but the field remains unfinished. AI understanding of human intent and context is important, but still mid-stage because deployment requires both technical reliability and social acceptability.

The greatest impact may not come from a single breakthrough product, but from the convergence of multiple interface technologies. XR, intent interpretation, haptic systems, and neural interfaces may together shift many activities toward more natural control and more individualized support. What remains unclear is long-term acceptance, price development, and the extent to which consumers accept the use of deep behavioral and neural data in everyday interfaces.



## ARTS IN THE GROUP

- ART 04.022 Immersive Augmented & Virtual Reality — maturity: 6  
— total impact score: 852
- ART 04.023 Brain-Computer Interfaces (BCI) — maturity: 5  
— total impact score: 275
- ART 04.024 Advanced Prosthetics & Exoskeletons — maturity: 6  
— total impact score: 420
- ART 04.025 Haptic and Multi-Sensory Feedback Systems — maturity: 4  
— total impact score: 264
- ART 04.026 AI Understanding of Human Intent & Context — maturity: 4  
— total impact score: 640
- ART 04.027 Brain-to-Brain Interfaces — maturity: 3 — total impact score: 57
- ART 04.028 Memory Prostheses — maturity: 4 — total impact score: 116

## GROUP SUMMARY

The strength of Group 4 lies in its ability to improve usability, accessibility and human capability in situations where current interfaces are too clumsy. The greatest uncertainties concern safety, data protection, clinical evidence and social acceptance. Strategically, the group matters because the interface often determines whether a technology remains a niche solution or becomes part of everyday life.

## Group 5 – Robotics & Physical Autonomy

### KEY CONCLUSION

Group 5 brings together the technologies of physical autonomy: self-driving vehicles, general-purpose robots, autonomous aerial and aquatic systems, and the environments that support them. This is one of the clearest directly transformative groups because it affects the division of labor, safety, the use of space, and the way services are delivered. The group is nevertheless internally uneven: self-driving vehicles and some autonomous robotic systems are already far along, while solutions such as power beaming are in much earlier development phases. Overall, the group marks a shift toward software-directed operation of the physical world.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the ability to shift sensing, movement and task execution partly or entirely from humans to machines. It addresses bottlenecks related to labor scarcity, safety risks, slow reaction, the difficulty of around-the-clock presence, and the fact that many environments are expensive, dangerous, or ergonomically poor for humans. Autonomy here does not mean a single robot, but whole systems of physical agents and the infrastructures that support them.

The strongest impact appears in transport, logistics, maintenance, inspections, semi-public spaces, and infrastructure. The group also changes ownership and power: when physical action becomes controlled by software stacks, maps, sensors, and remote operations centers, markets may concentrate in new ways. This is therefore not only about automating tools, but more broadly about who controls the physical service layer.

## DEVELOPMENT OUTLOOK

The most mature subtracks are self-driving vehicles, fully autonomous drones and robots in certain environments, and supportive infrastructure for autonomy. These already have strong regulatory, pilot, and delivery evidence. Humanoid and general-purpose robots and soft robotics appear to be progressing quickly, but the realism of deployment varies greatly by task. Optical and microwave power beaming for persistent robotics is clearly an earlier and narrower subtrack.

The group is likely to advance less through a single robot than through a whole operating system of sensors, rules, remote control, charging, infrastructure, and safety verification. Autonomy will probably move first in bounded environments where tasks are repetitive and risks manageable. What remains unclear is how quickly work roles change, to what extent citizens accept large-scale robotic presence, and how lasting the early cost advantages will be.

## ARTS IN THE GROUP

- ART 05.029 Self-Driving Vehicles — maturity: 6 — total impact score: 1044
- ART 05.030 Drone Swarms & Aerial Robots — maturity: 5 — total impact score: 485
- ART 05.031 Humanoid and General-Purpose Robots — maturity: 5 — total impact score: 985
- ART 05.032 Soft Robotics & Bio-Inspired Machines — maturity: 5 — total impact score: 355
- ART 05.033 Fully Autonomous Drones, Robots & Underwater Vehicles — maturity: 6 — total impact score: 612
- ART 05.034 Supportive Infrastructure for Autonomy — maturity: 5 — total impact score: 645
- ART 05.035 Optical/Microwave Power Beaming for Persistent Robotics — maturity: 4 — total impact score: 116
- ART 05.036 Gecko-Inspired Dry-Adhesion Mobility & Manipulation — maturity: 5 — total impact score: 115

## GROUP SUMMARY

The strength of Group 5 lies in the way it shifts the impact of radical technology into the physical environment in the most visible way. The greatest uncertainties concern safety, liability, the infrastructure costs of deployment, and social acceptance.

Strategically, the group matters because it can transform entire service models rather than merely make current processes somewhat more efficient.

## Group 6 – Additive, Agile & Digital Manufacturing

### KEY CONCLUSION

Group 6 concerns manufacturing flexibility, digital steerability, and the renewal of material forms. It is not as visibly consumer-facing as autonomy or energy, but it is an important transformation layer in the production economy: it determines how quickly products can be designed, modified, repaired, and manufactured close to demand. Maturity varies clearly; digital twins and agile production systems are already far along, while parts of 4D printing and bio-fabrication remain in earlier development phases. The group is therefore mainly enabling, but in many industrial networks it can also be directly transformative.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the move away from rigid, long-series, and geographically dispersed production toward more rapidly adjustable, data-driven, and partly more local production. It addresses bottlenecks related to long development and lead times, high setup costs, weak production visibility, and the fact that product variation and repairability clash with the logic of mass-production optimization.

The strongest impact appears in manufacturing, maintenance, spare parts, supply-chain flexibility, and the possibilities of local production. The group can also affect how dependent companies remain on distant production hubs. At the same time, it shifts competition toward model-based definition, software integration, material expertise, and the reprogrammability of production systems.

### DEVELOPMENT OUTLOOK

Digital twin and simulation-driven production is the most mature and systematic subtrack in the group. Reconfigurable and agile factories, as well as circular and sustainable manufacturing, are also clearly on a practical development path. Multi-material and hybrid 3D printing works, but remains a more limited area of proof-of-concept and specialized use. 4D printed and programmable materials and bio-fabrication technologies are in earlier development phases, and the material does not yet indicate a broad industrial breakthrough for them.

The core of the group's development is the softwareization of manufacturing. This means that competitiveness increasingly comes from simulation, data, rapidly switchable processes, and the ability to manufacture smaller batches economically. What remains unclear is how far this really brings manufacturing closer to demand, or how quickly the cost advantage scales beyond high-skill niche applications.

## ARTS IN THE GROUP

- ART 06.037 Multi-Material & Hybrid 3D Printing — maturity: 4  
— total impact score: 348
- ART 06.038 Digital Twin & Simulation-Driven Production — maturity: 6  
— total impact score: 546
- ART 06.039 Reconfigurable & Agile Factories — maturity: 5  
— total impact score: 490
- ART 06.040 Circular & Sustainable Manufacturing — maturity: 4  
— total impact score: 356
- ART 06.041 Bio-fabrication technologies — maturity: 5 — total impact score: 190
- ART 06.042 4D Printed & Programmable Materials — maturity: 3  
— total impact score: 147
- ART 06.043 Volumetric Additive Manufacturing — maturity: 5  
— total impact score: 225

## GROUP SUMMARY

The strength of Group 6 lies in increasing the flexibility, visibility, and modifiability of production without requiring the whole industrial base to be replaced at once. The greatest uncertainties concern material acceptance, quality assurance, integration into legacy factory environments, and the speed at which new manufacturing logics become cost competitive. Strategically, the group matters because it directly affects the future shape of industrial resilience, security of supply, and production structure.

## Group 7 – Advanced Materials & Nano-engineering

### KEY CONCLUSION

Group 7 brings together material technologies whose role is to improve performance, durability, energy efficiency, and new physical properties. The group is broad and internally dispersed: it includes both very long-term ambitions such as room-temperature superconductors and solutions much closer to market, such as coatings, composites, thermal materials, and power semiconductors. The group is mostly enabling, but in some subtracks it has a clearly directly transformative role as an enabler of other shifts, especially in energy and mobility. This is precisely why it is strategically important, even when individual materials are not directly visible to the end user.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the transformation of the material base: the conduction and storage of energy, wear, mass, thermal properties, surfaces, and component durability are being redefined. It addresses bottlenecks that arise when

current materials are no longer sufficient for lighter vehicles, more efficient powertrains, smart surfaces, safer electronics, or longer lifetimes. The group therefore often acts as a foundational layer of change for other technology groups.

The strongest impact appears in energy, transport, manufacturing, electronics, buildings, and thermal systems. The presence in the same group of power semiconductors, smart thermal materials, composites, catalysts, and advanced coatings shows that this is not one market but many critical intermediate technology layers. At the same time, materials tie development strongly to supply chains, testing, certification, and long service lives.

## DEVELOPMENT OUTLOOK

The most mature subtracks are metamaterials for novel optics and connectivity, nano-catalysts and advanced coatings, self-healing and smart polymers, and smart thermal materials. In addition, rare-earth-free magnets and several lightweight composites are progressing as usable solutions. Ultra-wide-bandgap power semiconductors still have a lower maturity classification, even though their impact potential is very high. Room-temperature superconductors are clearly the earliest and most uncertain subtrack in the group.

The group's impact is likely to come not from one giant material breakthrough, but from the accumulation of several medium-sized improvements within the same system. For example, thermal materials, coatings, lightweight composites, and power semiconductors can together change the energy balance, safety, and maintainability of an entire product. What remains unclear is the cost curve of these materials, the speed of scaling, and the extent to which environmental and recycling issues begin to limit the broad use of some solutions.

## ARTS IN THE GROUP

- ART 07.044 Metamaterials for Novel Optics & Connectivity — maturity: 6  
— total impact score: 360
- ART 07.045 Room-Temperature Superconductors — maturity: 2  
— total impact score: 134
- ART 07.046 Self-Healing & Smart Polymers — maturity: 5  
— total impact score: 300
- ART 07.047 Nano-Catalysts & Advanced Coatings — maturity: 5  
— total impact score: 310
- ART 07.048 High-Entropy Alloys & Advanced Metals — maturity: 4  
— total impact score: 188
- ART 07.049 Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation — maturity: 5  
— total impact score: 155
- RT 07.050 Graphene and Nanotube Composites for Lightweight Strength  
— maturity: 4 — total impact score: 272

- ART 07.051 Smart Thermal Materials for Energy-Efficient Heating & Cooling — maturity: 5 — total impact score: 345
- ART 07.052 Rare-Earth-Free Magnets for Sustainable Motors — maturity: 4 — total impact score: 236
- ART 07.053 Nano-Engineered Membranes for Low-Energy Desalination — maturity: 6 — total impact score: 138
- ART 07.054 Ultra-Wide-Bandgap (UWBG) Power Semiconductors — maturity: 3 — total impact score: 216
- ART 07.055 Solid Hydrogen Storage Materials for Safe, Dense Fuel — maturity: 4 — total impact score: 124

## GROUP SUMMARY

The strength of Group 7 lies in its broad impact on the performance of other technology groups. The greatest uncertainties concern manufacturability, critical raw materials, long-term testing, and approval processes. Strategically, the group matters because many visible transformations only become practical once materials make them economically and technically possible.

## Group 8 – Energy Generation, Storage & Conversion

### KEY CONCLUSION

Group 8 brings together the technologies of energy generation, storage, and conversion that largely determine the cost, reliability, and emissions profile under which the rest of society can operate. The group includes both technologies close to large-scale deployment and long-term options with high uncertainty. Microgrids, grid-scale storage, solid-state batteries, and thin-film solar appear to be at the core of practical transformation, while fusion is clearly in earlier development stages. Overall, the group is directly transformative, because energy is not merely an input variable but the basis of the operating cost and reliability of all other technological changes.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the ability to produce, store, distribute, and use energy more flexibly, more decentrally and more cleanly. It addresses bottlenecks related to electrification, peak-power management, recovery from outages, energy supply for remote sites, and the fact that many new technologies require more electricity, heat, or safe energy storage than current systems allow.

The strongest impact appears in transport, industry, buildings, distributed networks, and the resilience of society as a whole. The group also changes power relations, because it shifts competition away from centralized energy generation toward more

flexible combinations of storage, microgrids, local production, new battery technologies, and alternative fuels. This makes it not only an energy-technical field but a broader political-economic layer of change.

## DEVELOPMENT OUTLOOK

The most mature subtracks are resilient microgrids, grid-scale energy storage, and thin-film solar cells. Solid-state batteries and green hydrogen and power-to-X are developing, but already clearly strategically significant. Small modular fission reactors are further along than fusion, but their large-scale impact still depends on regulation, delivery capacity, and cost. Fusion energy reactors remain mainly in the realm of experimental and program-level development.

In most practical networks, the change in this group is likely to come through decentralization. Energy will not only be produced more cleanly, but also stored, transferred, and prioritized more locally. This makes microgrids and storage strategically more important than one might conclude from looking at a single production form. What remains unclear is when the total costs of different energy technologies settle permanently at new levels, or how quickly bottlenecks in electrification ease across sectors.

## ARTS IN THE GROUP

- ART 08.056 Fusion Energy Reactors — maturity: 3 — total impact score: 219
- ART 08.057 Small Modular Fission Reactors (SMRs) — maturity: 5 — total impact score: 325
- ART 08.058 Thin-film solar cells — maturity: 6 — total impact score: 510
- ART 08.059 Bionic Leaf Technology — maturity: 4 — total impact score: 88
- ART 08.060 Grid-Scale Energy Storage — maturity: 6 — total impact score: 612
- ART 08.061 Solid-State Batteries — maturity: 5 — total impact score: 535
- ART 08.062 Green Hydrogen & Power-to-X — maturity: 5 — total impact score: 430
- ART 08.063 High-Efficiency Wind Turbines — maturity: 6 — total impact score: 294
- ART 08.064 Wireless & Space-Based Power Transfer — maturity: 3 — total impact score: 75
- ART 08.065 Advanced geothermal technology — maturity: 4 — total impact score: 228
- ART 08.066 Resilient microgrids — maturity: 6 — total impact score: 744

## GROUP SUMMARY

The strength of Group 8 lies in its direct connection to nearly all other technology groups: without energy there is no electrification, no distributed automation, and no computation-intensive systems. The greatest uncertainties concern scale, regulation,

system integration, and material dependencies. Strategically, the group matters because the energy system determines how quickly the wider technological transition can become part of everyday life in an economically sustainable way.

## Group 9 – Bio-engineering & Life-Science Technologies

### KEY CONCLUSION

Group 9 brings together breakthroughs in bioengineering, genetic technologies and biomedicine that can transform health, nutrition, materials, and biological production. The group is highly heterogeneous: some technologies, such as mRNA platforms and precision diagnostics, are already fairly mature, while artificial wombs or gene-drive solutions are earlier and much more socially contested. The group is both directly transformative and strongly institutional, because many effects depend on clinical evidence, regulation, and social acceptance. It changes not only production or services, but also the operating logic of the human body, disease, and biological design.

### SIGNIFICANCE OF THE TECHNOLOGY AREA

The common denominator of the group is the programmability of biological processes. It addresses bottlenecks related to the precision of care, biological production, the sustainability of nutrition, the design of biological materials, and the fact that many current medical and productive processes are slow, coarse, or difficult to personalize. In this group, biology becomes part of a design and development platform rather than only a natural resource or an object of intervention.

The strongest impact appears in health care, nutrition, biomaterials and, in the longer term, also in disability, aging, and societal risk management. At the same time, the group brings with it an exceptional number of ethical, regulatory, and social boundaries that do not appear in the same way with purely digital technologies. For this reason, market potential and deployability do not always advance at the same pace.

### DEVELOPMENT OUTLOOK

The most mature subtracks are mRNA therapies and vaccines and precision medicine and genomic diagnostics. Next-generation gene editing, synthetic biology, and cellular agriculture are emerging but already clearly credible and fast-moving. Engineered living materials, gene-drive pest control, and artificial wombs and synthetic embryos are in much earlier development phases or more strongly conditioned by social acceptance. Microbiome engineering also appears promising, but as a fragmented field.

The next phase of change is likely to be built around platform logic. mRNA, gene editing, synthetic biology, and diagnostics are not only individual products, but are beginning to function as generic development and manufacturing platforms.



This may accelerate the creation of new products, but may also concentrate expertise, data, and regulatory capability in the hands of a small number of actors. What remains unclear is how quickly acceptance broadens into large-scale consumer or clinical use, or how strongly ethical boundaries shape the progress of different sub-tracks.

## ARTS IN THE GROUP

- ART 09.067 Next-Generation Gene Editing — maturity: 5  
— total impact score: 330
- ART 09.068 mRNA Therapies & Vaccines — maturity: 6 — total impact score: 288
- ART 09.069 Cellular Agriculture & Cultured Meat — maturity: 5  
— total impact score: 345
- ART 09.070 Organoids & Tissue Engineering — maturity: 5  
— total impact score: 170
- ART 09.071 Synthetic Biology & Designer Microbes — maturity: 5  
— total impact score: 380
- ART 09.072 Microbiome Engineering — maturity: 5 — total impact score: 170
- ART 09.073 Precision Medicine & Genomic Diagnostics — maturity: 6  
— total impact score: 456
- ART 09.074 Organs-on-Chips & Bio-Computational Hybrids — maturity: 4  
— total impact score: 104
- ART 09.075 Biological Aging & Longevity Barriers — maturity: 4  
— total impact score: 320
- ART 09.076 Engineered Living Materials — maturity: 3 — total impact score: 171
- ART 09.077 Gene Drive Pest Control — maturity: 3 — total impact score: 111
- ART 09.078 Artificial Wombs & Synthetic Embryos — maturity: 3  
— total impact score: 90

## GROUP SUMMARY

The strength of Group 9 lies in opening entirely new ways to treat, produce, and design biological systems. The greatest uncertainties concern safety, long-term effects, regulation, and social acceptance. Strategically, the group matters because it can generate both very high-value health and production platforms and, at the same time, new political and ethical fault lines.

# Group 10 – Space & Aeronautical Engineering

## KEY CONCLUSION

Group 10 is the smallest group, but the contrast within it is large: on the one hand it includes a fairly mature satellite-based connectivity infrastructure, and on the other, very long-term space-resource and life-support systems. The group matters

because it extends infrastructure above the atmosphere and makes communication, observation, and resource acquisition partly space dependent. At present the group is primarily enabling, but ART 10.079 shows that even one subtrack can already be highly influential. Overall, this remains a technology area with uneven maturity.

## **SIGNIFICANCE OF THE TECHNOLOGY AREA**

The common denominator of the group is the relocation of infrastructure away from the Earth's surface. It addresses bottlenecks related to global coverage, connectivity in remote areas, crisis resilience, broad fields of observation and, in the very long term, scarce resources. In practice, this means that some critical societal functions increasingly rely on satellites, high-altitude platforms, and other space- or atmosphere-based solutions.

The strongest impact appears in communications, positioning, remote sensing, and services in exceptional conditions. Space resource utilization and closed-loop life support are much more immature in comparison, but they broaden thinking about what counts as a realistic environment for production or life support. The group is therefore strategically important, especially from the perspective of resilience and long-term geopolitical dependence.

## **DEVELOPMENT OUTLOOK**

Satellite mega-constellations and space internet are clearly the most mature and broadest-impact subtrack in the group. High-altitude platforms and balloons are also a usable and developing infrastructure solution, even if their impact is more limited. Closed-loop life support is an intermediate technology whose practical applications are still far from everyday markets. Space resource utilization is the most immature and most uncertain technology in the group.

The group's near-term impact is likely to concentrate almost entirely on communication and wide-area observation, while the significance of resource utilization and closed systems remains a longer-term strategic option. What remains unclear is how the regulation, security, and geopolitical concentration of space infrastructure affect the pace of adoption. The long-term cost trajectory is also difficult to assess in detail.

## **ARTS IN THE GROUP**

- ART 10.079 Satellite Mega-Constellations & Space Internet — maturity: 6  
— total impact score: 888
- ART 10.080 Space Resource Utilization (SRU) — maturity: 3  
— total impact score: 39
- ART 10.081 Closed-Loop Life Support System — maturity: 4  
— total impact score: 16
- ART 10.082 High-Altitude Platforms & Balloons — maturity: 5  
— total impact score: 300

## **GROUP SUMMARY**

The strength of Group 10 lies in offering an alternative infrastructure layer in situations where terrestrial solutions are slow, expensive, or vulnerable. The greatest uncertainties concern geopolitical dependence, security, and whether the impact remains concentrated in a few infrastructure lines or later expands into resource and production systems. Strategically, the group matters because its most mature subtrack is already highly influential, even though the rest of the group is in a much earlier development stage.

## **Group 11 – Digital Platforms & Collective-Intelligence Systems**

### **KEY CONCLUSION**

Group 11 brings together technologies for digital platforms, trust, data exchange, and collective organization. Its maturity is relatively strong: most ARTs lie in the upper middle range, and some are already close to broad practical use. The group matters less because it changes a single physical process and more because it changes how people, organizations, and networks coordinate, share data, learn, and govern common resources. This is therefore above all an institutional and governance transition.

### **SIGNIFICANCE OF THE TECHNOLOGY AREA**

The common denominator of the group is a new logic of digital coordination. It addresses bottlenecks related to lack of trust, the difficulty of sharing data, the scalability of collective action, platform power, and the fact that current digital markets and communities are often either too centralized or too fragile. The group's technologies offer alternative ways to govern transactions, open innovation networks, learning networks, foresight, and cooperatively owned services.

The strongest impact appears in platforms, data markets, education, community organization, and new trust architectures. Many technologies in the group derive their value not only from software, but from whether practices, standards, and accepted governance models emerge around them. The group is therefore both a technical and a social infrastructure.

### **DEVELOPMENT OUTLOOK**

The most mature and strongest subtracks are decentralized trust networks, open data sharing marketplaces, collective open innovation networks, and digital learning networks and skill credentialing. Secure and resilient social platforms and scalable decentralized governance also appear to be developing credibly. Platform cooperatives and fair work are among the lower-maturity subtracks, not because the model is theoretical, but because economic scale-up and competitive position against large platforms remain uncertain.

The main bottlenecks in the group are not primarily algorithmic but governance-related. Technical solutions can be built, but their value depends on accepted rules, trust between actors, regulation, and network effects. This favors solutions that can connect to existing practices rather than only offering a technically superior model. What remains unclear is to what extent decentralized models truly break platform concentration or remain niche and institution-specific alternatives.

## **ARTS IN THE GROUP**

- ART 11.083 Decentralized Trust Networks (Web3 & Blockchain) — maturity: 6  
— total impact score: 654
- ART 11.084 Platform Cooperatives & Fair Work — maturity: 4  
— total impact score: 416
- ART 11.085 Open Data Sharing Marketplaces — maturity: 6  
— total impact score: 576
- ART 11.086 Secure & Resilient Social Platforms — maturity: 5  
— total impact score: 475
- ART 11.087 Collective Open Innovation Networks — maturity: 6  
— total impact score: 504
- ART 11.088 Scalable Decentralized Governance — maturity: 5  
— total impact score: 410
- ART 11.089 Digital Learning Networks and Skill Credentialing — maturity: 5  
— total impact score: 585
- ART 11.090 Prediction-Market Forecasting Platforms — maturity: 7  
— total impact score: 378

## **GROUP SUMMARY**

The strength of Group 11 lies in its ability to change the rules of coordination, trust, and data sharing without rebuilding all physical infrastructure from scratch. The greatest uncertainties concern network effects, the viability of governance models, and the speed at which new trust solutions can displace today's centralized platforms. Strategically, the group matters because this layer increasingly determines who gets the data, who organizes the community, and who controls the digital distribution of value.

## **Group 12 – Protocols, Standards & Socio-Technical Infrastructure**

### **KEY CONCLUSION**

Group 12 brings together the protocols, standards and socio-technical infrastructure that make other technologies interoperable, auditable, and governable. The group is strategically exceptional because it directly determines whether future technologies

become fragmented point solutions or scalable ecosystems. Maturity is mostly above the midpoint: many subtracks are not yet fully established, but they are already supported by standards, recommendations, and deployment paths. The group is clearly enabling, but in many networks it is also directly transformative because it changes the enforcement of rules and the interplay between systems.

## **SIGNIFICANCE OF THE TECHNOLOGY AREA**

The common denominator of the group is the language of coordination. It addresses bottlenecks related to system incompatibility, data portability, the slow implementation of regulation, the portability of identity and payments, and the fact that without standards each technology scales only within its own closed ecosystem. The group makes the other groups practically governable and connectable.

The strongest impact appears in IoT ecosystems, data transfer, identity, payments, regulation, the portability of digital twins and collaboration-protecting protocols. At the same time, the group shifts power toward standard setters, certifiers, trust frameworks and the actors that control the machine-readable implementation of rules. This makes it a core area of technology policy.

## **DEVELOPMENT OUTLOOK**

The strongest subtracks in the group are universal IoT interoperability standards, machine-readable regulation, content authenticity infrastructure, personal data portability and trust frameworks, and global supply chain traceability networks. Interoperable digital twin ecosystems and privacy-preserving collaboration protocols are also clearly developing and strategically important. Interoperable digital currency payment networks are in somewhat earlier development phases, or at least more institutionally contingent, than many other technologies in the group.

The impact of the group is likely to grow as the wider technological environment becomes more complex. When automation, sensors, identities, and payments are connected, standards and machine-readable regulations no longer support functions but conditions of operability. This may accelerate deployment, but it may also increase dependence on a small number of actors in the standards and trust layer. What remains unclear is when certain protocols reach de facto status or how strongly geopolitical differences fragment the standards landscape.

## **ARTS IN THE GROUP**

- ART 12.091 Universal IoT Interoperability Standards — maturity: 5  
— total impact score: 820
- ART 12.092 Interoperable Digital Twin Ecosystems — maturity: 5  
— total impact score: 560
- ART 12.093 Global Supply Chain Traceability Networks — maturity: 5  
— total impact score: 655
- ART 12.094 Personal Data Portability & Trust Frameworks — maturity: 5  
— total impact score: 665

- ART 12.095 Interoperable Digital Currency Payment Networks — maturity: 4  
— total impact score: 356
- ART 12.096 Machine-Readable Regulation (Rules as Code) — maturity: 5  
— total impact score: 705
- ART 12.097 Open Metaverse Interoperability Protocols — maturity: 5  
— total impact score: 290
- ART 12.098 Content Authenticity Infrastructure — maturity: 6  
— total impact score: 678
- ART 12.099 Privacy-Preserving Collaboration Protocols — maturity: 4  
— total impact score: 464
- ART 12.100 Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure — maturity: 5 — total impact score: 550

## GROUP SUMMARY

The strength of Group 12 lies in turning individual technologies into ecosystems. The greatest uncertainties concern ownership of standards, the power of certification, shared cybersecurity failure risks, and how open the resulting practices truly remain. Strategically, the group matters because this layer is likely to become one of the most important arenas of competition and regulation across the whole radical technology transition.

# Methodology

## Principles of Radical Technological Inquirer

The present study is the latest foresight iteration using the Radical Technology Inquirer (RTI) methodology developed for the Committee for the Future of the Finnish Parliament. In the RTI framework, the anticipation of technological change does not begin from single inventions alone, nor only from abstract societal megatrends. Instead, it combines a technology-oriented perspective with a societal need- and value-oriented perspective. The former concerns the identification and grouping of anticipated radical technologies (ARTs), which might solve technological bottlenecks in value production, while the latter concerns their assessment in relation to broad societal value-producing networks (GVNs), their dominant and challenger regimes, and the changing ways in which societal needs may be met. The purpose of the methodology is not to describe which technologies are currently dominant, but to identify from which directions the challengers to currently dominant socio-technical arrangements are emerging and what their various impacts may be. RTI is a methodology for anticipating societal transformation rather than for merely cataloguing technical novelty.

Historically, RTI should be understood not as a single report-specific invention, but as an iterative foresight framework that has developed through successive rounds of application, evaluation, and refinement. Here, only reports that contributed to the development of RTI are mentioned and listed in references. According to the report tradition, the development of the method began in 2012, and the first monitoring round was conducted in 2013 (Linturi et al., 2013). In 2016, a follow-up report (Linturi, 2016) assessed how each anticipated development had evolved and how the method could be further developed. The 2018 report (Linturi & Kuusi, 2018) implemented these suggestions and represented a substantially expanded

and methodologically refined continuation of that earlier work while preserving the same basic analytical logic. In 2022, RTI was described in detail as a methodology that can be repeated in a peer reviewed journal EJFR (Linturi et al., 2022). Thereafter, preparing further development, in 2025 a pilot report (Björkroth et al., 2025) focused on one anticipated radical technology, humanoid robotics, providing one further iterative step in which the method's most labor-intensive phases were renewed through AI assistance while the core framework remained intact.

The core structure of RTI rests on two elements. First, society is modeled through twenty value creation networks that cover broad and organized forms of value creation, such as transport, logistics, exchange, health care, and acquiring information. Within each value creation network, RTI distinguishes between a dominant regime and a challenger regime. The dominant regime describes the currently prevailing way in which value is created; the challenger regime describes a plausible future direction in which emerging technologies, changing practices, and new institutional arrangements may reorganize value creation. Second, RTI treats radical technologies as general-purpose means rather than as solutions locked to one sector. This is methodologically important because the same technology may transform several different value creation networks, and because transformative effects often arise precisely when a technology developed in one context diffuses into another. A practical example is the development of lithium-ion batteries. Although their early commercial development was strongly linked to portable consumer electronics, especially mobile phones, their wider significance emerged much later in another domain. Improvements in energy density, reliability, and manufacturability made it possible for lithium-ion batteries to become one of the central enabling technologies of the electric vehicle transition. In this sense, the most consequential societal effects of the technology did not remain confined to the sector in which its development was first accelerated. Instead, they appeared through cross-sectoral diffusion, when a technology developed for one purpose began to reorganize transport, energy systems, industrial value chains, and related policy choices. One of the central strengths of RTI is that it is able to make such spillover effects visible.

In practical RTI work, this logic has been operationalized through a phased process. In the full implementation, the method includes the identification and grouping of anticipated radical technologies, their maturity assessment, the definition of twenty value creation networks, the qualitative creation of weak signals linking technologies to those networks, and the scoring of transformative significance on a logarithmic scale. The 2018 report (Linturi & Kuusi, 2018) carried out this work as a broad national foresight exercise based on extensive crowdsourced and expert-supported source gathering. The 2025 pilot retained the same basic architecture but focused on one technology family, humanoid robots, and concentrated AI use especially in refining the value creation network descriptions for AI use, identifying future impacts, and evaluating their significance.

The present study follows these same core RTI principles documented in detail in the EJFR 2022 article (Linturi et al., 2022). It retains the view that technological change must be interpreted through value creation networks, that transformation



concerns both direct and indirect societal effects, and that technologies must be assessed as potential contributors to wider challenger regimes rather than as isolated gadgets. At the same time, the study differs methodologically from both RTI 2018 (Linturi & Kuusi, 2018) and the 2025 (Björkroth et al., 2025) pilot report in one important respect: AI was not used only to accelerate the identification of societal effects, but also much earlier in the process, in the generation, curation, description, and evidencing of the ART set itself. This also made it possible to operationalize the ART concept more rigorously than before by identifying and describing ARTs as generic groups of potential solutions promising to open bottlenecks in value chains or capability bundles in a similar sense, outlined in the RTI methodology literature, rather than merely as lists of promising technologies. In this respect, the present round can be seen as bringing the practical ART-identification process more closely into line with the conceptual logic articulated in the defining EJFR article.

A central principle of the present implementation was therefore continuity with RTI at the level of analytical logic, combined with methodological renewal at the level of workflow. The study did not seek to invent a new foresight method from scratch. Rather, it asked whether the RTI process could be updated so that AI would support the production of a full ART and GVN assessment while the research team remained responsible for framing, selection, validation, and interpretation. This principle also explains why the method places emphasis on structured prompting, explicit scoring rules, source-quality hierarchies, manual checking, and iterative refinement, rather than on unconstrained generative output.

## Using AI according to Radical Technology Inquirer principles

The use of AI in this study followed a deliberate attempt to distinguish between loosely generative output and methodologically disciplined AI-assisted foresight. In the 2025 (Björkroth et al., 2025) pilot, one of the main methodological findings was that large language models could produce broad and sometimes exceptionally rich societal impact analyses when they were guided by a strong analytical framework, whereas open-ended prompting tended to generate more conventional and less useful answers. The pilot also emphasized that the quality of results depends fundamentally on the quality of the questions posed to the model. This observation was adopted here as a starting point. AI was not treated as an autonomous analyst, but as a structured inference and synthesis tool operating within the RTI framework.

In practice, this meant that AI use was organized as a sequence of bounded tasks rather than as one continuous conversation. The process began with AI-assisted identification of broad technology domains and bottlenecks in which candidates for anticipated radical technologies might be emerging. Instead of relying on volunteer-based gathering of technology news, as in the earlier RTI rounds, or on manual researcher-led prospecting for a single focal technology, as in the pilot, the present study used AI as an upstream prospecting instrument. The aim was first to identify

where potentially significant technological developments might be located, and only then to move toward candidate ARTs. In methodological terms, this altered the origin of the prospect list while keeping intact the later RTI logic of grouping, description, and impact assessment. Quantitatively, this structured inference and synthesis meant a staged screening process in which searches were first widened technology group by technology group and then narrowed through successive filtering, summarization, elimination of overlap, and recombination. In rough terms, the AI-assisted process made it possible to read and screen tens of thousands of articles and documents, from which around two thousand more relevant items were filtered into a working corpus for further synthesis. Compared with purely manual work, the gain was not only speed but also the ability to carry out a much broader and more systematic first-pass scan before the researcher-led curation and interpretation phases began.

The candidate ART list produced in this way was not accepted automatically. The research team reviewed the prospect list manually, identified duplicates, removed technologies judged to be too mature, too marginal, or insufficiently radical for the purposes of the exercise, and in some cases reassigned items to more suitable technology groups. This human curation phase was indispensable. It ensured that AI-assisted prospecting would not determine the final ART set on its own, and that the resulting technology portfolio remained conceptually coherent from the standpoint of RTI. Only after this curation step were the retained ARTs expanded into fuller descriptions with AI assistance.

The ART descriptions were then written in a standardized form designed to remain sufficiently generic for later cross-GVN analysis. This again followed an RTI principle already visible in the pilot: ARTs should not be described so narrowly that their future uses are predetermined in advance. The AI-assisted descriptions therefore emphasized the capability of the technology, the kinds of bottlenecks it could plausibly address, its dependencies and constraints, and the sort of mature technological bundle it might represent. In this way, the descriptions functioned as analytical inputs for later societal-impact analysis for generative AI, rather than as mini market reports.

A further AI-assisted phase consisted of creating evidence dossiers for each ART (for final curated dossiers, see Attachment 2). Here too the objective was not open-ended content generation, but a constrained evidencing task. Each ART description was entered into a standardized Deep Research prompt that asked the model to produce a compact dossier of recent sources, prioritize peer-reviewed and otherwise authoritative evidence, and assign a single maturity score on the RTI 1–7 scale for the ART. The prompt required a single integrated analysis of the technology bundle rather than separate scores for subcomponents, and it explicitly specified a four-year publication window, a hierarchy of acceptable source types, and a distinction between plausibility and maturity.

Importantly, these evidence dossiers were not treated as final outputs. The dossier documents were reviewed by researchers, links were checked manually, and problematic cases such as missing or misdirected sources were identified and discussed within the research team. This procedure was necessary not only because large language models may hallucinate sources or misclassify their relevance, but also because the source-selection logic or described ART definition itself can produce skewed representations. One concrete example concerned the self-driving vehicle dossier, where the evidence selection underrepresented Tesla despite the company's public salience in the field. Whether this reflected prompt bias, source-availability effects, model behavior, or some combination of these could not be resolved conclusively, but the case demonstrated that even technically strong prompts require human review for completeness and balance. In the methodology of this study, transparency about such cases is preferable to overclaiming flawless AI-supported evidence gathering.

The most consequential AI-assisted phase concerned the creation of weak signals and impact scoring for ART-GVN pairs. Here the study adopted the “AI-optimized” GVN descriptions from the 2025 pilot report as the basis for prompting, because those descriptions had already been refined for use with large language models. In methodological terms, the most desirable option would have been a single integrated analysis in which all ARTs and all GVNs were assessed together, since this would most fully reflect the RTI ambition of examining technological transformation as an interacting whole. In practice, however, this was not feasible with the available model context limits: such runs became too shallow, and the analytical depth did not remain at a satisfactory level. For that reason, two more bounded alternatives were compared in benchmarking: analyzing one ART across all GVNs, and analyzing all ARTs within one GVN. The level of depth in the resulting analyses proved broadly similar, but the latter option was considered methodologically preferable. Instead of implicitly treating each ART as if it developed in isolation, a GVN-specific run allowed the model to assess technologies in relation to one another within the same sociotechnical field. This made it easier for the model to identify spillovers, complementarities, substitution effects, and institutional interactions inside a given value creation network, and thus better matched a central RTI insight: radical technologies develop side by side and simultaneously, not as isolated trajectories.

The prompt used for this phase was strongly structured (see Attachment 6 for details in scoring maturity and impact). It asked the model to assume each ART in a mature state, to score each ART for the selected GVN using the discrete RTI scale of 0, 1, 3, 5, 10, or 20, and to interpret impact magnitude in relation to a rough western-society baseline of 5.5 million inhabitants. The prompt also explicitly required that the model include 1st-order, 2nd-order, and 3rd-order pathways in its assessment and that the score reflect the largest plausible total impact magnitude across these layers rather than only direct operational effects. In addition, it defined weak signals as observable early indicators of a pathway and included an explicit low-density rule for cases where a linkage was weak. In RTI, weak signals are short interpretive statements derived from observable developments that may indicate a wider emerg-

ing pathway of change. Thus, an observed technical capability such as increasingly autonomous vehicle operation is treated not merely as a “fact in itself”, but as a possible signal of broader future developments such as the emergence of robotaxi services. All these prompt elements were designed to counter direct-use bias, false precision, and generic filler in a manner that would not impact the direction of results.

This part of the process also involved methodological calibration. The 2025 pilot’s humanoid-robot analysis was used as a checkpoint for what the pilot had termed “intelligent creative tension,” that is, the deliberate forcing of the model to explore interactions between a radical technology and the goals, values, and structures of a value creation network. In early iterations of the present prompt, second- and third-order effects often appeared in the narrative justification but were not clearly enough reflected in the actual score assignment. For that reason, the prompt was revised so that systemic and spillover effects would shape not only the wording of the analysis but also the formal scoring outcome. This tuning process should be understood as part of the method itself rather than as a purely technical adjustment, because in RTI the quality of the scoring depends directly on how well indirect and cross-sectoral pathways are captured.

As an assessment of the renewed methodology, it can be said that AI was used according to RTI principles as four conditions were met. First, the model was given a clearly bounded analytical task. Second, each task was embedded in a strong conceptual structure, especially the ART and GVN descriptions and the RTI scoring logic. Third, the outputs were subject to manual review and iterative correction. Fourth, the process remained transparent about its own limitations. This is also why the study does not describe AI as an independent researcher. It functioned instead as a catalyst for broader search, richer combinatorial analysis, and more consistent formalization, while the human research team retained responsibility for design choices, relevance judgments, and the final interpretation of outputs.

A further consequence of this AI-assisted operationalization was that the 2025 pilot, and especially the present full RTI iteration, were able to capture both positive and negative potential impacts more broadly and more evenly than the 2018 version. This reflected not only a deliberate methodological choice, but also the practical affordances of AI-assisted analysis: the report no longer had to be constrained to a narrowly human-scale format, and alternative prompt versions could be tested repeatedly on large masses of material at a fraction of the effort that comparable manual operationalization would have required. In practice, this is also visible in the scale of the outputs themselves: the 2018 RTI report extended to 483 pages, the 2025 humanoid-robot pilot to 271 pages, and the present 2026 full RTI material to well over 2 000 pages. This expansion in length should not be understood merely as verbosity, but as an indication that opportunities, risks, inhibiting factors, and cross-effects could now be documented in much greater breadth than was previously feasible. This can especially be seen in Attachment 2 in how each ART is broken into subtasks and analysed, but also in Attachment 3, how ART – GVN impacts are broken into a list of weak signals that is much more widespread than in 2018 report. This present study is not more verbose, it has much larger number of perceptions.

## AI-assisted RTI: framework validation, limitations, and next development steps

The broader AI-assisted workflow used in the present iteration affected not only how the ART set was identified and analyzed, but also how the resulting material had to be organized. Because the project now produced a much larger and more layered corpus of ART descriptions, impact assessments, weak signals, and supporting evidence than in earlier rounds, it became necessary to structure that material in a form that could support consistent retrieval, comparison, and synthesis across the project. The 2018 report already had a rigorous structure sufficient in principle, but to make the results fully explorable with a tailored RTI-GPT model, it needed finetuning.

To meet this need, the material was structured in separate files, each with a topic based record or data-card-like structure and a map-like table showing which ART's impact which GVN. In practice, this meant structuring the data so that corresponding ARTs, GVN, scores, weak signals, and descriptions were systematically named and each type of data found in specific file, and giving the model explicit instructions on where to find and how to identify the relevant matching entries when generating responses. The current report draft of the technology-group and GVN summary sections was produced with the help of this RTI-GPT using RAG-type retrieval. Its role was not merely to reproduce stored content, but to support systematic retrieval, comparison, and synthesis from the project corpus in a more consistent way than would have been practical through manual querying alone. The RTI-GPT was also tested internally through a structured question set and by research team members in different use scenarios. Methodologically, this should still be understood as a supporting interpretive and summarizing tool rather than as a separate analytical phase of RTI itself.

More important than the RTI-GPT was the question of whether the GVN descriptions themselves remained analytically valid. The 2025 pilot (Björkroth et al., 2025) had already emphasized that refining value creation network descriptions was crucial for good AI-assisted analysis. In that pilot, the 2018 descriptions were considered sufficiently up to date to serve as a basis, but they were reformulated for AI use and separated more clearly into goals, values, and regime descriptions. The present study inherited those AI-optimized GVN descriptions and used them in the ART  $\times$  GVN analysis phase. This created continuity across the method, but it also made it possible to observe where the old transformation logics remained persuasive and where they had become outdated or incomplete.

On the whole, the GVN framework remained in good condition. Most of the twenty value creation networks still offered analytically believable descriptions of dominant and challenger regimes, and they remained usable as scaffolds for systematic AI-assisted impact assessment. This is in itself a noteworthy result, because it suggests that the core RTI sociotechnical architecture has retained much of its explanatory value over the period from 2018 to 2026. At the same time, the study also found

that one GVN, Acquiring Information (GVN 14), now raises more substantial questions about the direction of transformation than was assumed in the earlier framework.

The challenge in GVN 14 does not appear to be that information acquisition has failed to become more data-rich, personalized, platform-mediated, or AI-assisted. On the contrary, those parts of the challenger direction have largely moved as anticipated. The more serious issue concerns credibility and trust. The earlier transformation logic assumed, in effect, that the movement toward more distributed, source-proximate, AI-assisted, and peer-supported information acquisition would also improve relevance and plausibility. Current development appears more contradictory. Relevance and personalization have increased, but credibility has not improved in the same movement. Instead, platform dependence, synthetic content, provenance uncertainty, and weakened common information environments have increased the need for authenticity infrastructures, content labeling, provenance standards, and new forms of technical and regulatory verification. In this respect, the transformation has not simply proceeded from centralized authoritative information toward better distributed knowing; it has also generated a stronger need for institutional and technical trust layers. This makes GVN 14 the clearest case in which the challenger direction itself should be reconsidered in the next RTI iteration.

At the same time, this framework-level weakness did not mean that the RTI-GPT or the report itself merely reproduced an outdated original transformation logic mechanically. On the contrary, in the generated report material the model often produced more credible and analytically balanced formulations than a literal reading of the inherited GVN description alone might have suggested. This is methodologically significant. It indicates that a well-configured large language model can interpret, synthesize, and reorganize the material rather than simply restate it. In that sense, the RTI-GPT functioned not only as a retrieval and summarization tool but also as a useful interpretive layer within the broader research process.

This positive result does not, however, remove the need for conceptual revision. If a model produces a more plausible output despite weaknesses in the underlying GVN definition, that should be treated as evidence of model-level interpretive capacity, not as proof that the framework itself remains fully adequate. The broader methodological conclusion is therefore twofold. First, AI can assist RTI-style work not only by accelerating analysis but also by revealing where inherited conceptual structures no longer fit present developments cleanly. Second, the most immediate next development step should be a systematic update of the GVN descriptions before the next full RTI round. Such an update should focus especially on those domains in which the sociotechnical environment has changed most rapidly since 2018, including acquiring information, collaboration and trust, and possibly also work and income, where platform concentration and infrastructural centralization have in several respects proceeded more strongly than earlier challenger-regime descriptions implied. In that sense, the present round should be seen both as a completed foresight exercise and as part of the iterative development that is intrinsic to

RTI. It functions not as a final methodological endpoint, but as one stage in the continuing refinement of the framework and, in that respect, as a bridge toward a renewed RTI architecture.

One AI-driven difference between these reports should also be noted. In the present report, the component technologies of ART development were identified, and their maturity was assessed at a considerably finer level of detail than in the 2018 report. Likewise, the weak signals were described much more precisely than in 2018, although not at the same level of granularity as in the 2025 (humanoid-robot) pilot. This reflected a practical trade-off built into the present iteration: whereas the pilot could devote multiple iterative weak-signal runs to a single ART, the full RTI exercise had to extend comparable logic across 100 ARTs. The result was therefore substantially more fine-grained than the 2018 iteration, but necessarily less detailed per individual ART than a single-technology pilot could be.

A final limitation should be stated explicitly. However structured the prompts and however extensive the manual checking, AI-assisted foresight remains sensitive to prompt design, source selection, model behavior, and corpus structure. It can widen the search space, accelerate synthesis, and formalize impact comparisons more consistently than unaided manual work. It does not eliminate the need for interpretation, selection, or conceptual judgment. The value of the present method lies not in removing human responsibility, but in reallocating human effort from repetitive collection and first-pass combinatorial work toward framing, checking, and methodological reflection. This was also the underlying principle of the 2025 pilot, and it remains the most defensible way of understanding AI-assisted RTI in the present study.

It is also important to place the present methodological experiment in a wider context. The rapid diffusion of generative AI has been accompanied by a growing volume of low-quality, weakly verified, and poorly accountable content, often described in public discussion as “AI slop.” In such uses, AI typically accelerates output without a corresponding increase in transparency, source criticism, or conceptual discipline. The present study has aimed in the opposite direction. Rather than using AI as a shortcut around analysis, it has sought to embed AI within a demanding foresight framework in which concepts, prompts, source hierarchies, scoring rules, and human review constrain what the model is allowed to do. In this sense, the AI-fication of RTI should be understood as an attempt to place new generative tools under rigorous methodological use and, by doing so, to demonstrate what they can contribute when they are not treated as substitutes for judgment, expertise, or responsibility.

Given all this, what about the future of RTI? How much foresight automation will AI eventually enable? Certainly, more than now, but while AI greatly facilitates the gathering of ART evidence and respective societal impact assessment, human reflection cannot fully be removed from the equation. Full AI-fication of RTI would mean that AI were able to inherently understand what we as individual humans and human societies wish to pursue. It is unlikely that the RTI-methodology would ever

be perfected to find the “final” form without human intuition. Thus, methodological decisions will always require at least human confirmation. Human aspirations are not deductions of previous understanding. One cannot logically derive a statement about what ought to be done solely from statements about what is the case, as David Hume’s guillotine famously states. We also pragmatically know from the earlier RTI update rounds that the accumulation of new evidence tends to necessitate reformulation of categories, as technological evolution renders some earlier conceptualizations obsolete and calls for new ones. AI can naturally be used to suggest new formulations, but do they resonate with our aspirations? Approving them needs to be done consciously by humans. Moreover, RTI methodology requires that the systemic implications of all the new evidence be considered and weighted jointly. This all means that the updating of the RTI results will also in the foreseeable future need to take place periodically in a human-led process rather than automatically and continually. But real time considerations partial as they may be, become easier than before. And RTI-GPT is one example in this regard.



# Conclusions

## What should policymakers pay attention to?

For policymakers, the relevant question is whether governance systems are capable of adapting to technological shifts before institutional lag itself becomes a bottleneck. The report shows the development status and maturity of each of the 100 assessed technologies in 2025-26, indicating which ones are likely to enter the markets fastest. But more importantly, the results reveal that radical technologies enable and encourage societal transformations which require different forms of coordination, certification, liability allocation, and institutional competence than ones that support the extant ways of value creation.

In logistics, for example, the dominant regime is still tied to industry- and trade-centric logistics, shared infrastructure with passenger transport, large shipments, consumer self-transport, and adherence to established norms and regulatory frameworks. By contrast, the emerging challenger regime is built around smart robotization, autonomous vehicles and drones, open digital platforms, cloud-based control services, and shared smart lockers. While opinions may differ on the desirability of such change, the essential questions are whether the change is already occurring in some places; why would it spread; what its spreading would mean for our society's value-creation; what we should do about it? The policymakers' attention should be directed toward identifying the points where old institutional arrangements and related regulation cease to match emerging operating models. The border between legitimate risk management and unnecessary lock-in to the old way of doing things should be actively scrutinized and debated. Failing this, the likely outcome is not the prevention of change but becoming its victim: jurisdictions, sectors, or actors better able to experiment, learn, and scale will lead the way. Thus, public institutions need alertness not only to risks, but also to timing.

Policymakers should also pay attention to the second and third-order impacts caused by new technological capabilities. What are the anticipated shifts in labor relations, liability, insurance, market structure, urban planning, and bargaining power? Who gains control over standards, compliance interfaces, data flows, software layers, and certification pathways as adoption proceeds? Technological transitions are also governance transitions: they can redistribute advantage between incumbents and entrants, between public authorities and private platforms, and between actors with differing capacities to absorb uncertainty, invest in new systems, or shape the rules of the game.

This points to a broader use of the report, and by extension to the use of the Radical Technology Inquirer GPT (RTI-GPT), as a policy tool. The value of the report is not only that it highlights technologies that may become important, but it offers a way to ask which institutional arrangements remain robust under challenger-regime conditions, which become bottlenecks, and which leave public responses systematically reactive rather than anticipatory. The task is to recognize early where technological change is likely to produce system-level consequences, where weak signals already indicate that institutional adaptation is becoming urgent, and where governance itself may become either an enabling capacity or an unintended barrier. RTI-GPT is equipped to retrieve answers to such questions from its database.

We believe that possibly the best way to think of this report and RTI-GPT as its reading method as a tool that helps to understand and anticipate potential cross-sectoral implications of technological change. To approach such systemic changes in a comprehensive manner is not as easy for the human mind. Nor is it easy from the organizational point of view: policy design typically is sector-specific, whereas the impacts of technological change ripple through the whole society. In the governance models of today, such impacts, risks, and opportunities are not anticipated in a holistic manner. RTI-GPT provides an example and an accessible starting point for such efforts. The RTI methodology is designed to recognize societal value creation and related promising or harmful effects independently of sectoral boundaries and responsibilities. Thus, the discursive RTI-GPT can readily provide insights into boundary-crossing questions that are challenging to comprehensively answer from the perspective of existing “silos”. This feature, above all, should make it useful in recognizing issues that need attention, in facilitating discussion and policy planning between ministries, and in recognizing types of stakeholders that should be involved.

## What should technology developers pay attention to?

For technology developers, the main value of this report is not in treating it as a list of predictions, but as a guide to where future competitive advantage may emerge. Its real usefulness lies in showing where technological capability, standards, regulation, infrastructure, and shifting value networks may begin to reinforce one

another. The next wave of success is unlikely to come only from better technical performance. It will also come from recognizing early when a technology starts to change demand, reshape competition, and open space for new business models.

The report should therefore be used as a strategic navigation tool. It helps developers identify promising growth directions, test assumptions about where bottlenecks are moving, and see where new combinations of technologies may create openings before markets are fully formed. In practice, this means paying attention not only to the technology itself, but also to standardization, platform dependencies, component availability, regulation, and changes in the surrounding ecosystem.

The broader lesson is that technology success will increasingly depend on combining technical excellence with strategic flexibility. The strongest positions are likely to go to those who are early enough to learn, influence, and build capabilities, but pragmatic enough to adapt as markets, rules, prices, standards, best practices and networks evolve. Used in this way, the report is less a static forecast than a practical tool for spotting the next credible directions for technology-based growth.

## What should business decision makers pay attention to?

In a rapidly evolving technological and societal environment, business leaders must strengthen their ability to anticipate change and translate emerging insights into strategic action. This report serves as a navigation tool for organizations, helping leaders understand key shifts in the external environment and assess their relevance for business.

It provides a structured perspective on emerging technologies and their implications for future operating environments. By connecting long-term trends, technological progress, and weak signals, the report supports more informed choices under uncertainty and helps organizations prepare for the context in which they will operate.

In addition, the report offers insight into evolving value networks, customer needs, and broader societal conditions. Used as a basis for reflection and dialogue, it can help leaders prepare their organizations to remain resilient and competitive over the long term.

Effective leadership also requires continuous change management and capability development. Organizations need a clear strategic direction and a deliberate approach to building the capabilities required for future success. The report helps identify which capabilities should be strengthened or newly developed.

Finally, the report supports organizations in anticipating changes in value networks and customer needs. Future customers will operate in new societal and technological

contexts, with shifting expectations and demands. By understanding these changes early, organizations can better position themselves for long-term competitive advantage.

## What should citizens pay attention to?

For citizens, understanding technologies shaping the future can support more informed choices in work, daily life, and society. This report offers a way to make sense of these changes at a high level, helping individuals grasp what kinds of transformations may lie ahead and how today's choices connect to longerterm developments. For generally curious citizens, the report provides perspectives on how technology, work, and society may evolve over the coming decades.

From an individual perspective, particular attention should be paid to working life and skills development. As work becomes more flexible, distributed, and technologymediated, individuals increasingly need to reflect on what kinds of competencies they want to develop to remain relevant and resilient. For younger generations especially, the report offers context that can support education and career choices by illustrating how different futures may shape labor markets, roles, and required skills.

The report also highlights broader societal change, including how technologies often emerge first in leisure and everyday life before becoming embedded in work and social structures. Looking ahead, society twenty years from now may look very different from today, containing both risks and opportunities. The report does not present a single utopian or dystopian vision, but instead encourages awareness and active engagement. While technology has contributed to many challenges, it also offers tools to address them. By understanding these dynamics, citizens can move beyond passive concern and instead reflect on how individual choices, skills, and everyday actions can help shape the future society they wish to live in.

## Discontinuous transformations: the race between utopian and dystopian futures

The 2018 report in the series, *Societal Transformations 2018–2037*, introduced the concept of the sociotechnical regime. For each value-creation network, a plausible transformative structural shift was identified, contingent on significant advances in the anticipated technologies. A substantial share of these anticipated transformations appeared not only likely but appeared also to be discontinuous—that is, disruptive. In light of this, the report drew the following conclusion:

**The broad changes that are proven to be possible in this report and that extend to the foundations of the functioning of society raise the idea of the beginning of a new Kondratiev cycle and the old one encountering a crisis, which is normal for Kondratiev cycles. This report shows that the challenger regimes are maturing quickly and comparatively simultaneously, proceeding towards a potential, extensive transformation of the existing structures. Previous crises related to the beginning of a new cycle were linked to major wars, economic collapse, and reorganization of power structures at the global level.**

**(SOCIETAL TRANSFORMATIONS 2018–2037, LINTURI & KUUSI , P. 457)**

Over the past eight years, this view has only grown stronger, as can be seen from this report, and many of the geopolitical tensions intensified by these developments have already materialized in new wars. The collapse of industries and national economies now appears more plausible, while the rapidly growing power over infrastructural capabilities of global technology companies, geopolitical bloc formation, and the rapid advance of artificial intelligence and robotics are creating unprecedented turbulence in societies.

In light of the report's findings, however, we are still only at the beginning of these transformations, and the most profound disruptions still lie ahead. These changes will bring both threats and opportunities for all actors. The role of regulators is to open up opportunities while preventing threats from materializing. This will take place amongst major power struggles not only between states and blocks, but also with business conglomerates. The role of businesses and citizens is to remain agile and alert.

We have entered an era that would have seemed like pure science fiction not only to someone living a hundred years ago, but even to those who experienced the early years of the internet in 1990's. And it seems there are outcomes that seem dystopian but also views that can be called utopian. Slow responses will increase societal and individual risks and will probably lead to turmoil and failure in global competition for prosperity. Rapid accommodation to anticipated change will be required.

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## Appendices

Attachment 1. Results scores table: 100 Arts, 20 GVN's

Attachment 2. Development evidence of ARTs

Attachment 3. Anticipated GVN impacts of ARTs

Attachment 4. ART descriptions used in evidence gathering

Attachment 5. GVN descriptions used in ART impact assessment

Attachment 6. Maturity and impact scoring criteria

## Attachment 1. Results scores table: 100 ARTs, 20 GVNs

| ANTICIPATED RADICAL TECHNOLOGIES (ARTs) ↓      | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
|------------------------------------------------|----------------------------------|------------------------|--------------|---------------------------|---------------|------------------|--------------|----------------------|-------------|------------------|------------------------|---------------------|-----------------|-----------------------------|---------------------------|-------------------------------|---------------------------|-------------------------|-----------------------------|-------------------------|----------------------|------------------------------------------------------------------------|---------|
| Global Broadband Connectivity                  | 6                                | 10                     | 10           | 5                         | 5             | 5                | 5            | 5                    | 20          | 20               | 10                     | 20                  | 10              | 10                          | 20                        | 5                             | 20                        | 10                      | 20                          | 20                      | 10                   | 1440                                                                   | 1       |
| Collaborative Multi-Agent AI                   | 6                                | 10                     | 20           | 10                        | 10            | 10               | 5            | 10                   | 10          | 10               | 20                     | 10                  | 5               | 5                           | 5                         | 5                             | 5                         | 10                      | 5                           | 5                       | 10                   | 1080                                                                   | 2       |
| Trustworthy AI Systems                         | 5                                | 10                     | 5            | 10                        | 5             | 5                | 3            | 10                   | 10          | 10               | 20                     | 10                  | 20              | 10                          | 10                        | 10                            | 5                         | 20                      | 10                          | 10                      | 20                   | 1065                                                                   | 3       |
| Self-Driving Vehicles                          | 6                                | 20                     | 20           | 5                         | 10            | 10               | 5            | 20                   | 10          | 5                | 10                     | 10                  | 5               | 10                          | 3                         | 5                             | 5                         | 10                      | 3                           | 5                       | 3                    | 1044                                                                   | 4       |
| Humanoid and General-Purpose Robots            | 5                                | 1                      | 10           | 20                        | 10            | 5                | 10           | 10                   | 10          | 20               | 20                     | 20                  | 10              | 10                          | 3                         | 5                             | 10                        | 5                       | 3                           | 10                      | 5                    | 985                                                                    | 5       |
| Edge AI for Sensor Data                        | 6                                | 10                     | 10           | 10                        | 5             | 5                | 5            | 5                    | 5           | 5                | 20                     | 5                   | 10              | 10                          | 10                        | 3                             | 10                        | 20                      | 5                           | 3                       | 5                    | 966                                                                    | 6       |
| Satellite Mega-Constellations & Space Internet | 6                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 10          | 10               | 10                     | 10                  | 5               | 5                           | 10                        | 5                             | 10                        | 10                      | 10                          | 10                      | 10                   | 888                                                                    | 7       |
| Immersive Augmented & Virtual Reality          | 6                                | 3                      | 5            | 5                         | 3             | 3                | 3            | 10                   | 5           | 10               | 5                      | 10                  | 5               | 5                           | 5                         | 10                            | 20                        | 5                       | 5                           | 20                      | 5                    | 852                                                                    | 8       |
| Universal IoT Interoperability Standards       | 5                                | 10                     | 10           | 10                        | 5             | 10               | 5            | 10                   | 10          | 10               | 10                     | 5                   | 10              | 10                          | 10                        | 1                             | 5                         | 20                      | 5                           | 3                       | 5                    | 820                                                                    | 9       |
| Resilient microgrids                           | 6                                | 5                      | 5            | 5                         | 5             | 20               | 5            | 10                   | 5           | 5                | 5                      | 10                  | 5               | 5                           | 3                         | 3                             | 3                         | 10                      | 5                           | 5                       | 5                    | 744                                                                    | 10      |
| Federated & Privacy-Preserving Learning        | 6                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 5           | 5                | 5                      | 3                   | 10              | 10                          | 5                         | 5                             | 5                         | 10                      | 10                          | 5                       | 10                   | 726                                                                    | 11      |

| ANTICIPATED RADICAL TECHNOLOGIES (ARTS) ↓        | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
|--------------------------------------------------|----------------------------------|------------------------|--------------|---------------------------|---------------|------------------|--------------|----------------------|-------------|------------------|------------------------|---------------------|-----------------|-----------------------------|---------------------------|-------------------------------|---------------------------|-------------------------|-----------------------------|-------------------------|----------------------|------------------------------------------------------------------------|---------|
| Federated & Privacy-Preserving Learning          | 6                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 5           | 5                | 5                      | 3                   | 10              | 10                          | 5                         | 5                             | 5                         | 10                      | 10                          | 5                       | 10                   | 726                                                                    | 11      |
| Machine-Readable Regulation (Rules as Code)      | 5                                | 10                     | 10           | 5                         | 5             | 5                | 5            | 10                   | 5           | 5                | 10                     | 5                   | 5               | 5                           | 5                         | 5                             | 3                         | 10                      | 10                          | 3                       | 20                   | 705                                                                    | 12      |
| Privacy-Preserving Pervasive Sensing             | 6                                | 5                      | 3            | 3                         | 3             | 3                | 1            | 5                    | 5           | 5                | 5                      | 3                   | 10              | 10                          | 10                        | 5                             | 5                         | 10                      | 10                          | 5                       | 10                   | 696                                                                    | 13      |
| Content Authenticity Infrastructure              | 6                                | 3                      | 3            | 1                         | 1             | 1                | 1            | 1                    | 5           | 10               | 3                      | 5                   | 3               | 1                           | 20                        | 10                            | 10                        | 10                      | 10                          | 5                       | 10                   | 678                                                                    | 14      |
| Personal Data Portability & Trust Frameworks     | 5                                | 5                      | 3            | 1                         | 5             | 3                | 0            | 3                    | 10          | 5                | 3                      | 10                  | 10              | 10                          | 5                         | 10                            | 10                        | 10                      | 10                          | 10                      | 10                   | 665                                                                    | 15      |
| Global Supply Chain Traceability Networks        | 5                                | 3                      | 20           | 10                        | 10            | 5                | 10           | 5                    | 10          | 3                | 5                      | 5                   | 5               | 3                           | 5                         | 1                             | 3                         | 10                      | 10                          | 3                       | 5                    | 655                                                                    | 16      |
| Decentralized Trust Networks (Web3 & Blockchain) | 6                                | 1                      | 5            | 3                         | 3             | 5                | 3            | 3                    | 10          | 5                | 5                      | 5                   | 3               | 3                           | 5                         | 5                             | 5                         | 5                       | 20                          | 5                       | 10                   | 654                                                                    | 17      |
| Supportive Infrastructure for Autonomy           | 5                                | 10                     | 10           | 10                        | 5             | 3                | 5            | 20                   | 5           | 5                | 20                     | 5                   | 5               | 5                           | 1                         | 1                             | 3                         | 5                       | 3                           | 5                       | 3                    | 645                                                                    | 18      |
| AI Understanding of Human Intent & Context       | 4                                | 5                      | 3            | 5                         | 5             | 1                | 1            | 5                    | 5           | 10               | 10                     | 10                  | 10              | 10                          | 10                        | 10                            | 20                        | 10                      | 10                          | 10                      | 10                   | 640                                                                    | 19      |
| Automated Machine Learning (AutoML)              | 6                                | 5                      | 5            | 5                         | 3             | 3                | 3            | 3                    | 5           | 3                | 10                     | 20                  | 5               | 5                           | 3                         | 5                             | 5                         | 5                       | 3                           | 5                       | 5                    | 636                                                                    | 20      |



| ANTICIPATED RADICAL TECHNOLOGIES (ARTS) ↓                                            | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
|--------------------------------------------------------------------------------------|----------------------------------|------------------------|--------------|---------------------------|---------------|------------------|--------------|----------------------|-------------|------------------|------------------------|---------------------|-----------------|-----------------------------|---------------------------|-------------------------------|---------------------------|-------------------------|-----------------------------|-------------------------|----------------------|------------------------------------------------------------------------|---------|
| Automated Machine Learning (AutoML)                                                  | 6                                | 5                      | 5            | 5                         | 3             | 3                | 3            | 3                    | 5           | 3                | 10                     | 20                  | 5               | 5                           | 3                         | 5                             | 5                         | 5                       | 3                           | 5                       | 5                    | 636                                                                    | 20      |
| Fully Autonomous Drones, Robots & Underwater Vehicles                                | 6                                | 3                      | 5            | 3                         | 5             | 5                | 5            | 10                   | 5           | 10               | 10                     | 5                   | 3               | 1                           | 5                         | 3                             | 3                         | 10                      | 3                           | 3                       | 5                    | 612                                                                    | 21      |
| Grid-Scale Energy Storage                                                            | 6                                | 5                      | 5            | 5                         | 5             | 20               | 5            | 5                    | 5           | 3                | 5                      | 5                   | 3               | 3                           | 3                         | 1                             | 3                         | 10                      | 3                           | 3                       | 5                    | 612                                                                    | 22      |
| Digital Learning Networks and Skill Credentialing                                    | 5                                | 3                      | 3            | 5                         | 3             | 5                | 5            | 5                    | 5           | 3                | 5                      | 10                  | 5               | 5                           | 5                         | 20                            | 5                         | 5                       | 5                           | 10                      | 5                    | 585                                                                    | 23      |
| Open Data Sharing Marketplaces                                                       | 6                                | 5                      | 5            | 3                         | 3             | 5                | 3            | 5                    | 5           | 5                | 5                      | 5                   | 5               | 3                           | 10                        | 3                             | 3                         | 5                       | 10                          | 3                       | 5                    | 576                                                                    | 24      |
| Interoperable Digital Twin Ecosystems                                                | 5                                | 5                      | 5            | 10                        | 3             | 5                | 5            | 10                   | 5           | 5                | 10                     | 5                   | 5               | 5                           | 3                         | 5                             | 3                         | 10                      | 5                           | 3                       | 5                    | 560                                                                    | 25      |
| Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure | 5                                | 1                      | 3            | 20                        | 5             | 5                | 20           | 10                   | 3           | 3                | 10                     | 5                   | 3               | 5                           | 1                         | 3                             | 1                         | 5                       | 5                           | 1                       | 1                    | 550                                                                    | 26      |
| Digital Twin & Simulation-Driven Production                                          | 6                                | 3                      | 3            | 10                        | 5             | 3                | 10           | 3                    | 3           | 5                | 10                     | 5                   | 3               | 3                           | 1                         | 5                             | 3                         | 5                       | 5                           | 3                       | 3                    | 546                                                                    | 27      |
| Solid-State Batteries                                                                | 5                                | 10                     | 10           | 5                         | 3             | 10               | 3            | 5                    | 5           | 5                | 10                     | 5                   | 5               | 10                          | 3                         | 1                             | 5                         | 5                       | 1                           | 3                       | 3                    | 535                                                                    | 28      |
| Causal Learning & Reasoning                                                          | 4                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 5           | 5                | 10                     | 5                   | 10              | 5                           | 10                        | 10                            | 5                         | 10                      | 5                           | 5                       | 10                   | 512                                                                    | 29      |
| Causal Learning & Reasoning                                                          | 4                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 5           | 5                | 10                     | 5                   | 10              | 5                           | 10                        | 10                            | 5                         | 10                      | 5                           | 5                       | 10                   | 512                                                                    | 29      |

| ANTICIPATED RADICAL TECHNOLOGIES (ARTS) ↓  | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
|--------------------------------------------|----------------------------------|------------------------|--------------|---------------------------|---------------|------------------|--------------|----------------------|-------------|------------------|------------------------|---------------------|-----------------|-----------------------------|---------------------------|-------------------------------|---------------------------|-------------------------|-----------------------------|-------------------------|----------------------|------------------------------------------------------------------------|---------|
| Thin-film solar cells                      | 6                                | 3                      | 3            | 3                         | 5             | 10               | 3            | 10                   | 3           | 3                | 3                      | 10                  | 3               | 3                           | 3                         | 1                             | 3                         | 5                       | 1                           | 5                       | 5                    | 510                                                                    | 30      |
| Ultra-Low Latency Networks                 | 5                                | 5                      | 5            | 5                         | 3             | 5                | 3            | 5                    | 5           | 10               | 5                      | 5                   | 3               | 5                           | 3                         | 3                             | 10                        | 5                       | 3                           | 10                      | 3                    | 505                                                                    | 31      |
| Collective Open Innovation Networks        | 6                                | 1                      | 1            | 5                         | 3             | 3                | 5            | 1                    | 3           | 3                | 5                      | 5                   | 3               | 5                           | 3                         | 5                             | 5                         | 3                       | 10                          | 10                      | 5                    | 504                                                                    | 32      |
| Reconfigurable & Agile Factories           | 5                                | 1                      | 5            | 20                        | 5             | 3                | 10           | 3                    | 5           | 3                | 10                     | 5                   | 3               | 5                           | 0                         | 3                             | 3                         | 3                       | 3                           | 5                       | 3                    | 490                                                                    | 33      |
| Drone Swarms & Aerial Robots               | 5                                | 3                      | 5            | 3                         | 5             | 5                | 3            | 5                    | 5           | 10               | 10                     | 5                   | 3               | 1                           | 5                         | 3                             | 5                         | 10                      | 3                           | 3                       | 5                    | 485                                                                    | 34      |
| Micro/Nano Sensor Networks                 | 5                                | 3                      | 5            | 5                         | 5             | 5                | 5            | 10                   | 5           | 5                | 5                      | 3                   | 5               | 5                           | 5                         | 1                             | 3                         | 10                      | 3                           | 3                       | 5                    | 480                                                                    | 35      |
| Secure & Resilient Social Platforms        | 5                                | 1                      | 1            | 1                         | 1             | 1                | 1            | 1                    | 3           | 10               | 1                      | 5                   | 3               | 3                           | 10                        | 3                             | 10                        | 10                      | 10                          | 10                      | 10                   | 475                                                                    | 36      |
| Privacy-Preserving Collaboration Protocols | 4                                | 5                      | 5            | 5                         | 5             | 5                | 3            | 5                    | 5           | 5                | 5                      | 5                   | 10              | 5                           | 5                         | 5                             | 3                         | 10                      | 10                          | 5                       | 10                   | 464                                                                    | 37      |
| Precision Medicine & Genomic Diagnostics   | 6                                | 1                      | 1            | 1                         | 5             | 0                | 0            | 0                    | 3           | 1                | 0                      | 5                   | 20              | 10                          | 5                         | 3                             | 1                         | 5                       | 5                           | 5                       | 5                    | 456                                                                    | 38      |
| Green Hydrogen & Power-to-X                | 5                                | 5                      | 5            | 5                         | 5             | 20               | 10           | 3                    | 3           | 1                | 3                      | 5                   | 1               | 1                           | 1                         | 3                             | 1                         | 5                       | 3                           | 3                       | 3                    | 430                                                                    | 39      |
| Advanced Prosthetics & Exoskeletons        | 6                                | 1                      | 5            | 3                         | 3             | 1                | 3            | 5                    | 1           | 1                | 3                      | 5                   | 5               | 20                          | 0                         | 3                             | 3                         | 3                       | 1                           | 3                       | 1                    | 420                                                                    | 40      |

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| Platform Cooperatives & Fair Work               | 4                                | 5                      | 3            | 1                         | 5             | 3                | 1            | 3                    | 5           | 3                | 5                      | 10                  | 3               | 3                           | 3                         | 3                             | 5                         | 3                       | 10                          | 10                      | 20                   | 416                                                                    | 41      |
| Scalable Decentralized Governance               | 5                                | 1                      | 3            | 1                         | 1             | 3                | 1            | 3                    | 3           | 5                | 3                      | 5                   | 1               | 1                           | 3                         | 3                             | 5                         | 5                       | 10                          | 5                       | 20                   | 410                                                                    | 42      |
| Compute-in-Memory & Neuromorphic Chips          | 5                                | 5                      | 3            | 5                         | 3             | 3                | 3            | 3                    | 3           | 3                | 10                     | 3                   | 5               | 5                           | 5                         | 3                             | 5                         | 5                       | 3                           | 3                       | 3                    | 405                                                                    | 43      |
| Synthetic Biology & Designer Microbes           | 5                                | 1                      | 3            | 5                         | 10            | 5                | 10           | 3                    | 3           | 1                | 3                      | 5                   | 5               | 1                           | 1                         | 3                             | 3                         | 5                       | 3                           | 3                       | 3                    | 380                                                                    | 44      |
| Prediction-Market Forecasting Platforms         | 7                                | 1                      | 3            | 1                         | 1             | 3                | 1            | 1                    | 3           | 3                | 3                      | 3                   | 3               | 1                           | 5                         | 1                             | 3                         | 5                       | 5                           | 3                       | 5                    | 378                                                                    | 45      |
| Metamaterials for Novel Optics & Connectivity   | 6                                | 3                      | 3            | 3                         | 1             | 3                | 3            | 5                    | 3           | 3                | 3                      | 1                   | 3               | 3                           | 3                         | 1                             | 5                         | 5                       | 3                           | 3                       | 3                    | 360                                                                    | 46      |
| Circular & Sustainable Manufacturing            | 4                                | 1                      | 5            | 10                        | 3             | 5                | 20           | 5                    | 3           | 1                | 3                      | 5                   | 3               | 3                           | 0                         | 3                             | 3                         | 3                       | 5                           | 5                       | 3                    | 356                                                                    | 47      |
| Interoperable Digital Currency Payment Networks | 4                                | 5                      | 3            | 1                         | 3             | 3                | 1            | 3                    | 20          | 5                | 3                      | 10                  | 1               | 1                           | 1                         | 1                             | 5                         | 3                       | 10                          | 5                       | 5                    | 356                                                                    | 48      |
| Soft Robotics & Bio-Inspired Machines           | 5                                | 1                      | 5            | 5                         | 5             | 3                | 3            | 5                    | 3           | 5                | 10                     | 3                   | 5               | 5                           | 1                         | 1                             | 3                         | 3                       | 1                           | 3                       | 1                    | 355                                                                    | 49      |
| Multi-Material & Hybrid 3D Printing             | 4                                | 1                      | 3            | 10                        | 1             | 3                | 10           | 5                    | 5           | 3                | 5                      | 5                   | 5               | 10                          | 1                         | 3                             | 5                         | 3                       | 3                           | 3                       | 3                    | 348                                                                    | 50      |

| ANTICIPATED RADICAL TECHNOLOGIES (ARTS) ↓                      | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
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| Quantum-Resilient and Secure Communication Networks            | 5                                | 3                      | 3            | 3                         | 1             | 5                | 1            | 3                    | 3           | 3                | 3                      | 3                   | 3               | 3                           | 5                         | 1                             | 3                         | 10                      | 5                           | 3                       | 5                    | 345                                                                    | 51      |
| Smart Thermal Materials for Energy-Efficient Heating & Cooling | 5                                | 5                      | 5            | 3                         | 5             | 10               | 5            | 10                   | 1           | 1                | 3                      | 3                   | 3               | 3                           | 0                         | 1                             | 3                         | 5                       | 1                           | 1                       | 1                    | 345                                                                    | 52      |
| Cellular Agriculture & Cultured Meat                           | 5                                | 0                      | 5            | 3                         | 20            | 3                | 1            | 3                    | 5           | 0                | 3                      | 5                   | 1               | 0                           | 0                         | 3                             | 5                         | 3                       | 3                           | 3                       | 3                    | 345                                                                    | 53      |
| Integrated Sensing and Communication (ISAC)                    | 4                                | 10                     | 5            | 5                         | 1             | 3                | 3            | 5                    | 3           | 5                | 5                      | 3                   | 3               | 3                           | 5                         | 1                             | 5                         | 10                      | 3                           | 3                       | 3                    | 336                                                                    | 54      |
| AI-Driven Autonomous Scientific Discovery                      | 5                                | 1                      | 1            | 5                         | 10            | 5                | 10           | 1                    | 1           | 1                | 3                      | 3                   | 5               | 3                           | 3                         | 3                             | 1                         | 3                       | 3                           | 3                       | 1                    | 330                                                                    | 55      |
| Next-Generation Gene Editing                                   | 5                                | 0                      | 1            | 3                         | 10            | 1                | 5            | 0                    | 1           | 0                | 1                      | 3                   | 10              | 10                          | 1                         | 1                             | 1                         | 5                       | 3                           | 5                       | 5                    | 330                                                                    | 56      |
| Small Modular Fission Reactors (SMRs)                          | 5                                | 3                      | 1            | 5                         | 5             | 10               | 5            | 5                    | 3           | 1                | 3                      | 5                   | 1               | 1                           | 1                         | 1                             | 1                         | 5                       | 1                           | 3                       | 5                    | 325                                                                    | 57      |
| Biological Aging & Longevity Barriers                          | 4                                | 1                      | 1            | 1                         | 1             | 1                | 0            | 3                    | 3           | 1                | 3                      | 10                  | 10              | 10                          | 1                         | 5                             | 3                         | 3                       | 3                           | 10                      | 10                   | 320                                                                    | 58      |
| Nano-Catalysts & Advanced Coatings                             | 5                                | 3                      | 3            | 5                         | 5             | 10               | 5            | 5                    | 1           | 0                | 3                      | 3                   | 5               | 3                           | 1                         | 1                             | 1                         | 5                       | 1                           | 1                       | 1                    | 310                                                                    | 59      |
| Self-Healing & Smart Polymers                                  | 5                                | 3                      | 3            | 5                         | 3             | 5                | 5            | 5                    | 1           | 1                | 5                      | 3                   | 3               | 5                           | 1                         | 1                             | 3                         | 5                       | 1                           | 1                       | 1                    | 300                                                                    | 60      |

| ANTICIPATED RADICAL TECHNOLOGIES (ARTS) ↓                 | Maturity of ARTs, situation 2026 | 1. Passenger Transport | 2. Logistics | 3. Manufacturing of goods | 4. Sustenance | 5. Energy supply | 6. Materials | 7. Built environment | 8. Exchange | 9. Remote impact | 10. Automation of work | 11. Work and income | 12. Health care | 13. Redressing disabilities | 14. Acquiring information | 15. Proficiency and its proof | 16. Producing experiences | 17. Safety and Security | 18. Collaboration and Trust | 19. Existential Meaning | 20. Power Structures | Potential impact of ARTs by 2045 (maturity * sum anticip. GVN impacts) | Ranking |
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| High-Altitude Platforms & Balloons                        | 5                                | 3                      | 3            | 1                         | 3             | 3                | 1            | 3                    | 3           | 5                | 3                      | 3                   | 3               | 1                           | 5                         | 3                             | 3                         | 5                       | 3                           | 3                       | 3                    | 300                                                                    | 61      |
| High-Efficiency Wind Turbines                             | 6                                | 3                      | 1            | 3                         | 3             | 10               | 3            | 3                    | 3           | 0                | 1                      | 5                   | 1               | 0                           | 1                         | 1                             | 1                         | 3                       | 1                           | 3                       | 3                    | 294                                                                    | 62      |
| Open Metaverse Interoperability Protocols                 | 5                                | 0                      | 0            | 1                         | 0             | 0                | 0            | 1                    | 3           | 10               | 1                      | 5                   | 1               | 3                           | 1                         | 5                             | 10                        | 1                       | 3                           | 10                      | 3                    | 290                                                                    | 63      |
| mRNA Therapies & Vaccines                                 | 6                                | 1                      | 3            | 3                         | 1             | 0                | 0            | 0                    | 3           | 0                | 0                      | 5                   | 10              | 5                           | 1                         | 1                             | 1                         | 5                       | 3                           | 3                       | 3                    | 288                                                                    | 64      |
| Brain-Computer Interfaces (BCI)                           | 5                                | 1                      | 1            | 1                         | 1             | 1                | 0            | 1                    | 1           | 3                | 1                      | 3                   | 5               | 10                          | 1                         | 3                             | 10                        | 3                       | 1                           | 5                       | 3                    | 275                                                                    | 65      |
| Graphene and Nanotube Composites for Lightweight Strength | 4                                | 5                      | 5            | 3                         | 1             | 5                | 10           | 5                    | 3           | 3                | 5                      | 3                   | 3               | 5                           | 3                         | 1                             | 3                         | 3                       | 1                           | 1                       | 0                    | 272                                                                    | 66      |
| Haptic and Multi-Sensory Feedback Systems                 | 4                                | 1                      | 3            | 3                         | 1             | 1                | 1            | 3                    | 3           | 10               | 3                      | 3                   | 3               | 5                           | 1                         | 5                             | 10                        | 3                       | 1                           | 5                       | 1                    | 264                                                                    | 67      |
| Quantum & High-Precision Sensing                          | 5                                | 3                      | 3            | 3                         | 3             | 3                | 3            | 3                    | 1           | 3                | 3                      | 1                   | 5               | 1                           | 3                         | 1                             | 1                         | 5                       | 1                           | 1                       | 1                    | 240                                                                    | 68      |
| Next-Gen Memory & Storage                                 | 5                                | 1                      | 1            | 3                         | 1             | 1                | 1            | 3                    | 3           | 3                | 5                      | 3                   | 3               | 3                           | 3                         | 1                             | 5                         | 3                       | 1                           | 3                       | 1                    | 240                                                                    | 69      |
| Rare-Earth-Free Magnets for Sustainable Motors            | 4                                | 5                      | 3            | 5                         | 3             | 10               | 5            | 3                    | 3           | 1                | 5                      | 3                   | 1               | 3                           | 1                         | 1                             | 1                         | 3                       | 1                           | 1                       | 1                    | 236                                                                    | 70      |
| Advanced geothermal technology                            | 4                                | 1                      | 1            | 3                         | 5             | 10               | 5            | 5                    | 3           | 0                | 3                      | 5                   | 1               | 0                           | 1                         | 1                             | 1                         | 5                       | 1                           | 3                       | 3                    | 228                                                                    | 71      |

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| Volumetric Additive Manufacturing                                 | 5                                | 1                      | 3            | 5                         | 1             | 1                | 5            | 3                    | 3           | 1                | 3                      | 3                   | 3               | 5                           | 0                         | 1                             | 3                         | 1                       | 1                           | 1                       | 1                    | 225                                                                    | 72      |
| Fusion Energy Reactors                                            | 3                                | 3                      | 1            | 5                         | 5             | 10               | 5            | 3                    | 3           | 1                | 3                      | 10                  | 1               | 1                           | 1                         | 1                             | 1                         | 10                      | 1                           | 3                       | 5                    | 219                                                                    | 73      |
| Ultra-Wide-Bandgap (UWBG) Power Semiconductors                    | 3                                | 10                     | 5            | 5                         | 3             | 10               | 3            | 5                    | 3           | 3                | 5                      | 3                   | 1               | 3                           | 1                         | 1                             | 3                         | 5                       | 1                           | 1                       | 1                    | 216                                                                    | 74      |
| Photonic and Optical Computing                                    | 5                                | 1                      | 1            | 3                         | 1             | 1                | 1            | 1                    | 3           | 3                | 3                      | 3                   | 3               | 1                           | 3                         | 1                             | 3                         | 3                       | 1                           | 3                       | 1                    | 200                                                                    | 75      |
| Bio-fabrication technologies                                      | 5                                | 0                      | 1            | 3                         | 3             | 0                | 1            | 0                    | 1           | 1                | 1                      | 1                   | 10              | 10                          | 0                         | 1                             | 1                         | 1                       | 1                           | 1                       | 1                    | 190                                                                    | 76      |
| High-Entropy Alloys & Advanced Metals                             | 4                                | 3                      | 3            | 3                         | 1             | 5                | 5            | 3                    | 1           | 1                | 3                      | 3                   | 3               | 3                           | 1                         | 1                             | 1                         | 5                       | 1                           | 1                       | 0                    | 188                                                                    | 77      |
| Engineered Living Materials                                       | 3                                | 3                      | 3            | 3                         | 3             | 5                | 10           | 10                   | 1           | 0                | 3                      | 3                   | 1               | 1                           | 1                         | 1                             | 3                         | 3                       | 1                           | 1                       | 1                    | 171                                                                    | 78      |
| Quantum Computing Platforms                                       | 5                                | 1                      | 3            | 3                         | 1             | 1                | 3            | 1                    | 1           | 1                | 1                      | 1                   | 3               | 1                           | 1                         | 1                             | 1                         | 3                       | 3                           | 1                       | 3                    | 170                                                                    | 79      |
| Organoids & Tissue Engineering                                    | 5                                | 0                      | 1            | 1                         | 3             | 0                | 0            | 0                    | 1           | 0                | 1                      | 3                   | 10              | 5                           | 1                         | 1                             | 1                         | 3                       | 1                           | 1                       | 1                    | 170                                                                    | 80      |
| Microbiome Engineering                                            | 5                                | 0                      | 1            | 1                         | 5             | 1                | 3            | 1                    | 1           | 0                | 1                      | 3                   | 5               | 1                           | 1                         | 1                             | 1                         | 3                       | 1                           | 3                       | 1                    | 170                                                                    | 81      |
| Advanced CO <sub>2</sub> Capture Materials for Climate Mitigation | 5                                | 1                      | 1            | 3                         | 1             | 5                | 5            | 1                    | 1           | 0                | 1                      | 1                   | 1               | 0                           | 0                         | 1                             | 1                         | 3                       | 1                           | 3                       | 1                    | 155                                                                    | 82      |
| 4D Printed & Programmable Materials                               | 3                                | 1                      | 1            | 3                         | 1             | 3                | 5            | 5                    | 1           | 3                | 3                      | 1                   | 5               | 5                           | 1                         | 1                             | 5                         | 3                       | 1                           | 1                       | 0                    | 147                                                                    | 83      |

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| Novel transistor technologies and materials beyond silicon CMOS | 3                                | 3                      | 1            | 3                         | 1             | 3                | 3            | 1                    | 3           | 3                | 5                      | 3                   | 3               | 3                           | 3                         | 1                             | 3                         | 3                       | 1                           | 1                       | 1                    | 144                                                                    | 84      |
| Nano-Engineered Membranes for Low-Energy Desalination           | 6                                | 0                      | 0            | 1                         | 3             | 3                | 1            | 1                    | 1           | 0                | 1                      | 1                   | 3               | 0                           | 0                         | 1                             | 0                         | 3                       | 0                           | 3                       | 1                    | 138                                                                    | 85      |
| Room-Temperature Superconductors                                | 2                                | 3                      | 3            | 5                         | 1             | 10               | 5            | 5                    | 3           | 1                | 3                      | 5                   | 5               | 1                           | 3                         | 1                             | 3                         | 5                       | 1                           | 3                       | 1                    | 134                                                                    | 86      |
| Solid Hydrogen Storage Materials for Safe, Dense Fuel           | 4                                | 3                      | 3            | 1                         | 1             | 5                | 3            | 3                    | 1           | 1                | 1                      | 1                   | 1               | 0                           | 0                         | 1                             | 1                         | 3                       | 0                           | 1                       | 1                    | 124                                                                    | 87      |
| Quantum-Accelerated AI Systems                                  | 5                                | 1                      | 1            | 1                         | 1             | 1                | 1            | 1                    | 1           | 1                | 1                      | 1                   | 3               | 1                           | 1                         | 1                             | 1                         | 3                       | 1                           | 1                       | 1                    | 120                                                                    | 88      |
| Memory Prostheses                                               | 4                                | 0                      | 1            | 1                         | 1             | 0                | 0            | 0                    | 0           | 1                | 1                      | 1                   | 5               | 5                           | 1                         | 3                             | 3                         | 1                       | 1                           | 3                       | 1                    | 116                                                                    | 89      |
| Optical/Microwave Power Beaming for Persistent Robotics         | 4                                | 1                      | 3            | 1                         | 1             | 1                | 1            | 3                    | 1           | 3                | 3                      | 1                   | 1               | 1                           | 1                         | 0                             | 1                         | 3                       | 1                           | 1                       | 1                    | 116                                                                    | 90      |
| Gecko-Inspired Dry-Adhesion Mobility & Manipulation             | 5                                | 1                      | 1            | 1                         | 1             | 1                | 1            | 3                    | 1           | 3                | 3                      | 1                   | 1               | 1                           | 1                         | 0                             | 1                         | 1                       | 0                           | 1                       | 0                    | 115                                                                    | 91      |
| Gene Drive Pest Control                                         | 3                                | 1                      | 3            | 0                         | 10            | 1                | 1            | 1                    | 1           | 3                | 1                      | 1                   | 1               | 0                           | 0                         | 0                             | 1                         | 5                       | 3                           | 1                       | 3                    | 111                                                                    | 92      |
| Organs-on-Chips & Bio-Computational Hybrids                     | 4                                | 0                      | 0            | 1                         | 3             | 0                | 1            | 0                    | 1           | 0                | 1                      | 3                   | 5               | 3                           | 1                         | 1                             | 0                         | 3                       | 1                           | 1                       | 1                    | 104                                                                    | 93      |

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| Artificial Wombs & Synthetic Embryos      | 3                                | 0                      | 0            | 0                         | 1             | 0                | 0            | 0                    | 1           | 0                | 0                      | 5                   | 3               | 1                           | 1                         | 1                             | 0                         | 1                       | 1                           | 5                       | 10                   | 90                                                                     | 94      |
| Bionic Leaf Technology                    | 4                                | 1                      | 1            | 1                         | 3             | 5                | 3            | 1                    | 1           | 0                | 1                      | 1                   | 1               | 0                           | 0                         | 0                             | 0                         | 1                       | 0                           | 1                       | 1                    | 88                                                                     | 95      |
| Wireless & Space-Based Power Transfer     | 3                                | 1                      | 1            | 1                         | 1             | 3                | 1            | 1                    | 1           | 3                | 1                      | 1                   | 1               | 1                           | 1                         | 0                             | 1                         | 3                       | 1                           | 1                       | 1                    | 75                                                                     | 96      |
| Brain-to-Brain Interfaces                 | 3                                | 0                      | 0            | 0                         | 0             | 0                | 0            | 0                    | 0           | 1                | 0                      | 1                   | 1               | 1                           | 1                         | 1                             | 5                         | 1                       | 1                           | 3                       | 3                    | 57                                                                     | 97      |
| Space Resource Utilization (SRU)          | 3                                | 1                      | 1            | 1                         | 0             | 1                | 3            | 0                    | 1           | 0                | 0                      | 1                   | 0               | 0                           | 0                         | 0                             | 0                         | 1                       | 1                           | 1                       | 1                    | 39                                                                     | 98      |
| Molecular Computing                       | 3                                | 0                      | 0            | 1                         | 0             | 0                | 1            | 0                    | 0           | 0                | 0                      | 1                   | 1               | 1                           | 0                         | 0                             | 0                         | 1                       | 0                           | 0                       | 0                    | 18                                                                     | 99      |
| Closed-Loop Life Support System           | 4                                | 0                      | 0            | 0                         | 1             | 0                | 0            | 1                    | 0           | 0                | 0                      | 0                   | 0               | 0                           | 0                         | 0                             | 0                         | 1                       | 0                           | 1                       | 0                    | 16                                                                     | 100     |
|                                           |                                  | 325                    | 386          | 426                       | 368           | 445              | 384          | 431                  | 386         | 380              | 496                    | 486                 | 452             | 413                         | 321                       | 280                           | 401                       | 564                     | 385                         | 409                     | 437                  |                                                                        |         |



# Attachment 2.

## Development evidence of ARTs

### Sisällys

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# Group 1 - Sensing, Measurement & Connectivity

## ART 01.001 Global Broadband Connectivity

### 1. ART extraction

**A) Primary capability:** A globally ubiquitous broadband internet service that can **deliver affordable, high-speed connectivity to any location on Earth**. This is achieved by orchestrating a hybrid network of LEO satellites, dense terrestrial 5G/6G cells, and local mesh nodes, so end-users experience reliable broadband regardless of geography or mobility. The system aims to **surmount coverage gaps and capacity constraints** of any single infrastructure by intelligently combining multiple technologies.

### B) Key sub-components/variants:

- **LEO satellite constellations for global coverage:** Swarms of low-Earth-orbit satellites (e.g., Starlink, OneWeb, Amazon's Kuiper) provide long-distance backhaul and reach sparsely populated or remote regions.
- **Terrestrial 5G/6G high-frequency networks:** Ultra-dense deployments of next-gen cellular (mmWave and Terahertz small cells, massive MIMO) in urban or high-demand areas to deliver multi-Gbps throughput locally. Future 6G research explores **THz links and advanced beamforming** for extreme data rates[1][2].
- **Community-operated mesh networks:** Local Wi-Fi/WiGig mesh nodes or micro-ISPs that use inexpensive equipment (often in unlicensed bands) to extend coverage in villages, rural communities, or within cities. These networks can route traffic peer-to-peer and leverage shared backhaul (including satellite links) to connect underserved users.
- **Reconfigurable Intelligent Surfaces (RIS):** Thin, electronically tunable metasurface panels on buildings or structures that **reflect or bend wireless signals** to fill dead zones and improve coverage without active repeaters. RIS can dynamically shape 5G/6G mmWave beams around obstacles[3][4], enhancing signal strength by tens of dB in trials.
- **Optical wireless links (Li-Fi and FSO):** Using light (e.g. LED-based Li-Fi or free-space lasers) to offload data in high-density indoor or point-to-point scenarios. Li-Fi, now standardized (IEEE 802.11bb-2023), can provide multi-Gbps wireless links via infrared/visible light, complementing radio Wi-Fi[5][6].
- **Adaptive, software-defined network control:** Intelligent management that auto-selects the best path (satellite vs. terrestrial vs. mesh) and handles user mobility, weather outages, or intermittent power. This includes software-defined networking (SDN) and adaptive compression/routing algorithms to maintain stable latency and throughput by shifting traffic among satellites, ground base stations, RIS-assisted links, or peer nodes as conditions change.
- **Rugged user terminals and small-cell access points:** End-user devices ranging from smartphone-integrated antennas to laptop-sized satellite terminals or solar-powered community Wi-Fi hubs. These automatically connect to the optimal available network and hide the underlying complexity from the user. Terminals must balance high performance with low power and cost, and new designs (e.g. phased-array flat panels) are emerging to meet these needs[7].

**C) Maturity indicators to look for:** Evidence of **working prototypes and commercial deployments** in each domain and successful integration among them. This includes: demonstration of multi-hop network "*hand-offs*" (e.g. a seamless switch from satellite to terrestrial connectivity), **field trials or pilots** offering broadband in remote areas via combined tech, and **standards or large-scale investments** that signal imminent scaling. Concrete signs would be: *operational services* (e.g. satellite broadband customers, mesh networks serving real communities), **proof-of-concept trials** for

new pieces like RIS or direct satellite-to-phone links, **multiple well-funded actors** (industry consortia, telcos, space companies) developing competing solutions, **performance milestones** (e.g. Gbps data rates at THz frequencies, RIS boosting signal by >10 dB in field, Li-Fi standard ratified), and **regulatory/standards adoption** (3GPP 5G NTN standards for satellite integration, IEEE Li-Fi standards, etc.). Evidence of *economies of scale* starting (cost/price reductions, volume production of equipment) and expanding use-cases (e.g. satellites used for cellular backhaul, or mesh networks adopted by governments) would indicate advancing maturity.

1. **Evidence (10–20 recent, reliable sources)**
2. **Starlink LEO constellation performance – Richter et al., IFIP Networking (2025):** *Peer-reviewed measurement study (Potsdam Univ.) – Published 2025.*  
Using ~2.5 years of data (2022–2024), this study shows **Starlink’s large LEO network** achieving median latencies ~100–150 ms (with best-case ~80 ms) and improving over time as more satellites & ground stations were added[8]. It notes a **bimodal latency distribution** (some links <100 ms, others ~150–250 ms) and non-trivial packet loss (e.g. >10% in Germany) due to network variability[9]. *This demonstrates the plausibility of global satellite broadband – latencies nearing terrestrial broadband and real deployments serving users – while also highlighting remaining challenges (performance inconsistency, need for more ground infrastructure) that ongoing R&D is addressing.*
3. **100 Gb/s THz wireless link demo – Keysight/NPL/Surrey (U.K., 04/2023):** *Industry lab press release (Keysight Technologies) – April 2023.*  
A collaboration between Keysight, the UK National Physical Lab, and University of Surrey achieved the **U.K.’s first >100 Gb/s wireless link at 300 GHz** (sub-THz band) using a 6G testbed[1]. The prototype used advanced 32/64-QAM modulation and precision front-ends to establish a stable data connection in the 300 GHz band[2]. *This result confirms the feasibility of the ultra-high-frequency wireless component (mmWave-to-THz) needed for future 6G: multi-Gbps throughput and low latency over short ranges. It addresses a key technical pillar (massive capacity) and indicates fast-paced progress towards 6G-grade backhaul and access links.*
4. **RIS-aided wireless field trials – Pei et al., preprint (08/2023):** *Experimental research preprint (X. Pei et al.) – Aug 2023.*  
Researchers built and tested a **Reconfigurable Intelligent Surface (RIS)** prototype in real environments for 5G. In indoor trials at 5.8 GHz, the passive RIS panel provided **+10–20 dB signal power gain** to a receiver, and even **+35 dB gain outdoors** by reflecting a base station’s signal[10]. However, when integrated into a live 5G network (2.6 GHz band), the RIS yielded a smaller 4–7 dB improvement in indoor cell coverage[11]. *These results validate that RIS devices can substantially boost wireless coverage and throughput, though effectiveness depends on deployment scenario. It marks a solved “lab to field” step for metasurfaces, a once-theoretical technology now demonstrated in office, corridor, and outdoor settings.*
5. **RIS technology survey and roadmap – Yuan et al., China Mobile (ZTE Communications, 03/2022):** *Industry research report – March 2022.*  
Experts from China Mobile Research Institute review **progress in reconfigurable intelligent surfaces over the past 2–3 years**, covering academic advances (metamaterials designs, channel modeling, joint BS-RIS optimization) and industry developments (field trials, control protocols, standardization)[12]. They discuss realistic performance targets, compare RIS with other coverage solutions, and propose a timeline toward **RIS standardization for 6G**. *This authoritative roadmap shows that major telecom stakeholders are actively investigating RIS as*

*a relay/coverage technology, with standard bodies and operators planning for its integration into beyond-5G networks. The presence of such a roadmap underscores that RIS has moved from theory into the engineering discussion needed for commercialization.*

6. **Community mesh networks scaling up – Internet Society report (10/2022):** *Technical report (Internet Society & Connect Humanity) – Oct 2022.*

This report documents case studies of community-owned connectivity. For example, a mesh Wi-Fi network in rural Thailand (Net2Home) operates **260+ wireless mesh nodes across 24 villages**, serving ~1,200 subscribers with affordable internet[13]. Another initiative developed the open-source “**LibreRouter**” – a low-cost mesh router hardware – to cut deployment costs and leverage free spectrum, supported by grants[14]. *These cases prove the viability of community-operated mesh networks as part of the global connectivity puzzle. They have demonstrated technical and financial feasibility (hundreds of nodes, thousands of users) in underserved areas, indicating that mesh networking can complement satellites and cellular in the “last mile” for remote communities.*

7. **Space-based 5G to smartphones – Vodafone & AST SpaceMobile (press release, 09/2023):** *Operator press release (Vodafone) – Sep 2023.*

In September 2023, Vodafone and AST SpaceMobile successfully placed a **5G voice call from a standard Samsung smartphone** to a satellite in LEO (BlueWalker-3)[15]. They also achieved a downlink data session ~14 Mb/s to the phone from space[16]. This world-first demonstration of direct satellite-to-handset 5G was quickly followed by plans to deploy five larger “BlueBird” commercial satellites in 2024. Vodafone notes it will also use LEO satellites to **backhaul traffic between remote cell sites and core networks**[17]. *This is a pivotal proof-of-concept for integrating non-terrestrial networks: it shows that existing 5G devices can connect via satellite with acceptable performance. It rules out fundamental feasibility concerns and indicates multiple major players (mobile operators, satellite startups) moving toward commercial “cell towers in the sky” for continuous global coverage.*

8. **Li-Fi standardization – IEEE 802.11bb Light Communications (ratified 06/2023):** *Standards body publication/news – June 2023.*

IEEE approved the 802.11bb amendment, creating the first global Li-Fi networking standard. It defines MAC/PHY changes to enable **bidirectional wireless networking over infrared/visible light** with rates from a minimum 10 Mb/s up to **9.6 Gb/s** (comparable to Wi-Fi 6)[5]. The Li-Fi spec operates in 800–1000 nm optical band and is designed to integrate with existing Wi-Fi ecosystems[6]. Industry groups (pureLiFi, Fraunhofer HHI) lauded this standard for allowing interoperable Li-Fi products that complement RF Wi-Fi – adding capacity where radio spectrum is crowded or security needs are high[18][19]. *This milestone shows that optical wireless tech has matured from experiments to standardized solutions. Early Li-Fi products (gigabit-class light modems for laptops and industrial use) are now being built to this standard, indicating the technology’s readiness to join the global connectivity toolkit, especially for specialized environments (offices, airplanes, secure facilities).*

9. **Amazon’s Project Kuiper (Amazon Leo) prototype deployment – GeekWire (11/2025):** *Tech news report (Alan Boyle, GeekWire) – Nov 2025.*

Amazon’s satellite broadband constellation (recently rebranded “**Amazon Leo**”) entered its pilot deployment phase in late 2025. They began shipping **production-grade user terminals** to select enterprise customers, after years of R&D[20]. The top-tier service “Leo Ultra” promises ~1 Gbps download and 400 Mbps upload, using a 20×30 inch phased-array antenna[21]. Two smaller terminal types will offer 100 Mbps (7" antenna) and 400 Mbps (11" antenna) for

standard users[22]. By Nov 2025 Amazon had ~153 satellites in orbit and partnered with airlines (JetBlue for in-flight Wi-Fi) and telecom operators (Verizon, Vodafone, etc.) to integrate the service[23][24]. *This demonstrates multiple well-capitalized actors racing into LEO broadband. Amazon's entry – with innovative low-cost antennas and cloud integration (direct AWS access) – underscores that the satellite component is moving rapidly toward scaled commercial offerings, driving competition, and likely lowering costs. The involvement of telcos and large clients also suggests growing confidence in satellite-terrestrial interoperability.*

#### 10. **5G-standard satellite integration – 3GPP Release 17 NTN (specs completed 03/2022):**

*Standards working group article (3GPP/GSOA) – July 2022.*

3GPP Release 17 introduced formal support for **Non-Terrestrial Networks (NTN)**. The specification (frozen in March 2022) allows standard 5G New Radio to run over satellites in low Earth orbit, in regular mobile bands, to **serve handheld devices globally**[25]. It also added satellite support for NB-IoT and LTE-M, enabling massive IoT use-cases via satellite. The report notes that with Rel-17 complete, the first commercial devices for satellite-direct 5G were expected by ~2024[26]. Work in Release 18+ is extending this to higher frequencies and mobility (e.g. satellite links to planes, ships, and integrating building-mounted terminals)[27]. *The presence of NTN in 5G standards is strong evidence of technical feasibility and imminent deployment: it means the global wireless industry has agreed on how to incorporate satellites for coverage and continuity. This pushes the concept beyond individual demos to a widely-adopted framework, smoothing the path for devices and networks to support multi-network handoff (e.g. phones using satellite when out of cell range).*

#### 11. **Metasurface coverage enhancement trial – NTT DoCoMo (press release, 01/2023):**

*Operator R&D press release – Jan 30, 2023.*

Japan's NTT DoCoMo announced a successful field trial using a **film-based transmissive metasurface (RIS) on a building window** to bend indoor 28 GHz signals down to street level outside. Conducted Oct–Nov 2022, the test showed that attaching a transparent metasurface film to the interior of office windows can **redirect mmWave 5G signals to fill coverage shadows at the foot of the building**, greatly improving throughput there[28][29]. The metasurface did not affect aesthetics or sub-6 GHz signals and requires no power. *This is a practical demonstration that reconfigurable surfaces can solve real deployment pain points – in this case, extending millimeter-wave coverage around obstacles without additional base stations. It lends plausibility to the ART's claim that simple, passive deployments (on windows, walls, etc.) can dramatically boost network efficiency and coverage in high-frequency systems.*

#### 12. **Maturity score (1–7) and reasoning**

**Final Score: 6 (Early Commercial).** The evidence suggests that **global broadband connectivity** as a unified, multi-technology concept is on the cusp of broad commercialization. *Key components have graduated from proof-of-concept into active use, and multiple industry giants are investing to scale them, although full seamless integration is still emerging.* Below, we map the findings to the rubric criteria:

- **Why not lower (levels 1–4)?** The core scientific feasibility was established long ago (satellite internet and wireless broadband are well-proven), and we now see much more than isolated lab demos. *There are working prototypes and commercial services (Starlink, OneWeb, 5G mmWave networks, community meshes) – satisfying and exceeding level 3.* In fact, Starlink's deployment of ~4,000 satellites and serving real customers demonstrates a solved prototype-to-product transition. Standards development (e.g. 3GPP NTN in 2022) and large-scale trials



(AST's satellite 5G calls in 2023) show that **previously blocking problems (latency, integration of sky and ground networks)** are being overcome – fulfilling the “Proof of Concept” threshold (level 4). Moreover, **clear advantages over legacy solutions** are evident: e.g. LEO satellites deliver <100 ms latency vs. ~600 ms on old GEO sats, and Terragraph mesh can provide fiber-like multi-Gbps in areas fiber can't reach[30][31]. These breakthroughs, plus active field testing of RIS and Li-Fi, collectively *rule out the lower maturity levels 1–4*. The technology family is no longer just theoretical or confined to labs – it is partially operational and steadily improving.

- **Why not fully highest (level 7)?** Not all pieces have reached mature market competition yet. While **satellite broadband is at level 6/7** (Starlink has millions of users and competitors are entering[23][24]), other elements like **RIS and 6G** are earlier in the pipeline (mostly at demo stage, not deployed at scale). The **integration of networks is not yet seamless or ubiquitous** – e.g. direct satellite-to-phone links only just hit their first voice call in 2023[15], and software to dynamically juggle traffic across satellites/terrestrial/mesh is still in development (initial standards exist, but few real deployments). In rubric terms, the overall “Global Connectivity” bundle has *pockets at level 7 and others around level 3–5*, so it hasn't uniformly achieved level 7's hallmarks (widespread competing products and self-sustaining market growth across all sub-techs). **Key missing evidence for level 7** includes: truly global, **affordable coverage at scale (billions of users)**, and fully integrated service offerings where a user's device roams between satellite, cellular, and local mesh as transparently as between cellular towers. Also, **cost and capacity challenges** remain before we declare the bottleneck solved: for instance, the capital expense for complete coverage is still enormous, and technologies like RIS or Li-Fi have not yet been mass-produced to drive down cost.
- **Sub-component breakdown:** To illustrate the mixed maturity, we assign sub-scores:
  - *LEO satellite broadband: 6–7.* Starlink and OneWeb are delivering service (Starlink's latency & throughput now rival basic terrestrial broadband[8]). Multiple funded competitors (Amazon, Telesat) are racing to deploy, matching rubric level 7's competition and rising demand – though global affordability and some regulatory aspects are still in progress.
  - *Terrestrial 5G (mmWave) networks: 6.* 5G infrastructure is widely deployed (billions of users covered), and mmWave small cells exist commercially (Verizon's 5G UW, etc.), albeit not yet pervasive. The tech works (multi-Gbps demos[32]) but dense build-out is ongoing. 6G research (THz links) is at lab prototype stage[33], roughly level 3, but since 6G will largely extend 5G capabilities, the current cellular system already provides a functional baseline.
  - *Community mesh networks: 4–5.* Proven in niche deployments (hundreds of node networks[13]), with support from NGOs and even some governments. Not yet a mass-market or corporate product, but practical know-how exists (open-source hardware, financing models[14]). This segment is moving past PoC into scalable pilots, but needs more funding to reach level 6.
  - *Reconfigurable Intelligent Surfaces: 3.* Strong experimental success (20–35 dB gains in trials[4], transparent films tested on real buildings[34]). RIS are not commercial yet; industry roadmaps target 6G for deployment. Thus RIS are at “functional prototype demonstrated” stage.



- *Li-Fi (optical wireless): 4.* Now standardized and early products exist (e.g. pureLiFi's Light Antenna module). It's moving toward commercial integration (some defense and industrial Li-Fi systems are already sold), but mainstream adoption and large-volume production are just beginning post-2023 standard, keeping it below level 6 for now.
- *Network integration & orchestration: 4.* The concept of a seamless global network is proven in parts (standardized APIs in 5G core for satellite, first satellite-cell handovers done). Some startups (AST, Lynk) are essentially creating “**space cellular**” networks, and 3GPP Rel-17 ensures regular phones can use them[25][26]. Still, truly dynamic multi-network routing (satellite ↔ mesh ↔ cellular on the fly) remains in early implementation. We've seen proofs (e.g. Vodafone using LEO backhaul for remote towers[17]), but not yet at scale or fully automated globally.

Given these facets, the **bundle's overall maturity is an average** of its parts rather than led solely by the most advanced element. Satellites and 5G push the score higher, while nascent tech (RIS, 6G) pull it down. **Aggregating these, we arrive at roughly a 5–6.** We choose **6** to reflect that a functioning albeit partial version of global broadband connectivity **is already in customer hands today** (millions benefitting from satellite internet and 5G), and the pace of progress is high. The “full vision” (truly ubiquitous, efficient, and integrated coverage) will likely materialize in the next few years as these components converge. In summary, the concept is in the **early commercial stage** – no longer speculative, with active deployment and rapid improvement underway, but not yet at the mature, ubiquitously adopted stage that would merit a 7.

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## ART 01.002 Ultra Low Latency Networks

**Primary capability** – Enables **near-instantaneous, deterministic network response** (end-to-end delays of only a few milliseconds) for distributed systems. This allows remote sensing, computing, and actuation to operate with **minimal lag and jitter**, approaching the reactivity of local (on-device) interactions. The goal is to support time-critical applications (e.g. industrial control, autonomous systems, collaborative robots, AR/VR) by guaranteeing bounded low latency across the network.

**Key sub-components or variants** – Achieving ultra-low latency networking requires progress on multiple fronts working in unison: - **Edge computing infrastructure:** Dense deployment of computing nodes closer to end-users and devices (metro or base station level) to shrink physical distance and propagation delay. Cloud providers and telcos are partnering to host compute at the network edge, exposing services with single-digit ms latencies. -

**Deterministic networking protocols (wired and wireless):** New standards like IEEE Time-Sensitive Networking (TSN) for Ethernet and 5G URLLC for wireless aim to provide guaranteed delivery within tight deadlines. This includes scheduling mechanisms, priority traffic lanes, and time slotting to avoid unpredictable queueing delays. - **Precise time synchronization:** Network elements use common time references (via IEEE 1588 PTP or GPS-disciplined clocks) to coordinate transmissions and processing, so that packets and tasks can be

scheduled with microsecond-level accuracy and avoid collisions or variability. - **Real-time network software stacks:** From NIC hardware up through OS kernels and application frameworks, the stack is optimized for low latency determinism. Examples include kernel bypass techniques, optimized interrupt handling, and real-time OS or container scheduling to ensure processing deadlines. - **Network slicing and QoS control:** The ability to carve out dedicated low-latency “slices” in 5G/6G networks or to prioritize time-critical flows in IP networks (DiffServ, Segment Routing, etc.), so that high-priority traffic (e.g. control signals) always preempts less critical data. - **Specialized hardware and spectrum:** Use of high-bandwidth channels (e.g. mmWave or future terahertz) and advanced physical-layer techniques (MIMO, diversity, coding optimized for short packets) to reduce transmission time. Custom silicon (switches with scheduling hardware, FPGAs for in-network processing) and high-precision oscillators are employed to meet tight timing requirements. - **Integration of wired and wireless deterministic networks:** Convergence of Ethernet TSN with 5G/6G wireless (e.g. 5G acting as a TSN bridge) to extend low-latency guarantees over the air. This hybrid ensures factory or vehicular networks can maintain hard real-time performance even when part of the link is wireless.

**Maturity indicators** – Evidence of progress toward ultra-low latency networks would include: - **Working prototypes and field trials:** e.g. demonstrations of sub-5 ms end-to-end latency in real-world scenarios (industrial robot control, remote driving, cloud VR streaming) under realistic loads. Successful PoCs showing deterministic latency and high reliability (e.g. >99.999% on-time delivery) would validate feasibility. - **Standards and interoperability tests:** Completion of relevant standards (5G URLLC in 3GPP Releases, IEEE TSN profiles like 60802 for industrial use) and multi-vendor interoperability demos. Regulatory certifications for safety-critical use (e.g. in energy or transportation) would signal technical maturity. - **Commercial services and hardware availability:** Low-latency edge computing services available in multiple regions; networking gear (switches, NICs, 5G modems) advertising TSN/URLLC capabilities and being deployed in pilot programs. Early adoption in sectors like manufacturing (private 5G+TSN installations) or telecom (edge cloud offerings) with performance reports. - **Investment and competition:** Significant R&D funding and involvement by major industry players (global telcos, cloud giants, industrial automation firms, chipset manufacturers). Multiple consortiums and alliances (e.g. 5G-ACIA for industrial 5G) working on solutions, indicating a competitive race to bring products to market. - **Scaling and cost trends:** Evidence that deployments are ramping up (even if in niche areas) – for example, increasing number of edge data centers built, or growth in sales of TSN-enabled devices. Signs that economies of scale are improving (cost per edge node or per device decreasing) and that energy/cooling challenges for dense edge nodes are being addressed would suggest approaching commercial viability.

## 2. Evidence (10–20 recent, reliable sources)

- **Wang et al. – “Ultra-Low Latency Wireless Communications for Deterministic Networking: A Cross-Layer Approach”** (IEEE ICC 2022 conference paper, 05/2022)[1][2]. *Provides a theoretical framework for achieving near-zero packet delay violation in wireless IIoT networks. It proves that strictly bounded latencies require exploiting frequency diversity, multi-antenna MIMO, and cooperative relays to overcome fading; under causal (real-time) channel conditions zero packet loss under hard deadlines is impossible with finite power, but with added diversity and scheduling foresight, ultra-reliable low-latency transmission becomes feasible. This*

indicates the physical-layer and MAC-layer innovations needed for plausibility of deterministic 5G/6G links.

- **Zhao et al. – “Latency Analysis and Field Trial for 5G NR”** (IEEE BMSB conference 2022, 06/2022)[3]. Describes new 5G features introduced to reduce latency (such as mini-slot transmission, enhanced scheduling) and reports results from a field trial of 5G New Radio latency. The trial demonstrated that under specific configurations, 5G can meet the latency targets for enhanced Mobile Broadband (eMBB) services (on the order of a few milliseconds). The authors also identify remaining gaps and suggest optimizations needed to reach the far stricter Ultra-Reliable Low-Latency Communication (URLLC) goals, underscoring that while 5G has made progress, further R&D is required for the most demanding applications.
- **Maghsoudnia et al. – “Ultra-Reliable Low-Latency in 5G: A Close Reality or a Distant Goal?”** (ACM HotNets workshop paper, 11/2024)[4][5]. A system-level analysis from EPFL and collaborators that evaluates the real-world status of 5G URLLC. It notes that several years into 5G deployments, achieving the promised 1 ms latency and high “five 9s” reliability in practice remains elusive, due to bottlenecks across software, hardware, and protocol layers. While some prototype implementations exist, none yet meet all latency/reliability specs simultaneously[5]. The paper outlines how 6G research is pursuing even stricter targets (0.1 ms one-way) and argues that only a holistic redesign (e.g. using application-specific hardware for many protocol layers[6]) could meet URLLC requirements. This highlights both the plausibility of ultra-low latency (with redesign) and that maturity is still at the experimental stage, requiring significant engineering to move beyond theory.
- **AWS (J. Naylor) – “Lower access latency for your apps with AWS Wavelength and our telco partners”** (AWS Industries Blog, 10/2024)[7]. Reports on measurements of a production edge computing service (AWS Wavelength) deployed inside 5G networks. It shows that placing compute and storage at the 5G edge can reduce round-trip latency by ~8–12 ms compared to routing to a distant cloud region[7]. For example, in one test a user’s ping to an AWS Region was ~48 ms, whereas to the nearest Wavelength Zone it was ~36 ms – a significant improvement purely from proximity. This confirms the feasibility of cutting network lag via edge infrastructure, and demonstrates a commercial offering already providing single-digit-ms improvements for mobile applications (e.g. cloud gaming, AR). It also notes factors like backhaul design and device connection (5G vs WiFi) that influence achieved latency.
- **Industrial Ethernet Book – “2023 Time-Sensitive Networking Technology Update”** (Trade magazine report, 03/2023)[8][9]. Summarizes input from industry experts on the status of IEEE TSN for real-time Ethernet. It highlights that many semiconductor companies are now integrating TSN capabilities into chips (switches and network controllers), and industrial consortiums are developing standardized profiles (e.g. IEEE/IEC 60802)[8]. However, the report notes that as of 2023, these new TSN-enabled components still need to be incorporated into final products by device vendors and go through testing/certification before widespread use. Middleware and industrial protocols (like Profinet, OPC UA) are each following their own roadmaps to adopt TSN[10]. This indicates that the building blocks for deterministic, low-latency wired networks are emerging (hardware and standards), but full market adoption is still in progress pending integration and proof of reliability at scale. It underscores active work and growing confidence in TSN as a cornerstone for ultra-low latency in factories.
- **Cumucore (Qualcomm & partners) – “TSN over 5G demonstration using commercial components”** (Industry blog, 08/2025)[11][12]. Announces the first public demonstration of Time-Sensitive Networking over a live 5G link using off-the-shelf hardware. In August 2025, Cumucore, Qualcomm, a Finnish operator (DNA) and others showed that a 5G Standalone network could transport TSN traffic with full synchronization and bounded latency. This demo,

involving use cases like coordinated welding robots, proved that wireless 5G can act as a seamless extension of deterministic Ethernet[11]. They report that the solution is moving from proof-of-concept toward practical deployment, with ongoing work to refine timing synchronization (Grandmaster clock integration) and scalability[12]. This is strong evidence of plausibility – it validates that sub-ms-level synchronization and low jitter can be maintained wirelessly – and it marks a maturity milestone: by 2025, wireless TSN is transitioning from lab demo to initial field integration, a step toward commercialization in high-value industrial scenarios.

- **Haque et al. – “A Comprehensive Survey of 5G URLLC and Challenges in the 6G Era”** (Preprint, arXiv Aug 2025)[13][14]. An exhaustive survey reviewing over 280 papers on URLLC. It emphasizes the challenge of achieving <1 ms end-to-end latency in real networks, noting that while 1 ms can be met at the radio link level in small local setups, ensuring that across a wide-area network (with processing, routing, queuing delays) is extremely difficult[13]. The authors explain the fundamental latency-reliability trade-off: URLLC needs very short packets and time slots to cut delay, but this limits error-correcting capabilities, so new techniques are needed to maintain 99.999% reliability within those tight latency budgets[14]. The survey also points out that much URLLC research remains theoretical or simulation-based, with relatively few real-world implementations reported. This source underscores that scientific interest and understanding are high (TRL1–2 achieved), but also that meeting the full URLLC spec in practice is still an open problem, requiring innovations in protocol design, cross-layer optimization, and perhaps AI-driven control to juggle the competing demands.
- **Kornacki et al. – “Meeting Industrial 5G Requirements for High Uplink Throughput and Low Control Latency in UGV Scenarios”** (Applied Sciences journal, 06/2025)[15]. Presents results from a 5G SA testbed at Gdańsk University of Technology controlling an Unmanned Ground Vehicle (UGV) with LiDAR. The study tweaked 5G base station parameters to optimize for an unusual combo: high uplink throughput (for LiDAR video) and ultra-low downlink latency (for control commands). It reports that by configuring CSI feedback, timing signals (TRS/SSB), and scheduling request intervals, the team achieved stable high-bandwidth uplink while keeping control-plane latency within the strict 3GPP industrial limits[15]. In good radio conditions, the best configurations met the sub-10 ms control latency and reliability needed for real-time remote driving, even with heavy sensor data flowing. This demonstrates a proof-of-concept system meeting URLLC-like specs: it shows that today’s 5G can be tuned to deliver industrial-grade performance on a small scale, supporting the feasibility of remote-operated vehicles and similar tactile internet applications once the network is properly optimized.
- **Alves et al. – “Beyond 5G URLLC Evolution: New Service Modes and Practical Considerations”** (ITU Journal: Future and Evolving Tech, 12/2022)[16][17]. An authoritative article by researchers from Nokia Bell Labs and Univ. of Oulu reviewing two advanced URLLC testbeds (in Finland and South Korea) and proposing future URLLC variants. It observes that current 5G URLLC has inherent limitations and likely cannot support emerging applications with even stricter needs (e.g. sub-millisecond latency, higher data rates, and device densities)[16]. The authors introduce concepts of Broadband URLLC, Scalable URLLC, and Extreme URLLC, which would extend 5G’s capabilities to cover these new extremes. They identify key enabling technologies for each (such as smarter scheduling, XR communication techniques, or AI for network optimization) and report practical lessons learned from their test networks[17]. This source highlights that industry and academia are actively pushing beyond 5G’s baseline, acknowledging that while 5G URLLC is on the path to deployment, truly ubiquitous ultra-low latency with higher reliability may only be realized with these next-generation improvements (e.g. 6G around 2030). It reinforces that the vision is plausible but will be an evolving target over the next decade, not a solved problem today.



(Additional evidence consulted includes NIST and Keysight reports on wireless TSN and standards progress, and demonstrations of remote surgery and VR over 5G, which further support these findings but are omitted for brevity.)

### 3. Maturity score (1–7) and reasoning

#### Final maturity score: 5 (Out of 7).

**Justification** – Ultra-low latency networking is **beyond the pure research phase** and has progressed into working prototypes and early services, but it is **not yet a widely deployed commodity**. Level 5 on the rubric corresponds to multiple well-funded actors developing production prototypes post-PoC, which is exactly the current situation: - **Exceeds Level 3/4:** We have more than lab demos – *functional PoCs* have been demonstrated meeting key requirements. For instance, the Cumucore/Qualcomm 2025 demo showed real 5G wireless TSN delivering deterministic low latency in an industrial scenario[11], and AWS offers an edge cloud service cutting latency by an order of magnitude for mobile apps[7]. These indicate that the core technical blockers (scheduling, edge placement, sync) *can* be solved in practice, ruling out the lower “proof of concept not yet done” levels. The 5G URLLC field trial in 2022 similarly proved that under tuned conditions, 5G can hit its latency targets[3]. This progress satisfies Level 4 (prototype viability demonstrated) and goes beyond it. - **Rationale for Level 5:** There is now **intense competition and investment** to productize these capabilities. Major telecom vendors (Ericsson, Nokia, Qualcomm), cloud companies (Amazon, Microsoft), and industry consortia (5G-ACIA, etc.) are all racing to deliver ultra-low latency solutions. Multiple prototypes are in late-stage development or early deployment – e.g. private 5G networks with TSN are being rolled out in trial industrial sites, and 5G Advanced and 6G research explicitly targets <1 ms latency[4][16]. The ecosystem has the hallmarks of Level 5: well-capitalized actors, clear commercial motivation, and rapid progress in standards and pilots (for example, 3GPP Release 16/17 adding deterministic features and companies aligning hardware to those standards[16]). - **Not yet Level 6:** However, **full commercial maturity has not been reached** – we do not yet see broad customer deliveries of “URLLC as a service” or pervasive ultra-low-latency networks in daily use. Current 5G networks largely fall short of the strictest latency/reliability goals[4], and the technologies are still in bespoke deployments or trials rather than mass production. Challenges around coverage (edge node proximity), cost, and integration are still being worked out. Thus, the technology isn’t at scale with economies of scale driving down price, which is what Level 6 would require. Reliability and safety certification in real operations (e.g. for autonomous driving or remote surgery) are in progress, not done. - **What’s missing for Level 6:** To reach the next level, we would need to see **routine delivery of ultra-low latency capabilities to end-users**. That means telecom operators offering guaranteed-ms latency slices as a product in many regions, industrial suppliers shipping turnkey low-latency wireless control systems, and a growing base of end devices and applications using them. Evidence such as large orders or deployments (hundreds of edge sites serving thousands of customers), multi-vendor product offerings, and falling costs would be expected. Also, regulatory frameworks (for reliability, data handling in critical latency services) would likely be in place. Those elements are only starting to form now.

**Sub-component breakdown:** The overall score of 5 is an **aggregate** reflecting different parts of this technology bundle: - *Edge cloud infrastructure:* **6** – Cloud/telco edge services are already deployed (e.g. AWS Wavelength, Azure Edge Zones) and increasingly adopted, demonstrating growing scale[7]. - *Wired deterministic networking (TSN):* **5** – Standards are

finalized and first products available; industry trials underway (e.g. TSN in automotive and manufacturing)[8]. Needs broader adoption but technically at prototype/early product stage.

- *Wireless URLLC (5G/6G)*: **3–4** – The concept is proven in labs (sub-ms radio frames, special scheduling) and some field demos, but current 5G networks do **not** yet meet full URLLC in practice[4]. It's at advanced R&D/prototype phase, with 6G work aiming to close the gaps.
- *Integration (5G + TSN + edge)*: **4** – Recent PoCs show it works in limited settings[11], but comprehensive commercial solutions (combining all elements reliably) are still in pilot stage.

These factors combined justify a **score ~5**. We chose **5 (competing development and imminent prototyping)** rather than 4, because many pieces have graduated from concept to implementation and are being aggressively developed concurrently. The functionality across sub-components contributes to one value proposition (real-time networked computing), so we consider the **system as a whole**. In this case the bundled capability is only as strong as its weakest link – wireless URLLC – which lags behind edge compute and TSN. But given the **high industry momentum** and the fact that partial services are already live, a mid-to-high maturity (5) best captures where Ultra-Low Latency Networks stand today, with the **caveat** that full performance is a couple of steps from wide rollout.

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## ART 01.003 Edge AI for Sensor Data

### 1. ART extraction

- **Primary capability:** Enabling *real-time, on-site AI processing of sensor data* at the point of capture. This allows immediate interpretation of raw signals and autonomous decision-making without relying on cloud connectivity. It dramatically reduces bandwidth usage and latency by filtering, compressing, or analyzing data locally[1][2], improving responsiveness and privacy.

- **Key sub-components/variants:**

- *Ultra-low-power edge AI hardware:* Specialized microcontroller units (MCUs), DSPs, or NPUs integrated in sensors or nearby modules, capable of running neural networks within tight energy and memory budgets[3][4]. Some approaches embed processing *in-sensor* (at the pixel or transducer level) versus *near-sensor* chips adjacent to the sensor[5][6].

- *Compact ML models (TinyML):* Neural networks optimized via quantization, pruning, and efficient architectures to fit on resource-constrained devices while maintaining accuracy[7][8]. Examples include tiny vision models for cameras or lightweight audio/vibration models for anomaly detection.

- *Robust sensor fusion & adaptation:* Algorithms combining multiple sensor modalities (video, audio, inertial, etc.) to improve reliability in noisy or adverse conditions. Techniques like self-calibration and on-device uncertainty quantification are used so the system can “gracefully degrade” when data is partial or corrupted[9][10].

- *Distributed edge networking:* Edge AI devices typically connect via local networks, performing autonomously when offline and syncing periodically. Standard dashboards or mobile apps allow humans to view sensor insights and adjust settings. Over-the-air updates and federated learning can be used to retrain or update models using aggregated field data, improving performance over time.

- *Application-specific variants:* Smart cameras with on-board object or event detection, intelligent microphones for keyword spotting or equipment noise analysis, wearables with built-in health anomaly detection, and industrial controllers with vibration/temperature analytics are all examples under this technology bundle. Each may use different model types but share the paradigm of on-site AI inference.

- **Maturity indicators:** Evidence would include **field trials and deployments** (e.g. sensors with embedded AI used in real farms, factories, etc.), **commercial products shipping** (smart sensors or devices with advertised on-board AI features), **multiple industry players** (sensor and chip makers, IoT platforms, consortia investing in edge AI), and **performance benchmarks** showing clear advantages over cloud-only solutions (e.g. reduced latency,



bandwidth, or improved reliability under real-world conditions). Signs like standard toolchains (TinyML frameworks, model libraries), *well-funded competition* among companies, and increasing adoption across sectors would also indicate rising maturity. Demonstrable **robustness in harsh environments** (dust, low-light, etc.) and compliance with safety/security requirements in deployments would further validate the technology's readiness.

## 2. Evidence (10–20 recent, reliable sources)

- **“Edge AI: A survey” – R. Singh, S. S. Gill – *Internet of Things and Cyber-Physical Systems* (peer-reviewed) – 2023.** *Comprehensive open-access survey of Edge AI.* It presents a “future blueprint” for deploying AI on edge devices, covering model optimizations for resource-constrained hardware and examining **standardization and performance benchmarks** for Edge AI environments[11][12]. It also identifies open challenges (latency, energy, tool integration) and trends, indicating broad academic and industry interest in making edge AI practical. This underscores that the field has matured to the point of formal surveys and recognized best practices.
- **“Deploying TinyML for energy-efficient object detection...” – Ch. M. Bhushan et al. – *Scientific Reports* (Nature, peer-reviewed) – Dec 2025.** *Demonstrates a real-time vision model on a microcontroller (“TinyML”).* The authors deploy a quantized MobileNetV2 on a 1 MB flash / 256 KB RAM MCU to perform person detection from a camera[3][13]. They achieved on-device inference in 3.5–15 ms per frame with only 10–22 mJ energy per inference, while maintaining **85%+ accuracy**[8]. This *lab-validated prototype* shows that non-trivial AI tasks (e.g. detecting people via a Visual Wake Words dataset) can run within millisecond latency and milliwatt energy on cheap hardware – a key feasibility proof for edge AI’s responsiveness and low-power operation.
- **“Edge intelligence through in-sensor and near-sensor computing for AIoT” – Y. Baek et al. – *npj Unconventional Computing* (Nature, perspective) – Oct 2025.** *Technical roadmap and perspective on moving computation into sensors.* It surveys emerging device and circuit innovations that turn sensors from passive data collectors into active computing nodes. For instance, it highlights **in-pixel and near-sensor processing** that eliminate costly data transfer and ADC steps[5][6]. The article notes that *bio-inspired, event-driven sensors* (neuromorphic vision, silicon cochlea, etc.) can perform **event detection and filtering on-device**, drastically reducing power and latency[14][15]. It also discusses challenges like device variability and the need for new architectures[16]. This evidence reinforces the plausibility of the ART, showing a clear scientific path for integrating AI logic at the sensor level and acknowledging what engineering hurdles remain.
- **“Resource-efficient Edge AI solution for predictive maintenance” – V. Artiushenko et al. – *Procedia Computer Science* (open-access conference) – 2024.** *Describes a prototype tool-condition monitoring system using Edge AI.* The paper presents a **low-cost hardware setup** where a microprocessor at a machine tool runs multiple ML models to monitor milling tool wear in real time[17]. Four classical ML models and one deep learning model were deployed on a “low-performance edge device” and validated during actual milling operations[18]. This prototype achieved the necessary functionality (detecting tool wear) locally, and the authors discuss integration challenges and future improvements. It is a concrete example of Edge AI enabling **real-time industrial monitoring** on the factory floor, confirming the ART’s practical value (latency reduction, autonomy) in manufacturing settings.

- **“Resource-Constrained Edge AI for Real-Time Pest Detection in Chili Fields” – H. Chung et al. – Agriculture (MDPI, peer-reviewed) – Feb 2026.** *Reports a field-deployable edge AI system for smart farming.* The team built an **on-premise IoT pipeline** using AI-Thinker ESP32-CAM modules (“sticks”) as smart camera sensors and a Raspberry Pi 5 as a local edge server[4]. They developed a two-stage model (tiny YOLOv8 for leaf detection plus ResNet-18 classifier) to identify crop diseases on chili pepper leaves. To handle patchy farm connectivity, the system uses dual protocols (HTTP for images, MQTT for alerts) with an offline buffer/recovery mechanism[19][20]. In tests, it achieved an end-to-end detection and alert latency of **0.86 s** and cut computation by >60% versus heavier models with minimal accuracy loss[21]. This is strong evidence of an **autonomous, multi-device edge AI network operating in a real-world, harsh environment** (outdoor agriculture) – illustrating both the performance gains (sub-second local decisions) and engineering of robustness (network resilience, “graceful degradation”) highlighted in the ART.
- **“Siemens Reinvents Factory Reliability with Edge AI-Driven Predictive Maintenance” – Arm News (industry blog) – Aug 2025.** *Describes Siemens’ deployment of edge AI sensors in industrial automation.* According to this report, **Arm Cortex-based AI sensors** in Siemens production lines continuously analyze vibration, temperature, and power draw from motors and equipment on-site[22][23]. Upon detecting anomalies (e.g. a bearing overheating), the system can *instantly adjust machine parameters* (slow down or cooling) **in real time**, not just send an alert[24]. The benefits reported include reduced energy use and scrap rates and extended equipment life due to proactive interventions[25]. Notably, Siemens is also using generative AI models at the edge to anticipate component failures and self-calibrate the process with each cycle[26]. This commercial example shows a *well-capitalized actor deploying edge AI at scale* in mission-critical settings (factories), confirming high plausibility (the technology meets strict latency and safety requirements) and indicating a transition toward autonomous, self-optimizing industrial systems.
- **“2025 Edge AI Technology Report (Chapter: TinyML)” – CEVA Inc., industry tech report – 2025.** *Industry survey of edge AI use cases and deployments.* CEVA (a major edge AI IP vendor) highlights multiple **real-world applications shipped or in pilot**: e.g., an AI cough detector by Hyfe that runs on-device to diagnose respiratory illness while preserving privacy[27], an automotive system (Globalsense) that listens for crash events via smart audio sensors for instant emergency response[28], **voice-activated earbuds** from a top manufacturer achieving sub-20 ms on-device inference for user commands[29], and a motion-sensor-based fall detection solution in senior care that processes data locally to trigger rapid alerts[30]. These examples, spanning healthcare, automotive, consumer electronics and eldercare, underscore that **edge AI for sensor data is already entering products across sectors**. The diversity of players and domains, along with mention of platform tools (Edge Impulse, NVIDIA kits) enabling these solutions[31], is evidence of an active ecosystem moving beyond prototypes to practical deployment.
- **“TinyML chipset shipments forecast” – ABI Research (market data) – Q3 2025.** *Market analysis showing growth and dominant use-cases for TinyML (edge AI) hardware.* ABI projects TinyML chipset shipments to grow at **29% CAGR through 2030**, largely driven by **audio/sound processing and sensor-data analysis** use cases which together account for >80% of these shipments[32]. This indicates that industry demand for on-sensor AI is accelerating, especially for always-on audio (e.g. wake-word detectors, acoustic monitors) and IoT sensor analytics. The significant growth and investment forecasted implies that multiple vendors are scaling up production of edge-AI-enabled chips/devices. This serves as a quantitative indicator of maturity: edge AI is moving towards mainstream adoption with improving economies of scale, rather than remaining a niche laboratory concept.

- **“QUTE: Quantifying Uncertainty in TinyML models ...” – N. P. Ghanathe, S. J. E. Wilton – ICML 2025 (poster, peer-reviewed) – May 2025.** *Presents a method for on-device uncertainty awareness in TinyML models.* The authors introduce “QUTE,” an early-exit ensemble technique that runs on a **256 KB RAM microcontroller** to estimate the confidence of its own predictions[33]. In tests, QUTE’s approach reduced model size by 59% and latency by 31% compared to prior methods, while successfully detecting instances when the model’s accuracy would drop[9][10]. This is important for **reliability in edge AI** – the system can know when its sensor data is too ambiguous or degraded and possibly request help or fallback. The existence of such research and its feasibility on tiny devices confirms the ART’s claim that techniques for graceful degradation (uncertainty-aware detection, self-checks) are being actively developed to make edge AI robust in real-world conditions.
- **“Edge AI for atrial fibrillation detection on wearables” – E. Cinotti et al. – Sensors (MDPI, peer-reviewed) – Nov 2025.** *Demonstrates medical-grade AI inference on a wearable MCU.* This study embedded a 1D convolutional neural network on an ARM Cortex-M7 microcontroller (with an ECG analog front-end) to detect heart arrhythmia (AFib) from heartbeat intervals in real time[34][35]. The edge AI model achieved **96–98% accuracy** in detecting AF episodes on unseen subjects[36] – comparable to cloud-based analysis – while running within the MCU’s memory/power constraints. They built a complete battery-powered prototype that streams an ECG only when an arrhythmia is detected for physician verification[37]. This illustrates how *even safety-critical, high-accuracy applications* (health monitoring) are becoming feasible with edge AI. It also validates the value proposition of offloading processing from cloud to wearable: continuous monitoring with **minimal data transmission**, extended battery life, and instant alerts, aligning with the ART’s bottleneck-reduction claims for sensitive or bandwidth-heavy scenarios.
- **“Edge-Cloud Synergy for AI-Enhanced Sensor Network Data (Predictive Maintenance)” – K. Sathupadi et al. – Sensors/Electronics (MDPI, peer-reviewed) – Dec 2024.** *Reports a hybrid edge/cloud framework deployed for machinery monitoring.* The system uses **lightweight anomaly detection at the edge** (KNN model on sensor-node devices) and heavier LSTM models in the cloud for deeper trend analysis[38][39]. In a real-time experiment, this split approach achieved a **35% reduction in latency, 28% lower energy consumption, and 60% less bandwidth use** compared to a traditional cloud-only solution[40]. It shows that pushing initial AI processing to local sensor units yields significant performance and efficiency gains while still leveraging the cloud for periodic aggregation – a practical confirmation of the ART’s core rationale. The success of this system in a predictive maintenance context (monitoring industrial sensor streams) is evidence that edge AI can meet commercialization requirements: it improved response speed and cut costs, satisfying key metrics that would drive adoption in industry.

### 3. Maturity score (1–7) and reasoning

#### Proposed Maturity Score: 6 (Early mainstream adoption).

**A)** The balance of evidence suggests that *Edge AI for sensor data* has progressed beyond proofs-of-concept (Levels 3–4) into the **early product delivery and scaling phase (Level 6)**. Multiple well-funded companies and research groups have working prototypes **and** actual deployments: e.g. Bosch’s self-learning AI sensor and voice-activated earbuds (consumer products), Siemens’ AI-enabled sensors in factories (industrial systems), and several startups’ solutions in healthcare and agriculture[41][22]. These are not isolated lab demos but are being delivered to end-users or tested in real environments, indicating that the technology meets basic performance requirements for real-world use. Importantly, evidence

shows *recent and rapid progress* – many sources from 2024–2025 report breakthroughs like sub-second on-device vision[21], >95% accurate wearable AI diagnostics[36], and latency/energy advantages over cloud baselines[40]. Such achievements go beyond academic curiosity (Levels 1–2) and even beyond initial prototypes (Level 3), showing that **key bottlenecks (compute efficiency, model compression, etc.) have been solved well enough for fieldable solutions (Level 4)**. For instance, we see that constrained devices can now run useful neural networks within millisecond latency and millijoule energy budgets[8], and can even quantify their own uncertainty on-device[9] – milestones that eliminate what used to be blocking technical hurdles. There is also clear **commercial momentum**: industry reports and market forecasts confirm growing investment, with shipments of TinyML-powered chips projected to rise sharply and audio/sensor analytics driving that growth[32]. This implies several competitors are racing to capture markets (characteristic of Level 5+) and that early products are scaling up in volume (approaching Level 6).

**B)** We choose Level 6 because numerous *products are being delivered to customers*, albeit not yet with the ubiquity and market saturation of a fully mature technology. Evidence of delivery includes the Bosch BHI260AP smart sensor (integrated into wearables since ~2022), edge-AI-equipped devices in agriculture and healthcare that have been deployed in the field[21][41], and industrial edge AI installations by a giant like Siemens in live factories[22][24]. Customers are benefiting from these (e.g. reduced downtime, faster alerts), and early adopters span multiple sectors, fulfilling much of Level 6’s description (expanding application areas, internal financing of R&D by companies). **Lower maturity levels are clearly ruled out**: The technology is well past theoretical feasibility – core principles were proven and prototyped years ago (TinyML, in-sensor computing, etc.), and we now have *validated real-world performance data* (latency, accuracy, power usage) showing it can outperform cloud-centric approaches or classical sensor systems[40][21]. Even Level 5 (production prototypes and competitive development) has been exceeded in some domains: we have *shipping commercial products and multi-actor ecosystems* rather than a single prototype waiting for launch. For example, the ARM-Siemens collaboration and the Edge Impulse platform’s multi-sector use cases demonstrate at least a couple of major players actively deploying or supporting edge AI solutions, not just prototyping[22][30].

**C)** *What holds it back from Level 7?* In short, **edge AI for sensors, while promising, is not yet omnipresent or “plug-and-play” across all industries**. There are still notable challenges and constraints that the evidence and sources acknowledge, preventing full maturation: For instance, power/thermal limits force trade-offs in model complexity, meaning the most advanced AI capabilities (large models or very high accuracy under all conditions) still often require cloud support or new hardware innovations[42][43]. This is why hybrid frameworks (edge + cloud) are being developed – to compensate for edge devices’ limits[38][40]. Moreover, maintaining robustness “in the wild” remains a non-trivial task: techniques like QUTE are just emerging to ensure reliability under uncertainty[9][10], and extensive real-world validation is needed in safety-critical areas. The ART description itself flags that unit costs may initially be high and that extensive testing in extreme conditions (dust, low-light, etc.) is required. These factors suggest that **wider adoption and trust are still building**. In many organizations, edge AI is just entering pilot stages or niche deployments rather than being the default for all sensor systems. We do see competition forming, but a *fully mature Level 7 scenario* (with robust standards, broad customer demand and ubiquitous deployment) likely awaits further progress: for example, simpler development tools, more universal standards,

and proven long-term reliability. Recent surveys explicitly list open challenges like integration complexity and the need for unified Edge AI standards and benchmarks[12], indicating the field is still coalescing around best practices. In summary, the **score of 6** reflects a technology that has clearly demonstrated commercial value and is scaling up from early adopters toward the mainstream, but which needs a bit more time and refinement before it achieves the wide, competitive ubiquity and user confidence associated with Level 7. The strong evidence of working products and multi-player involvement rules out Levels 4–5, while the ongoing constraints and patchy deployment keep it just shy of the highest maturity level.

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## ART 01.004 Quantum & High Precision Sensing

### Core Capabilities and Components

Quantum and high-precision sensing technologies exploit **engineered quantum states of matter and light** and **ultra-stable photonic or biochemical structures** to detect extremely small changes in physical quantities – far beyond the limits of conventional sensors. By harnessing phenomena like matter-wave interference and single quantum events, this family of sensors can make *“previously invisible phenomena measurable in routine settings.”* Key capabilities and components include:

- **Ultra-Sensitive Magnetometers:** Quantum magnetometers (e.g. using atomic vapor or diamond NV centers) can detect minute magnetic fields (femtotesla to picotesla scale) such as those from neural activity. These devices operate at room temperature and achieve sensitivities and dynamic range well beyond classical fluxgate or SQUID sensors. For example, researchers have demonstrated magnetometers capable of measuring tiny biomagnetic signals (brain waves) for medical diagnostics, a feat that previously required cryogenic equipment. Quantum magnetometers also offer high stability and do not require cooling, making them suitable for field use in geoscience and archaeology.
- **Optical Atomic Clocks:** Next-generation atomic clocks use optical-frequency transitions (e.g. in strontium or iodine-stabilized lasers) to keep time with **extreme stability**. These optical clocks “tick” at frequencies thousands of times higher than microwave clocks, making them tens of thousands of times more precise. Laboratory optical clocks can achieve such precision that they would lose less than a second over the age of the universe. Efforts are underway to miniaturize these clocks into **chip-scale or portable systems** without sacrificing too much performance. Such clocks provide ultra-stable time/frequency references for navigation, communications, and fundamental tests (e.g. enabling GPS-like positioning with centimeter accuracy in the future).
- **Quantum Gravimeters:** Using cold-atom interferometry, quantum gravimeters detect subtle changes in local gravitational acceleration. They can sense density variations underground (tunnels, voids, mineral deposits) by measuring the gravitational gradient with high resolution. In a 2022 field test, a portable cold-atom gravimeter was able to **map an underground tunnel** 1 m below the surface by detecting the tiny gravity dip it caused. The device discerned minute gravitational differences from

nearby structures that classical gravimeters would average out. Quantum gravimeters offer drift-free stability and high sensitivity, which can monitor geological or hydrological changes continuously without the long averaging needed by older sensors. Practical units remain somewhat bulky, but ongoing integration efforts aim for deployable systems for civil engineering, geophysics, and climate monitoring.

- **Cold-Atom Inertial Measurement Units (IMUs):** These devices use atom interferometers as ultra-stable accelerometers and gyroscopes. By splitting and recombining matter waves, they measure acceleration and rotation with unprecedented accuracy (potentially **orders of magnitude better** than today's best ring lasers or MEMS sensors). Quantum IMUs provide an **inertial navigation reference in GPS-denied environments**, with negligible drift over long durations. For instance, research prototypes with continuous cold-atom beams show high signal contrast and low noise, pointing to significantly extended navigation time without GPS aiding. While current devices are primarily laboratory prototypes, they promise to revolutionize submarine, spacecraft, or autonomous vehicle navigation once engineered into compact, rugged packages.
- **Single-Photon and Single-Molecule Sensors:** Advanced optical and biochemical sensors can register individual quanta – single photons of light or single molecules binding in a reaction. This capability allows detection of extremely low-concentration substances or weak light signals with **quantum-limited sensitivity**. In recent years, various biosensors have achieved *single-molecule* detection in different assay formats, enabling medical tests and environmental monitoring with unprecedented sensitivity. Likewise, single-photon avalanche diodes and superconducting nanowire detectors count individual photons for applications like LIDAR, quantum communication, and low-light imaging. These sensors often integrate into chip-scale photonic circuits or microfluidic devices, bringing quantum-level detection into portable, “routine” analytical tools.

**Integrated Design and Readout:** A unifying theme of this technology bundle is the push toward **miniaturized, integrable designs**. Many quantum sensors are being developed in chip-scale packages, optical fiber networks, or compact probe formats that can piggyback on existing instruments. They feature standard digital interfaces and on-board processing for calibration and noise filtering. Over time, these sensors “learn” background patterns and apply signal processing to isolate the quantities of interest. The goal is to deliver lab-grade sensitivity in field-deployable units – some as handheld tools or embedded modules, others as larger rack-mounted or cabinet instruments analogous to high-end lab equipment.

**Operational Constraints:** Despite their potential, these sensors face practical engineering challenges. They often require **strict environmental control** – magnetic shielding, vacuum chambers or low-temperature operation, vibration isolation, and ultrapure materials – to protect their fragile quantum states. Specialized lasers, vacuum hardware, or nanofabrication methods are needed to build and maintain them. Outside of controlled labs, maintaining calibration and performance is non-trivial; even minor vibrations or temperature fluctuations

can disrupt measurements. Robust packaging and self-monitoring systems are being designed to mitigate these issues (for example, robust quantum sensors that actively reject interference are under development). Regulatory certification for critical uses (like navigation or healthcare) will also be a hurdle until these devices prove long-term stability and reliability in real-world conditions.

**Value Proposition:** If successfully engineered, this family of sensors can alleviate key bottlenecks in current measurement and decision-making processes. They enable continuous, **non-invasive monitoring of slow or subtle processes** that today are impractical to observe. For example, quantum sensors could monitor structural health (by detecting minute strain or density changes) or agricultural soil conditions over large areas, without requiring destructive sampling or months of averaging. They can **reduce dependence on sparse reference infrastructure or expert operators** by allowing remote and automated measurements with lab accuracy. In domains where decisions are limited by coarse or infrequent data, quantum sensors offer more precise and timely insights – allowing tighter safety margins and early detection of issues. In summary, these technologies aim to provide **new eyes and ears** for industry and science, making the invisible visible and drastically improving the precision of our measurements in fields ranging from navigation and timing to medicine and materials analysis.

#### **Recent Key Developments and Sources (Last ~4 Years)**

To gauge the plausibility and maturity of this technology bundle, we collected a set of relevant, reliable sources from the past four years. These include peer-reviewed studies, industry roadmaps, government lab reports, and company technical disclosures, each highlighting progress in one or more of the component technologies:

1. **“Recent Progress of Atomic Magnetometers for Geomagnetic Applications” – T. Zhao et al. (Aerospace Info. Research Inst., CAS), *Sensors* (MDPI) review, 2023.** This open-access review details advances in optically-pumped atomic magnetometers and their use in geomagnetic surveys. It notes that modern alkali-vapor and helium atomic magnetometers have achieved nT to pT-level sensitivity at practical size/weight, making them **one of the most sensitive sensor types** for weak magnetic fields. The authors discuss engineering improvements (anti-vibration designs, micro-fabricated vapor cells) that now allow deployment in geophysics, archaeology, biophysics, and other areas. URL: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10256078/>
2. **“First successful demonstration of a dual-media NV diamond laser system” – Fraunhofer IAF Press Release, Oct 2024.** Researchers at Fraunhofer IAF (Germany) reported a breakthrough in **laser-threshold magnetometry** using diamond NV centers. By integrating an NV-diamond crystal with a semiconductor laser diode in a single resonator, they achieved magnetic field detection in the femtotesla range with 100% signal contrast. The press release (summarizing a *Science Advances* article) highlights that **quantum diamond magnetometers are already widely used** for precise field measurements at room temperature, and this new dual-media laser



approach greatly extends sensitivity and dynamic range. The goal is to apply these sensors to measure tiny biomagnetic signals (e.g. neuron activity) for brain-computer interfaces and medical diagnostics. URL: <https://www.iaf.fraunhofer.de/en/media-library/press-releases/Demonstration-NV-diamond-laser-system.html>

3. **“Startups Squeeze Room-Size Optical Atomic Clocks Into a Briefcase” – D. Genkina, *IEEE Spectrum* (Feature article), Oct 15, 2024.** This article profiles the race to commercialize **portable optical atomic clocks**. It describes how three companies – Vector Atomic (US), Inflection (US), and QuantX Labs (Australia) – have each developed a compact optical clock that “*matches or beats*” existing commercial atomic clocks in stability, yet fits in a 3U rack or briefcase form factor. The piece explains the engineering trade-offs (reducing laser systems, using robust thermal vapor cell optics) that allowed Jun Ye’s lab-grade clock to be transformed into field-deployable products. These optical clocks are cited as **GPS backups** for timing in telecom, finance, and power grids, and as enablers of future navigation with cm-level precision. URL: <https://spectrum.ieee.org/optical-atomic-clocks>
4. **“Quantum sensor identifies underground tunnel” – H. M. Hill, *Physics Today News & Analysis*, Apr 1, 2022.** This news article reports on the first outdoor test of a **cold-atom quantum gravimeter** by University of Birmingham researchers. The quantum device (based on rubidium atom interferometry) successfully detected a 2-meter wide utility tunnel buried one meter below ground by measuring subtle variations in the local gravity gradient. Notably, the prototype achieved comparable or better accuracy than commercial classical gravimeters while requiring far less averaging time. The piece discusses how vibration noise was overcome by a unique dual-cloud interferometer technique, marking a significant step in making quantum gravity sensors practical for civil engineering (e.g. surveying infrastructure or archaeology). URL: <https://physicstoday.scitation.org/doi/10.1063/PT.6.1.20220401a/full/>
5. **“Quantum Gravimeter and Quantum Gravity Gradiometer Report” – ICV Tank (Tech Vision think-tank) analysis, Oct 30, 2024.** This industry report provides a **global overview of quantum gravity sensing** development. It outlines the evolution from lab concepts in the 2000s to the first commercial quantum gravimeters in the 2010s, and forecasts trends into the 2020s. The report finds that “*several companies have commercialized quantum gravity instruments,*” but notes that most quantum gravity **gradiometers** (which measure gradients for higher spatial resolution) are still at proof-of-concept or prototype stage, reflecting lower technical maturity overall. It highlights emerging players (startup and national lab spin-offs in Europe and China) and expects devices to become more compact and less expensive as the technology matures, potentially expanding use from military toward civilian applications like oil & gas exploration. URL: <https://www.icvtank.com/newsinfo/970240.html> (ICV Tank Quantum Reports)
6. **“Cold atom inertial sensors for navigation applications” – M.J. Wright *et al.* (Univ. of Liverpool), *Frontiers in Physics*, Oct 3, 2022.** This peer-reviewed paper examines the prospects of **quantum inertial sensors** in navigation. It reviews the fundamental

limits of inertial navigation and how atom-interferometer accelerometers and gyroscopes could mitigate drift in current systems. The authors note “*significant advances have been made to move these devices outside of the laboratory and into the real world*”, citing demonstrations of mobile cold-atom sensors. However, they also discuss practical limitations: current cold-atom IMUs have low update rates (Hz-level) and finite measurement dead-times due to the cooling cycle. The paper concludes that quantum IMUs will likely augment rather than fully replace classical sensors in the near term, for example by providing periodic ultra-precise calibration to a classical IMU to correct its drift. URL: <https://doi.org/10.3389/fphy.2022.994459>

7. **“China’s Space-Based Atom Interferometer Pushes Limits of Inertial Sensing” – M. Swayne, *The Quantum Insider*, May 16, 2025.** This article covers a major milestone: a **cold-atom quantum gyroscope in orbit** aboard China’s Tiangong space station. According to the report (summarizing a *National Science Review* publication), the Chinese team demonstrated rotation sensitivity on the order of  $50 \sim \mu\text{rad/sec}$  and acceleration sensitivity  $100,000\times$  better than a phone accelerometer. The device, roughly microwave-oven sized, uses rubidium atom matter-waves to detect tiny changes in motion, and achieved stable operation in microgravity. This achievement shows quantum inertial sensors working in one of the most challenging environments (space), underscoring their strategic potential to eventually supplement or replace conventional gyros in satellites, submarines, and spacecraft. URL: <https://thequantuminsider.com/2025/05/16/chinas-space-based-atom-interferometer-pushes-limits-of-inertial-sensing/>
8. **“Single-Molecule Optical Biosensing: Recent Advances and Future Challenges” – S. Dey et al., *ACS Physical Chemistry Au*, vol. 3, no. 2, Feb 2023.** This perspective (peer-reviewed) summarizes how optical biosensors have attained **single-molecule sensitivity** in various assay formats. It highlights improvements in photonic resonators, nanoparticle labels, and fluorescence techniques that now allow researchers to detect and count individual biomolecular binding events. The authors discuss the remaining challenges in moving these methods from lab to practice, such as integrating on-chip optics, handling complex real-world samples, and achieving continuous monitoring capabilities. Nonetheless, the article cites successful demonstrations of single-molecule detection in clinical diagnostics and environmental monitoring, illustrating the impressive biochemical sensing capabilities included in this technology bundle. URL: <https://pubs.acs.org/doi/10.1021/acspphyschemau.2c00061>
9. **“From fragile to field-ready: RoQS program launches first phase” – DARPA News Release, Aug 27, 2025.** This U.S. Defense Advanced Research Projects Agency announcement introduces the **Robust Quantum Sensors (RoQS)** program. It explicitly acknowledges that while quantum sensors offer unmatched precision, their “*extraordinary sensitivity has made them notoriously fragile in real-world environments*”. The RoQS program aims to redesign quantum magnetometers, gravimeters, and inertial sensors for field deployment by making them inherently robust against vibrations, acceleration, and electromagnetic interference. In Phase 1, teams will build

compact, “**walk-on/walk-off**” quantum sensors to be tested on a vibrating helicopter platform – a deliberately harsh environment. This reflects a systematic effort by a government agency to transition quantum sensing from lab to practical use, by solving engineering issues of hardening and manufacturability. URL:

<https://www.darpa.mil/news/2025/roqs-launches-first-phase>

10. “**NRL charters Navy’s Quantum Inertial Navigation path to reduce drift**” – U.S. Naval Research Lab Press Release, Apr 8, 2024. This release discusses a patent-pending **Continuous Cold-Atom Beam Interferometer** developed at NRL for next-generation navigation systems. The Navy’s researchers created a device that continuously feeds atoms into an interferometer, aiming to overcome limitations of pulsed cold-atom sensors. The press note explains that **quantum inertial navigation** could improve accuracy by orders of magnitude and reduce reliance on GPS. The NRL device achieved high measurement contrast and low noise by using a continuous 3D-cooled atomic beam, showing promise for maintaining long-term navigation with negligible drift. The Navy’s interest and ongoing R&D in this area underscores the strategic value of ultra-stable quantum IMUs for submarines and ships operating in GPS-denied scenarios. URL: <https://www.navy.mil/Press-Office/Press-Releases/display-pressreleases/Article/3734498/>

*(Additional sources: The above list highlights recent advances and efforts across the key subdomains of this technology bundle. Further references, such as national quantum technology roadmaps (e.g., Canada’s National Quantum Strategy on sensing) and standardization efforts, also corroborate the accelerating progress and investment in quantum and high-precision sensing.)*

#### **Overall Maturity Assessment (NETTI\_TUVJ 1–7 Framework)**

**Integrated Maturity Rating:** Based on the evidence gathered, the overall technology bundle “Quantum & High-Precision Sensing” is at approximately **Level 5** on the NETTI\_TUVJ maturity scale. This corresponds to the stage where a **proof-of-concept has been demonstrated and multiple well-funded actors are developing prototypes toward commercial products**. Some aspects are beginning to approach Level 6 (initial products delivered to early customers), but taken as a whole, the family of technologies has not yet achieved widespread deployment or fully proven robustness in everyday operational environments.

According to the NETTI\_TUVJ rubric:

- **Level 4 (Proof of Concept)** is surpassed: We have numerous functional prototypes that meet the basic performance requirements and clearly outperform prior solutions in sensitivity or stability. For instance, a quantum gravity sensor demonstrably detected underground structures better than classical instruments, and a chip-scale optical clock achieved short-term stability comparable to a hydrogen maser. These successes show that the core principles are proven in practical setups, not just theory or isolated lab experiments. Moreover, many prototypes have recently solved key material and engineering problems (e.g. portable gravimeters overcoming vibration

noise, or integrated photonic components stabilizing lasers for clocks), moving them beyond the lab-demo stage.

- **Level 5 (Competitive prototype development)** best describes the current state: There is now a “*competition situation with several well-capitalised market actors*” pursuing these technologies. Evidence of this includes multiple startups building optical clocks (Vector Atomic, Infleqtion, QuantX) all in parallel, at least two companies offering cold-atom gravimeters (e.g. Muquans/Exail in France and Q-Systems in the UK), and several vendors of quantum magnetometers (e.g. QZabre and SBQuantum for NV-diamond sensors, QuSpin for atomic vapor OPM sensors). Many of these firms have significant funding from VCs or government programs, and some are partnerships with large defense contractors (e.g. Safran’s work with DARPA on quantum inertials). The presence of **investment and prototypes in the “finishing phase”** is clear – for example, Infleqtion’s Ticker clock entered pilot production in 2024, and early units have been tested under field conditions (thermal, vibration) with minimal degradation. Progress is “*fast-paced*,” as new milestones are reported yearly (e.g. the first quantum gravimeter survey in 2022, the first space quantum gyro in 2025). This aligns with Level 5 criteria.
- **Level 6 (Initial products and scaling)** is on the horizon for some components but not fully realized across the board. Level 6 entails products being delivered to customers in increasing numbers and early scaling of production with cost reduction. We do see *partial signs* of this: for instance, chip-scale atomic clocks (CSACs, a prior generation of quantum clocks) are already commercially used in niche markets, and **Infleqtion’s Ticker Prime optical clock has multiple pre-production units built and tested** as of 2024. Similarly, quantum magnetometers based on optical pumping have been sold for applications like magnetoencephalography and mineral exploration (dozens of units, though not yet mass-market). Quantum gravity sensors have only a handful of deployments so far (mostly to research or defense customers), reflecting **low-volume, high-cost initial product status**. Even where products exist, they are often one-of-a-kind or small batch (e.g. a few optical clocks delivered to national labs or a defense agency). Economies of scale are therefore still unrealized – current devices remain expensive and require expert operation, which is why efforts like DARPA RoQS are focusing on ruggedization and manufacturability. In summary, **some elements are nearing Level 6**, but the *integrated bundle is best characterized as transitioning between Levels 5 and 6*.
- **Level 7 (Mature industry adoption)** – characterized by competing products widely delivered, rising demand, and self-sustaining growth – has **not** been reached. There is no broad market penetration yet for most of these sensors. Customer demand, while growing, remains mostly from specialized sectors (scientific labs, military, high-end industrial users) rather than a general market “pull.” For example, the ICV report notes that quantum gravimeters are still primarily used in military and research contexts, with civilian market expansion (like oil/gas exploration) still anticipated rather than realized. Similarly, the quantum timing and navigation devices are just beginning to

find pilot customers; we do not see “*customer demand on the rise*” in a mass-market sense – rather, it’s a targeted demand by niche stakeholders who are often directly involved in the R&D programs. Competition is present, but major industrial players are only cautiously entering (many efforts are still government-funded consortia or startups rather than, say, broad product lines from companies like Intel or Bosch, aside from a few exceptions). The criteria of Level 7 (significant internal financing by industry, wide adoption) are not broadly met yet.

**Justification with Evidence:** The assignment of **Level 5** is supported by concrete developments mapped to the rubric criteria:

- *Functional Proof-of-Concept Exceeding Prior Solutions:* Nearly every sub-technology has a working prototype that **demonstrably outperforms classical sensors** in core metrics. For instance, a quantum clock prototype by Vector Atomic achieves time stability better than high-end microwave clocks (losing  $\approx 1\text{s}$  in 32 million years), clearly exceeding previous standards. A cold-atom gravimeter in field tests showed 1.5–4 $\times$  lower uncertainty than a commercial gravimeter. These fulfill Level 4’s requirement of clear functional advantage. Additionally, the prototypes are not static – they show *recent significant progress*, such as the Fraunhofer dual-media magnetometer enhancing NV sensitivity into the fT range in 2024, solving a key problem to reach biomedical use.
- *Multiple Actors & Investment (Level 5):* There is robust evidence of a **competitive ecosystem** forming. The IEEE Spectrum report confirms “*in the past year, three separate companies have developed their own versions of compact optical atomic clocks*” – indicating a race among firms to commercialize the PoC. Likewise, the existence of *consortia and startup companies in quantum gravimetry* is documented, and DARPA’s RoQS program has drawn multiple performer teams to build field-ready sensors. This proliferation of players and funding corresponds exactly to Level 5’s hallmark: multiple well-capitalized entities pushing toward productization. The **fast pace of progress** is noted in sources like ICV Tank, which highlights *rapid development from 2020–2023* and increasing market confidence in quantum sensors.
- *Prototype to Product Transition (Levels 5–6):* We see that several prototypes are **entering the manufacturing and deployment phase**. Infleqtion’s Tiqker Prime optical clock is a prime example: it has a specific design for manufacture, with a 3U rack form, and a *pilot production line now underway* as of late 2024. Early units have been environmentally tested (thermal/vibration) and are being prepared for delivery to initial customers (likely government or large industrial labs). Similarly, QuSpin’s tabletop quantum magnetometers have been sold to research institutions for MEG brain imaging experiments, indicating initial adoption. These cases demonstrate partial fulfillment of Level 6 criteria – *products delivered in increasing (if still limited) amounts, with expansion financing in place*. Notably, venture capital and government grants have financed the scaling of these prototypes (e.g., ARPA-E funded Infleqtion’s clock development), suggesting that the **economic and manufacturing groundwork for Level 6 is being laid**. However, true economies of scale or broad market expansion are

not yet realized, as evidenced by the high costs and the fact that most devices remain custom-built or low-volume.

- *Constraints and Remaining Gaps:* The decision to not assign Level 6 fully (or Level 7) is justified by multiple source indications that **significant challenges remain before wide deployment**. The DARPA release explicitly states quantum sensors are “*notoriously fragile in real-world environments*” and are still largely lab-bound, requiring fundamental design changes to become field-viable. The Frontiers paper on inertial sensors explains that current devices have limitations (low update rate, dead times, limited dynamic range) that prevent them from replacing classical IMUs outright. These technical barriers translate to a slower commercialization timeline. Furthermore, the **market pull is still emerging** rather than present: as the ICV analysis notes, broader adoption in civil sectors is expected as devices become cheaper and smaller in the future – implying we are not there yet. Even the most advanced product, the optical clock, while debuting commercially, targets specialized uses like data centers and military timing where customers can tolerate high price and some complexity. This niche adoption, as opposed to ubiquity, is characteristic of Level 5/early Level 6 rather than a mature Level 7 technology.
- *Mixed Maturity Among Components:* It’s important to note that within this bundle, **different sub-technologies are at slightly different maturity levels**. For instance, single-photon detectors are arguably quite mature (SPAD sensors are in some consumer devices, which is a Level 7-like scenario for that narrow component), whereas quantum gyroscopes are still in one-off demonstrator stage (around Level 3–4 for a full IMU). According to the NETTI\_TUVJ framework, when an ART comprises several technologies at different stages, an average scoring is used if their applications differ. Here the applications do diverge (sensing magnetic fields vs. time vs. gravity, etc.), so an averaging approach is appropriate. The more mature elements (like certain optical/biochemical sensors already in products) raise the score, while less mature ones (quantum inertials) lower it – yielding an integrated assessment around the mid-range. We therefore assign **Level 5 as a balanced aggregate**. If one considered the subset of quantum timing and magnetometry alone, the score might lean closer to 6 given early products in use. Conversely, considering quantum inertial navigation alone might be Level 4 due to being mostly in research labs. **Level 5 captures the situation that fundamental feasibility is proven and the transition to practical products is actively in progress, but full deployment and routine use are still upcoming.**

In conclusion, **Quantum & High-Precision Sensing technologies are in the late prototype and early commercialization stage (Level 5)**. They have shown significant recent advancements and clear superiority over legacy sensors in performance, motivating strong investment and multi-actor development. Some first-generation products are reaching select end-users, hinting at Level 6, but the overall field must overcome further engineering and scaling challenges to achieve the robust, widespread adoption characteristic of Level 7. This Level 5 rating is supported by the documented achievements (proof-of-concept successes, multiple competing developers, pilot deployments) and tempered by the acknowledged limitations (fragility, cost, and nascent market uptake) evidenced in the sources above.

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## ART 01.005 Micro/Nano Sensor Networks

### 13. ART extraction

**A) Primary capability:** Enable **massive, fine-grained monitoring** of physical environments and assets using swarms of *ultra-small, low-cost sensor nodes*. These “micro/nano” sensors would be **deployed in large constellations** to collect continuous data (e.g. temperature, vibration, chemical markers, humidity, light, etc.) with much higher spatial and temporal resolution than today’s instruments. They promise to **push sensing closer to the phenomenon** (even embedding sensors in materials or environments) and reduce reliance on sparse manual measurements, thereby catching early signs of faults or environmental changes.

### **B) Key sub-components/variants:**

14. **“Smart dust” sensor specks** – millimeter- or sub-mm scale wireless sensor nodes (often MEMS-based) with integrated sensors and micro-radios, sometimes called motes. Variants include *chip-based motes* (tiny CMOS/MEMS devices) and *chip-less tags* (e.g. purely passive resonant sensors).
15. **Flexible/thin-film sensor patches** – networks of *printed or flexible sensors* (e.g. on polymer films or stickers) that can be attached to surfaces or even worn. These often use *printed electronics* or *nanomaterial sensors* and can be made transparent or conformal<sup>[1][2]</sup>.
16. **Energy harvesting power sources** – ultra-low-power designs enabling nodes to run on *ambient energy* (light, heat, vibration, RF) or tiny batteries. This includes advanced

power management and, in some cases, *battery-free operation* via RF backscatter or piezoelectric harvesting[3][4].

17. **Low-power wireless communication** – specialized radios and protocols for tiny sensors, e.g. *backscatter communication* (reflecting ambient signals instead of transmitting[3]), Bluetooth Low Energy, UWB, or custom mesh networks. Must work under severe energy constraints and avoid spectrum interference.
18. **Edge processing & network architecture** – local microcontrollers or logic on the nodes for basic processing (thresholding, event detection) and multi-hop mesh networking to gateway nodes. Gateways handle heavier computation, data aggregation, and forwarding to the cloud. Over-the-air provisioning and firmware updates are included in the architecture.
19. **Scalable manufacturing & deployment** – methods to produce **billions of sensors** cheaply (e.g. leveraging CMOS/MEMS batch fabrication or roll-to-roll printing) and strategies to deploy them in the field (e.g. mixing with seed planters in agriculture[5][6] or integrating into equipment during manufacturing). Variants include *biodegradable sensors* for environmental deployment to avoid e-waste[6].

**C) Maturity indicators:** Evidence of this ART's progress would include: **laboratory prototypes** of millimeter-scale sensor nodes with full sensing/comm functionality; **field trials or pilot deployments** of large sensor networks (hundreds or more nodes) demonstrating continuous monitoring; **commercial products or platforms shipping** (e.g. sensor “dust” kits, battery-free sensor tags) and **multiple organizations investing** (startups, industry partnerships, government programs). Key indicators: working batteryless sensors with multi-month lifetime, reliable data relay at scale, compliance with regulations (radio emissions, safety), evidence of solving calibration and data management at scale, and early **adoption in real applications** (industrial condition monitoring, environmental sensing, etc.). Signs of competition (several well-funded companies or consortia) and **roadmaps for scaling to massive deployments** would also indicate increasing maturity.

## 20. Evidence (10–20 recent, reliable sources)

21. **Ultrathin Transparent Wireless Sensor Network (2024)** – Y. Jin et al., *npj Flexible Electronics*, Feb 2024. **(Peer-reviewed)** Demonstrates a **battery-free UHF RFID sensor tag** that is only 4.5  $\mu\text{m}$  thick and 90% transparent, for unobtrusive deployment on objects or skin[1][2]. Multiple such tags were wirelessly read over *room-scale distances (up to 8 m)*, tracking human motion and vitals without batteries[7][8]. *Why it matters:* Shows feasibility of **“invisible” sensor networks** embedded in environments, with *multiple nodes operating simultaneously* and communicating to a single reader. Achieves needed performance (meters-range RF comms, multiplexed sensing) in a tiny, flexible form factor – a strong proof that micro-scale sensors can be integrated and networked in real settings.
22. **Chip-less E-skin for Vital Monitoring (2022)** – Y. Kim et al., *Science* 377(6608):859, Aug 2022. **(Peer-reviewed)** Reports a **chip-less, wireless “electronic skin”** based on a *surface-acoustic-wave (SAW) sensor* on ultrathin GaN that monitors pulse, sweat ions, and UV exposure[9]. The device requires **no battery or IC chips**, instead harvesting and transducing mechanical strains into RF signals. Demonstrated continuous **week-long monitoring of a human pulse** with a purely passive patch[9]. *Why it matters:* Confirms the scientific feasibility of **dust-sized, battery-free sensors** with biomedical-grade sensitivity. It solved a key blocker (eliminating bulky chips/power) and maintained stable operation over days on a living subject[10], indicating that such microdevices can be made reliable enough for real-world use, at least in controlled scenarios.

23. **Smart Dust for Chemical Mapping (2025)** – I. Mondal & H. Haick, *Advanced Materials* 37:2419052, Mar 2025. **(Review – peer-reviewed)** A comprehensive review of *submillimeter-scale autonomous sensors* for environmental chemical sensing[11]. It notes that **several miniaturized sensor platforms have been demonstrated** – e.g. ingestible gas sensors for the gut and “aerosolizable” nano-electronic sensors that detect gases in air[12][13] – proving core sensing and communication principles. **However**, the review emphasizes that *smart dust development has lagged* other tech (like wearables) and faces ongoing challenges: limited multi-chemical detection, calibration complexity, device retrieval and environmental risks if billions are deployed[14][15]. *Why it matters*: It provides an authoritative reality-check – while the **conceptual and experimental groundwork is laid** for micro-sensor networks, issues of *scalability, reliability, and eco-safe mass deployment* remain. This indicates plausibility is high (no physical law barriers), but **maturity is still emerging**, requiring advances in multi-sensor integration, printable manufacturing, and data handling to reach practical deployments[16][17].
24. **Batteryless IoT Sensor Node Kit (2022)** – Everactive Dev Kit release, *EdgeIR*, Oct 2022. **(Industry news)** Everactive (US startup) launched a **batteryless IoT sensor system** powered by indoor light via a small solar cell[18][19]. Each wireless node measures temperature, humidity, pressure, and 3-axis vibration, transmitting data **every 15 seconds** using an ultra-low-power custom protocol, all on harvested energy[19]. The system includes cloud data visualization and is sold as a development kit (≈\$599)[20]. *Why it matters*: It proves a **commercial-grade prototype**: maintenance-free sensor nodes continuously streaming data in real time, without batteries. This addresses the key power constraint and shows that *data deluge and networking can be handled* (Everactive built a custom data delivery backend for the “massive influx” from these always-on nodes[21]). The availability of dev kits and initial customers means the technology is moving from lab to practical evaluation in industry.
25. **Industrial Partnership for Battery-Free Sensors (2023)** – Rockwell Automation press release, Sep 2023. **(Industry report)** Announces that Rockwell (major automation vendor) is partnering with Everactive to integrate **batteryless wireless sensors** into Rockwell’s industrial monitoring suite[22][23]. Everactive’s self-powered sensors (which harvest ambient energy) will feed into Rockwell’s FactoryTalk platform for continuous asset health data, *eliminating battery maintenance* in industrial sensor deployments[24][25]. Rockwell notes this will “*increase uptime... and customer profitability*,” and specifically highlights that **replacing batteries was a barrier** to wider use of wireless sensors[26]. *Why it matters*: This is evidence of **well-capitalized industry adoption**. A top-tier industrial player sees the technology as ready enough to invest and integrate – signaling that battery-free micro-sensor networks are *on the cusp of scaled deployment in real factories*. The partnership also suggests confidence in reliability (meeting commercialization requirements like ruggedness and data accuracy in harsh settings[27]).
26. **Mass-Scale Ambient IoT Tags (2026)** – Tageos & Wiliot joint announcement, *BusinessWire via AFP*, Jan 2026. **(Industry report)** Wiliot (IoT startup) and Tageos (RFID tag manufacturer) launched a new **battery-free Bluetooth sensor tag (“IoT Pixel” Gen3)** designed for **massive scale in retail/logistics**[28][29]. The passive tag harvests radio energy and broadcasts data on standard Bluetooth frequencies, transmitting item-level information like location, temperature, humidity, and motion to the cloud[29][30]. Tageos can produce the inlays at **up to 12 billion units/year** across facilities in France, US, China[31][32]. *Why it matters*: This shows the **infrastructure for scaling to billions of sensors is being put in place now**. Standardizing on Bluetooth Low Energy (global protocol) and leveraging existing supply-chain readers lowers deployment barriers. The enormous production capacity and a “Gen3” product imply that *multiple iterations and pilots have succeeded*. It underscores that micro-sensors as cheap,

disposable tags are moving toward *mainstream commercial rollout*, at least in supply chain applications (item tracking, cold-chain monitoring) where the value of dense data is clear.

27. **Air Quality Micro-Sensor Networks (2025)** – E. Bagkis et al., *npj Climate & Atmos. Sci.*, Oct 2025. **(Peer-reviewed review)** Surveys the deployment of **low-cost air quality sensor networks (LCSNs)**. Over the past decade, thousands of <\$2,500 sensors (many palm-sized or smaller) have been installed by citizens and cities, yielding **real-time, high-resolution pollution data** at local scales that complement sparse official stations[33][34]. However, it finds *significant maturity gaps*: lack of unified calibration methods or data standards, and difficulties in data sharing between different networks[35][36]. *Why it matters*: This is a **real-world use case of distributed sensors easing a measurement bottleneck** – more granular air quality monitoring – demonstrating the value creation of dense networks. It also highlights the **practical challenges of scaling up** sensor networks: even when individual sensors are cheap and widely deployed, ensuring data quality, consistency, and integration remains hard. The need for better calibration and protocols echoes the ART’s constraints (reliable manufacturing/calibration at volume, data handling). The LCSN experience thus supports the plausibility (people are indeed deploying lots of small sensors) but shows that **standardization and quality control** are key next steps for maturity.
  
28. **Energy-Harvesting Bluetooth SoC (2022)** – Atmosic Tech. press release, Jan 2022. **(Vendor technical doc)** Atmosic introduced the **ATM33 series Bluetooth 5.3 System-on-Chips** with integrated energy harvesting, aimed at IoT devices[37][38]. The chip achieves **extremely low power draw** (0.7 mA RF receive current) and can operate on ambient energy or vastly extend battery life (3–5× longer than competitors)[39]. It includes an ARM Cortex-M33 microcontroller and improved energy harvest circuits (broader input range, lower cold-start voltage) in packages as small as wafer-level chip-scale (for ultra-compact sensor designs)[38]. *Why it matters*: It shows **industry efforts to adapt mainstream wireless tech (BLE)** to micro-power domains. By cutting power consumption and adding energy harvesting, even standard protocols can be used in “perpetual” sensor nodes. This chip is essentially a *production-ready platform* for third parties to build tiny sensor devices that communicate with ordinary phones/hubs. The availability of such commercial components lowers the barrier to creating micro sensor networks and indicates that **multiple tech approaches (backscatter, custom mesh, and now BLE) are converging on feasible solutions** for ultra-low-power sensor communications.
  
29. **Biodegradable Soil Sensor Network Demo (2022)** – S. S. Pathak et al., *Scientific Reports* 12:9041, May 2022. **(Peer-reviewed)** Developed “**DIRTS**” – a **fully biodegradable, chipless wireless sensor tag** for subsoil monitoring[40][6]. The tags (made of biodegradable polymers and zinc foil) sense soil moisture via an RF resonance shift. They demonstrated deploying many tags *simultaneously with crop seeds* (distributed by a seeder) and reading them via a drone carrying an RF interrogator that scans the field[5][41]. Each tag operated reliably through a growing season, then **naturally decomposed** in the soil over months[6]. *Why it matters*: This is a **field-validated prototype of large-scale sensor deployment** – effectively a **wireless sensor network in an agricultural setting**. It tackles deployment and disposal challenges: sensors were deployed in bulk (one per seed) and required no retrieval thanks to biodegradability. The drone-based data collection also shows a novel solution to data backhaul for massive in-situ sensors. This experiment signals that even *cost-sensitive, hard-to-access scenarios can be addressed by micro sensor networks* when clever design (chipless passive sensing, eco-friendly materials) is employed. It boosts plausibility that the full vision (billions of tiny sensors in the wild) can be managed sustainably.
  
30. **Maturity score (1–7) and reasoning**  
**A) Final maturity score: 5 (Out of 7).**



**B) Justification:** The evidence places **Micro/Nano Sensor Networks at roughly Level 5** on the maturity rubric. We see that **key blockers at Levels 3–4 have been overcome in prototypes**: fundamental feasibility is proven by multiple lab demos (e.g. millimeter-scale, batteryless sensors measuring real phenomena[42][5]), and even **proof-of-concept deployments in realistic environments are underway**. For instance, Everactive’s battery-free nodes and Wiliot’s tags show that functional prototypes meet basic commercial requirements (continuous operation, integration with existing systems) – satisfying Level 4 criteria of a working PoC that is viable for production[25][19]. What pushes the score to *Level 5* is the **entry of well-capitalized and multiple actors**: at least two startups (Everactive, Wiliot, among others) have significant funding and industry partners, and large companies like Rockwell and tag manufacturers are investing to scale production[22][28]. This competitive and fast-moving development indicates the transition from isolated demos to **refining production prototypes and initial market launch**. Recent progress – e.g. partnerships and Gen3 products – has been rapid, matching the rubric’s description of Level 5.

**Evidence ruling out lower levels:** The ART is clearly beyond Level 2 or 3: it’s not just theoretical or a single lab device anymore. We have **multi-node networks functioning outside the lab** (the soil sensor field trial[5], ambient intelligence room with multiple tags[43]), and critical technical hurdles like ultra-low-power comms and energy harvesting have working solutions in peer-reviewed studies and commercial chips[3][39]. The existence of **real pilots and beta products** (batteryless sensor systems on sale, large-scale tag manufacturing) demonstrates that it’s no longer a tentative lab curiosity (Level 3) but a budding practical technology.

**Evidence lacking for Level 6:** To reach Level 6, we’d expect **broad customer deliveries and scaling production with economies of scale**. While there are early deployments, we do not yet see *wide adoption across industries or orders-of-magnitude shipment growth* publicly documented. The sources show pilot-stage and early adopter activity (e.g. “select group of customers” in 2021[44], or initial integration with Rockwell systems in 2023), but not that **competing products are widely delivered in increasing volumes** to many clients. We also see ongoing issues in standardization and data management (e.g. the air quality sensor networks still face calibration hurdles[35]), meaning the ecosystem is not fully mature. In short, **the foundation is laid and first products exist, but mainstream, scaled commercialization is just beginning** – which is characteristic of Level 5. Achieving Level 6 will require evidence of many thousands/millions of these micro-sensors deployed reliably, falling unit costs, and more autonomous large-scale data handling – developments not fully realized yet (but possibly within a few years given current trajectories).

**C) Sub-component breakdown:** This ART is a bundle of technologies, each at slightly different maturity, but all contributing to the overall vision:

- **Battery-free industrial sensors: Level 5–6.** Everactive’s self-powered sensor networks are **in pilot deployments with Fortune-500 partners**, and a major automation company is incorporating them[22][23]. This suggests near-production prototypes and initial scaling (on the cusp of Level 6, with financing and manufacturing in place, but not yet a ubiquitous product). Key source: Rockwell-Everactive partnership[22][25].
- **Passive ambient IoT tags: Level 5.** Wiliot’s Bluetooth IoT Pixel tags and similar are being scaled up with large manufacturing capacity[31] and have gone through multiple

generations. Big retail/logistics clients are testing them, but full deployment (billions in use) is just starting. Key source: Wiliot/Tageos 2026 press[29][31].

- *Micro-scale biomedical “dust”*: **Level 3–4**. Injectable or implantable micro-sensors (neural dust, etc.) remain in research and early trials. E.g. the SAW e-skin patch works in lab settings for a week[42], but no mass deployment yet. Motivation and funding exist (for medical diagnostics), so they are proven functional (Level 3) and approaching PoC (a body network of such devices would be Level 4). Key source: Science 2022 e-skin[9].
- *Printed/flexible sensor networks*: **Level 4**. We have prototypes like the transparent sticker network (room-scale demo)[43] and biodegradable soil sensors proven in field conditions[5][6]. These meet specific deployment needs (e.g. environmental monitoring) and show performance beyond classical approaches (no wires, minimal manual effort). They are essentially PoCs demonstrated in relevant environments, but not yet widely manufactured – consistent with Level 4. Key sources: Scientific Reports 2022 (soil)[5][6], npj Flex Elec 2024 (ambient stickers)[43].

These sub-components cluster around **Level 5 on average** – the more commercially pushed aspects (industrial and supply-chain sensors) pull the average up, while the more nascent areas (medical microdevices) pull slightly down. Since the ART’s **“functionality is largely the same across variants”** (all aim to densely instrument the world with tiny sensors), we assign the **overall score based on the leading edge** of progress. Level 5 is justified because **the core promise – cheap, pervasive sensor nets – is already in early commercial rollout in some domains**, even as other domains trail slightly. In summary, the strongest evidence of multi-actor investment and pilot-scale deployment (Level 5) outweighs the pockets of lower maturity, but the ART has *not yet fully proven* its ease of mass scalability and integration needed for Level 6.

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## ART 01.006 Privacy Preserving Pervasive Sensing

### 31. ART extraction

32. **Primary capability:** Enables **continuous sensing with privacy by design**, ensuring that personal or sensitive data from ubiquitous sensors (cameras, microphones, wearables, etc.) is **processed and anonymized locally**. Only heavily **encrypted, aggregated, or de-identified information** leaves the device, preventing exposure of raw data.

### 33. Key sub-components/variants:

- *On-device analytics (Edge AI):* Sensors and IoT devices embed machine learning or signal processing locally to interpret data (e.g. speech recognition, image classification) without cloud upload.
- *Trusted hardware enclaves:* Devices use **secure chips/TEEs** (Trusted Execution Environments) to protect data and computations on-device, ensuring raw data and cryptographic keys remain isolated and tamper-resistant.
- *Privacy-preserving ML protocols:* Techniques like **federated learning** (devices send model updates instead of raw data) and **differential privacy** (adding noise



or aggregating results) allow collaborative analytics or model training while provably limiting personal data exposure.

- *Cryptographic data protection*: Strong encryption (in transit and at rest) and emerging methods (secure multi-party computation, homomorphic encryption) ensure that any data leaving the local environment is unintelligible without keys, or is only shared in statistical form.
- *Policy & interface layer*: Standardized software interfaces let users or admins **configure privacy policies** – deciding which sensors collect data, retention duration, and who (if anyone) receives processed outputs – enforcing privacy preferences and regulatory compliance by design.

34. **Maturity indicators**: Evidence would include **lab prototypes and field trials** of sensor systems achieving on-device processing with acceptable performance; **commercial product integrations** (e.g. smartphones, smart cameras) shipping with privacy-preserving sensing features; **standards or frameworks** (from consortia like IRTF/IEEE, or platform OS support like Android/Apple) that enable widespread adoption; **multiple industry players** investing in and competing on privacy-by-design IoT solutions; as well as **regulatory endorsements or compliance uses** (e.g. deployments seen as GDPR-compliant due to local data minimization). Signs of maturity range from research demos (e.g. privacy filters on microphones) up to **scaling deployments** (billions of devices doing on-device AI, federated analytics in real-world use). Key milestones include achieving real-time local analytics, power-efficient secure chips in low-cost devices, and organizations routinely choosing edge-resident data processing over cloud for privacy reasons.

35. **Evidence (10–20 recent, reliable sources)**

36. *Privacy-Preservation Techniques for IoT Devices: A Systematic Mapping Study* – D. Torre et al. – **IEEE Access (peer-reviewed)** – Jan 2023. [1][2] <br> *Survey of 260 papers (2017–2021) on IoT privacy techniques*. It finds **active research in cryptographic protocols, authentication, and privacy attack defenses** for IoT, underscoring that embedding privacy in IoT systems is a major R&D focus. This breadth of work (funded by DHS/AFRL) signals the scientific feasibility and interest in privacy-by-design IoT[1]. It establishes the landscape of tools (encryption, differential privacy, etc.) that underpin the ART’s plausibility.

37. *Privacy-Preserving Intelligence at the Edge: New Horizons in Federated Learning* – S. Mandava – **Preprint (SSRN)** – Mar 2025. [3][4] <br> *Evaluation of prominent federated learning (FL) frameworks in real edge environments*. Reports that FL can **train AI models across IoT devices without centralizing data**, improving performance and privacy by keeping data on the edge[3]. It notes fast development of FL for “privacy-preserving intelligence,” with enhancements in encryption and governance, and sees healthcare trials adopting fully privacy-compliant federated analytics[4][5]. This shows the core distributed learning approach of the ART is **operational in practice**, with frameworks benchmarking well on scalability and privacy-utility tradeoffs.

38. *“Protecting Audio Privacy at the Source” (Kirigami project)* – Y. Agarwal et al. (Carnegie Mellon University) – **ACM Ubicomp/MobiCom 2024 (peer-reviewed); news release** – Apr 2025. [6][7] <br> **Demonstrates on-device sensor filtering**: The *Kirigami* system runs on a tiny microcontroller and **automatically strips human speech from audio streams in real time**, before any data leaves a microphone[6]. It uses a lightweight classifier to delete speech segments while retaining other sounds for activity

recognition. This protects privacy even against advanced speech-recognition AI that could recover muffled speech. Notably, Kirigami is tunable (aggressiveness of filtering) and can be retrofitted to field-deployed mics[7][8]. This peer-reviewed prototype **solved a previously blocking problem** (open mics capturing private speech) and ran under the power/compute constraints of cheap IoT chips – strong evidence that privacy-preserving sensing is technically feasible for everyday devices.

39. *A Fallen Person Detector with a Privacy-Preserving Edge-AI Camera* – K. Hashemifard, F. Florez-Revuelta, G. Lacey – **ICT4AWE Conference (peer-reviewed)** – Apr 2023. [9][10] <br> **Prototype of a smart camera that never streams raw video.** Uses a Luxonis OAK-D edge-AI camera (with on-board Myriad X VPU) on a mobile robot to detect when an elder has fallen, as part of assisted-living tech. The team trained a YOLOv5 object-detection model (via knowledge distillation) to run entirely on-camera at **15 frames/s with 96.5% precision and 95.1% recall** for fall detection[10]. Only the **alert (fall detected)** is transmitted, not the video feed. This shows that fairly complex vision tasks can be executed locally with high accuracy and low latency, making continuous monitoring possible **without sending any identifiable video to the cloud**. It validates the ART's claim that edge processing can meet functional needs (fast, accurate detection) while drastically limiting data exposure.
40. *Privacy-preserving fall detection at the edge using Sony IMX636 event-based vision sensor and Intel Loihi 2* – L. Khacef et al. – **arXiv preprint (Intel Labs & partners)** – Nov 2025. [11][12] <br> **Cutting-edge “smart sensor” proof-of-concept combining a neuromorphic camera and processor.** An event-based vision sensor (Sony's IMX636, which outputs asynchronous pixel changes rather than images) is paired with Intel's Loihi 2 neuromorphic chip to detect falls with strict power and privacy constraints[11]. The system performs always-on inference at the sensor, consuming only ~90 mW on Loihi2. It achieved an **84% F1-score for fall detection** on a realistic dataset, using highly sparse spiking neural networks[12]. Notably, all computation occurs in a **secure, analog neural format on-device**, and only the detection result is output – the raw video is never produced in the first place. This exemplifies an emerging class of hardware designed for privacy-preserving sensing (in-sensor processing), showing that even **future-forward tech like neuromorphic AI is aligning with the ART's goals** to maximize privacy, latency, and energy advantages.
41. *Android Private Compute Core Architecture* – E. Marchiori et al. (Google) – **Technical whitepaper (arXiv) & Android open-source** – Sep 2022. [13][14] <br> **Industry deployment in OS:** Describes Android's *Private Compute Core (PCC)*, introduced in Android 12, as a secure OS partition for on-device data analytics. The PCC runs ML features like **Live Caption, Now Playing (music ID), and Smart Reply entirely on-device**, isolated from apps[13]. It also enables federated learning updates via “Private Compute Services” – devices receive model improvements and contribute encrypted gradients, but raw user data never leaves the device[15]. This open architecture (partly open-sourced) shows a major platform's commitment to privacy-by-design: hundreds of millions of Android phones now perform sensitive computations in a locked-down local environment, **sharing only model updates or anonymized stats**. This real-world adoption by Google demonstrates **commercial viability and scalability**, as well as compatibility with existing hardware (using secure enclaves and the phone's AI accelerators).

42. *Confidential Computing: Hardware-Based Trusted Execution for Applications and Data* – Confidential Computing Consortium (Linux Foundation) – **Industry consortium whitepaper (v2)** – Nov 2022. [16][17] <br> **Evidence of secure hardware adoption for IoT edge:** Reports that *confidential computing* techniques (hardware TEEs that keep data encrypted even during use) are “**already in use**” by software vendors and organizations, including deployment “at the network edge for IoT use cases”[16]. For example, devices can now store and process cryptographic keys and sensitive sensor data inside standard secure enclaves, achieving security formerly only possible with dedicated HSM modules[17]. This indicates that **specialized secure chips have become practical and are being scaled out** beyond the data center into edge/IoT devices. It validates the ART’s assumption that the cost and performance of secure processing hardware are now compatible with embedded sensing nodes.
43. *Privacy-preserving federated learning for collaborative medical data mining in multi-institutional settings* – R. Haripriya et al. – **Scientific Reports (Nature, peer-reviewed)** – Apr 2025. [18][19] <br> **Demonstration of cross-organization analytics without data sharing:** This study combined federated learning with transfer learning to train medical image classifiers (for chest X-ray TB detection, brain MRI tumor classification, etc.) across multiple hospitals **without pooling patient data centrally**[18]. Using adaptive aggregation methods, the federated models achieved accuracy on par with models trained on merged data, proving that high-precision AI diagnosis is possible under strict privacy constraints[20][19]. The work also introduced a novel FedAvg/FedSGD switching strategy to improve convergence. This is a **peer-reviewed validation in a sensitive domain (healthcare)** that privacy-preserving sensing and learning can deliver real-world utility. It also signals growing trust: medical institutions are beginning to adopt such techniques to comply with privacy laws while still extracting collective insights – aligning with the ART’s value proposition of easing data-sharing bottlenecks.
44. *Internet of Things (IoT) Edge Challenges and Functions (IRTF RFC 9556)* – J. Hong et al. – **IRTF Informational Report (research consensus)** – Apr 2024. [21][22] <br> **Standards-community perspective:** This report by the IETF/IRTF research group on IoT recognizes privacy as a **key driver for moving processing from cloud to edge**. It explicitly states that performing computations “closer to data generators” (IoT devices) and **aggregating/anonymizing data before sending to cloud is a major use-case** for edge computing in IoT[21]. The RFC notes that many IoT applications face privacy, latency, and cost requirements that “cannot be addressed by centralized cloud” and thus require distributed edge solutions[23][24]. The document provides a general model where edge nodes handle data management and analytics (Section 4.5.2) and even mentions techniques like homomorphic encryption for processing encrypted data[25]. This broad consensus by an international standards body underscores the plausibility of the ART approach and indicates that **the industry is coalescing around privacy-preserving edge architectures** as a path forward.
45. *Enhancing IoT privacy with artificial intelligence: Recent advances and future directions* – A. Tsouplaki et al. – **Internet of Things (Elsevier) – Review Article** – Nov 2025. [26] <br> *Contemporary survey of AI techniques for IoT privacy.* Highlights a taxonomy of approaches and identifies **federated learning and encryption as central methods** for protecting IoT data[26]. The authors review about 40 recent papers and note that combining AI with encryption, distributed learning, and anomaly detection can mitigate many privacy challenges. They emphasize “real and substantial results” achieved in major sectors via these techniques.

The survey's analysis of **implementation feasibility and gaps** shows that while further work is needed (e.g. on resource efficiency and ethical compliance), the core building blocks of privacy-preserving sensing (on-device AI, secure aggregation, etc.) have made tangible progress in recent years. This comprehensive assessment by academic and industry researchers reinforces that the ART's components are not speculative – they are active areas producing working solutions.

#### 46. Maturity score (1–7) and reasoning

**Score: 6 (Early commercial deployment).** The evidence suggests that privacy-preserving pervasive sensing is **well beyond laboratory proof-of-concept (Levels 2–3)** and even beyond isolated prototypes (Level 4). **Key elements are in active production use:** For example, billions of consumer devices now run on-device analytics in secure enclaves (Apple's devices, Android's Private Compute Core) and share only anonymized aggregates[13][14]. Multiple tech giants are **competing on privacy features** – e.g. Google and Apple tout on-device AI for voice, photos, etc., and startups and consortia are advancing enabling hardware and software – indicating a **Level 5+ commercial momentum**. We assign Level 6 because **products are being delivered at scale** and steadily improved: real customers are using these privacy-preserving sensor capabilities today (from smart cameras to health wearables), and adoption is growing as data regulations tighten. For instance, the CMU *Kirigami* filter (Level 3 demo in 2024) was quickly followed by smartphone OS integrations (Level 5–6 in the same timeframe), showing fast-paced progress[6][13].

*Justification:* Evidence of **shipping implementations** rules out Levels 1–4. Android's PCC and Apple's on-device AI deployments prove that the core “compute-at-edge with privacy” principle is *viable at scale* (Level 4) and has moved into widespread productization[13]. The presence of **multiple independent actors and consortia** (Google, Apple, CCC, healthcare collaborations, etc.) demonstrates we are at least at Level 5 – there is clear investment and competition to build out these features. We choose **Level 6** because the technology is **not just in prototype or pilot: it's in mass production and increasing use**. Secure IoT chip platforms and edge AI cameras are being rolled out commercially, and costs are expected to drop with scale (e.g. standard secure elements replacing costly bespoke hardware[16][17]).

However, we stop short of Level 7 because full **market penetration and “default” status** are not yet achieved. Many IoT deployments still rely on cloud processing, and not all sensor makers have adopted privacy-first designs. Some sub-components (like fully homomorphic encryption or standardized user policy frameworks) are still maturing and not ubiquitous. In other words, **the foundation is laid and substantial value is being delivered (Level 6), but the paradigm hasn't completely overtaken legacy approaches**. Continued advances in efficiency, industry standards, and regulatory pressure will likely drive it to Level 7 in the coming decade as privacy-preserving sensing becomes the expected norm.

*Sub-component breakdown:*

- **Edge AI analytics: Level 6** – Already in millions of devices (e.g. on-device fall detection cameras, offline voice assistants) and reducing need for cloud data[10].
- **Secure hardware (TEE/secure elements): Level 6** – Widely deployed in consumer and industrial devices; standardized solutions via ARM TrustZone, SGX, etc.[16].
- **Federated learning & encrypted analytics: Level 4–5** – Proven in pilots (Gboard, medical imaging) with ongoing improvements, but not yet standard in all products[18][19].
- **Privacy policy frameworks: Level 4** – Early standards (IRTF, ISO privacy-by-design) exist and some OS support for user data control, but full interoperability is nascent.

These aspects collectively support an overall **Level ~5.5**, which we round up to **6** given that the **most crucial components (local processing and secure data handling) are already at production scale**. The less-mature elements (e.g. broad federated learning adoption) currently limit the total realization of the vision, but they do not negate the fact that **the integrated approach is already delivering value in real products**. Thus, **6** best captures the ART's status: significant deployment and growth, on the cusp of becoming a standard practice once remaining pieces fall into place.

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## ART 01.007 Quantum-Resilient and Secure Communication Networks

1. **ART extraction**
2. *Primary capability – quantum-resilient secure networks*: Enables end-to-end communications that remain confidential and authenticated even against adversaries with large-scale quantum computers. It prevents “harvest-now, decrypt-later” attacks by using cryptographic methods that cannot be broken by quantum algorithms, thereby future-proofing long-lived data and sensitive communications.
3. *Key sub-components/variants*: Post-quantum cryptographic algorithms (encryption and digital signatures) integrated into network protocols (VPN, TLS, 5G, etc.) to replace current RSA/ECC-based schemes; quantum key distribution (QKD) links optionally added to share encryption keys via quantum physics for extra security; upgraded network hardware (routers, base stations, SIM cards, etc.) and secure modules supporting these new algorithms; crypto-agility frameworks and policy engines that negotiate algorithm choices and key lengths dynamically for seamless migration as standards evolve; mechanisms for metadata protection and traffic-obfuscation to limit traffic analysis and impersonation (e.g. encrypting not just content but also headers/patterns); integrated monitoring and automated response systems to detect anomalies (key compromise, downgrade attacks, hardware tampering) and reroute traffic through trusted paths; and global interoperability standards and certification programs (e.g. NIST PQC standards, QKD protocol specs, telco guidelines) to ensure different organizations’ equipment can communicate securely and be audited for quantum-resistant security.
4. *Maturity indicators – evidence to look for*: Successful **field trials or pilot deployments** of quantum-safe communications over existing fiber, satellite, or wireless networks (demonstrating real-world feasibility); **lab prototypes in networking gear** (e.g. quantum-safe routers, 5G systems or QKD devices) achieving required performance and reliability; **multiple industry actors and consortia engaged** (vendors, telecom operators, cloud providers, national labs) competing or collaborating to develop standards and products, indicating significant investment; **standards milestones and adoption roadmaps** (e.g. NIST finalizing post-quantum crypto standards, telecom industry guidelines, government mandates with timelines for PQC migration); early **commercial offerings or hardware support** for quantum-resistant encryption (prototype services, software updates, or add-on cards available to customers); and evidence that **performance/cost constraints are being addressed** (e.g. acceptable latency and energy overhead in post-quantum encryption, successful integration of QKD with classical traffic, incremental upgrade costs comparable to normal tech refresh cycles rather than massive new infrastructure builds).
5. **Evidence (10–20 recent, reliable sources)**
6. **UK quantum-secure network demo – University of Cambridge (Optics/Photonics conference 2025)** – *Phys.org news (Cambridge press)* – Apr 2025. *Researchers from Cambridge and Bristol demonstrated the UK’s first long-distance ultra-secure*

quantum network (>410 km fiber between cities) using two types of QKD (keys encoded in single photons and entanglement distribution). They achieved the first quantum-secured video call and encrypted data transfer over this network[1][2]. This is the first time a large-scale network combined entanglement-based QKD with classical data links, showing that multiple quantum-safe technologies can operate together over existing fiber infrastructure – a significant feasibility milestone for quantum-resilient communications.

7. **Deutsche Telekom field trial of quantum entanglement over telecom fiber** – Deutsche Telekom T-Labs (press release) – Mar 2025. DT's innovation labs, with startup Qunnect, achieved 17 days of sustained entanglement distribution at 99% fidelity over 30 km of deployed fiber[3]. They also dynamically routed entangled photons across an 82 km fiber network in parallel with normal Internet traffic, maintaining >92% fidelity[4]. This long-duration field trial on real telecom infrastructure – the first by a major carrier – demonstrates that quantum link technology (for QKD or future quantum internet applications) can be stably integrated into today's networks without disrupting classical data, underscoring the practical plausibility of quantum-secure network layers.
8. **Nationwide quantum-safe network pilot in Singapore** – Telecoms.com (industry news) – Aug 2024. Singtel (Singapore's telecom) launched Southeast Asia's first National Quantum-Safe Network Plus (NQSN+) pilot, a platform employing modern quantum-resistant security to protect enterprise communications[5]. The initiative supports various network devices and is rolling out in phases – from lab integration testbeds to live trials – to validate interoperability and performance before full deployment[6]. Singtel's program (backed by govt. agencies) illustrates the transition from prototypes toward production: it provides a path for enterprises to trial quantum-safe links (using post-quantum encryption and QKD) and reflects growing telecom industry commitment to upgrading national infrastructure for the quantum era.
9. **Post-quantum encryption on 5G: SK Telecom & Thales trial** – Telecoms.com (industry news) – Dec 2023. Korean operator SK Telecom and security firm Thales tested quantum-resistant cryptography on a 5G standalone network, focusing on encrypting subscriber identity data to protect user privacy from future quantum decryption. The trial used Thales's post-quantum SIM cards in SKT's 5G core network[7]. While large quantum attacks aren't yet real, this shows telcos are proactively implementing PQC to counter "record now, decrypt later" threats[8]. SKT's demo indicates that mobile network infrastructure (5G) can be upgraded with post-quantum authentication/encryption without waiting for quantum computers to emerge – a key proof-of-concept for wireless network readiness.
10. **Hybrid quantum-safe network PoC in EU (Nokia & HellasQCI)** – Nokia & GRNET (press release) – Dec 2023. In Greece, Nokia and the national quantum consortium HellasQCI successfully completed a proof-of-concept Quantum-Safe Network over a three-node, optical fiber ring. The trial demonstrated a hybrid key management approach: using both classical cryptography and QKD-generated keys to encrypt optical data links[9]. Nokia's system included a security management server that orchestrated quantum-safe keys and continuously monitored the encrypted links, automatically reverting to classical keys if the QKD layer had issues[10]. This shows not only interoperability of QKD with standard network equipment but also the kind of policy-driven agility and fail-safe mechanisms envisioned (the network maintained

secure operation by switching algorithms on-the-fly). It's a concrete step toward commercializing quantum-safe transport networks in critical infrastructure.

11. **Cisco ships quantum-safe VPN encryption features** – Cisco Systems (vendor technical documentation) – 2023. Cisco has implemented post-quantum VPN capabilities in its IOS XE 17 routers, introducing support for the IETF's hybrid key exchange standard (RFC 8784). This feature allows mixing a Post-Quantum Key (PPK) into IKEv2/IPsec sessions[11]. Cisco's "Secure Key Integration Protocol" (SKIP) lets routers import keys from external quantum-safe sources (like QKD devices or a PQC key server) over a TLS channel, so that IPsec VPNs gain quantum-resistant pre-shared keys[12]. The feature is available on mainstream router models (Catalyst 8000, ASR 1000, etc.), indicating that quantum-resilient encryption is moving from lab to product: major networking gear now offers quantum-safe options that customers can configure for sensitive links.
12. **Global telecom industry coordination (GSMA Task Force)** – GSMA Post-Quantum Telco Network Initiative – Sept 2023. The GSMA (which represents mobile network operators worldwide) formed a "Post-Quantum Telco Network" task force in late 2022 to coordinate quantum-safe transition across the telecom sector. By 2023 the task force grew to 50+ companies (including ~20 major operators) and released quantum risk management guidelines for telcos at MWC 2023[13]. These industry guidelines help carriers assess quantum threats and plan upgrades (e.g. inventorying vulnerable systems, testing PQC algorithms in 5G/LTE, integrating QKD where applicable). The broad participation and formal guidance show that the telecom industry as a whole is actively preparing for quantum-resistant security, an important indicator of moving beyond isolated research to sector-wide readiness and standards.
13. **Government mandate for quantum-safe communications (USA)** – U.S. Federal initiatives (policy news) – May 2025. The U.S. government has issued directives to accelerate adoption of post-quantum cryptography in federal networks. A 2022 White House memorandum (NSM-10) requires federal agencies to transition to NIST-approved quantum-resistant encryption by 2035[14]. By mid-2024, agencies must update procurement requirements so new systems support PQC[15]. NIST finalized three core PQC standards (encryption and signature algorithms) in 2023[16], yet as of 2025 only ~5% of organizations have started deploying them[17]. Furthermore, the U.S. Office of Management and Budget estimates over \$7 billion investment will be needed this decade for PQC migration[18]. These mandates and resource commitments underscore that quantum-secure communication is technologically feasible and now a national security priority, though large-scale implementation is just beginning.
14. **Academic study – PQC standards and timelines (EU/US)** – Souvatzidaki & Limniotis, *Cryptography journal* – Nov 2025. A scholarly analysis of post-quantum TLS performance provides context on global transition plans. The European Commission issued a 2024 recommendation outlining a coordinated roadmap to shift EU organizations to post-quantum cryptography by 2035[14]. In the US, a national strategy likewise sets 2035 as the deadline for quantum-proofing federal systems (per NSM-10)[19]. The study notes that NIST's multi-year process has standardized five PQC algorithms (for encryption and signatures) by 2025[20], giving a clear basis for implementation. This evidence indicates the underlying science is settled and international standards bodies and governments have defined concrete milestones for



*rolling out quantum-resilient encryption in the coming decade – a strong sign of late-stage R&D transitioning into deployment.*

15. **Telecom Italia Sparkle quantum-safe service PoC** – Sparkle (TIM Group) press release – Aug 2024. Sparkle, a major global carrier, successfully ran a quantum-safe Network-as-a-Service PoC on its fiber network, and announced a commercial launch by year-end. The trial (in Athens) integrated post-quantum encryption from Arqit into an Intel-based network card and used Adtran’s software to automatically provision a secure “Quantum-Safe Internet” connection on demand[21]. It followed an earlier inter-country quantum-safe VPN test between Italy and Germany, and demonstrated fully automated setup of encrypted links using post-quantum keys within a standard NaaS platform[22]. Sparkle’s PoC showed that deploying quantum-resistant encryption can be as agile and cloud-managed as today’s services, and importantly that a commercial telecom sees the technology as viable for rollout (not just experiment)[23][24]. This reflects a competitive push to offer quantum-safe connectivity to customers, marking progress toward real-world productization.

#### 16. Maturity score (1–7) and reasoning

**Score: 5 (Proof-of-Concept demonstrated, moving toward commercial prototypes with industry momentum).**

**A) Rationale for score:** The evidence shows that quantum-resilient networking is **well beyond theory (levels 1–2)** and even beyond isolated lab demos. We have multiple successful **field prototypes and PoCs (level 3–4)**: e.g. sustained quantum entanglement in telecom fiber[3], long-distance quantum key distribution networks with live traffic[2], and post-quantum encryption trials in 5G and IP networks[25][11]. These achievements prove that the key technical hurdles (new algorithms, integration with existing infrastructure, basic performance feasibility) have been overcome in practice. Moreover, the transition is not limited to one team or one demo – **numerous well-funded actors are now involved (a hallmark of level 5)**. Telecom giants (Deutsche Telekom, BT, Singtel, Telefónica, etc.), networking vendors (Cisco, Nokia, Thales) and government programs (NIST, EU EuroQCI) are all running trials or developing standards in parallel[13][26]. This broad competition and investment indicate that the technology is in the **late prototype stage, approaching productization**. For instance, Cisco has already added quantum-safe VPN features to shipping routers[11], and Sparkle plans to commercially launch a quantum-safe service by the end of 2024[23][24] – these are strong signs of maturation beyond a proof-of-concept. Such momentum and multi-actor engagement rule out maturity levels 3–4, which correspond to single prototypes or early PoCs without industry uptake. We are effectively seeing the **first generation of market-ready solutions being prepared**, consistent with level 5.

**B) Missing evidence for higher levels:** The overall ecosystem has not yet reached full deployment or widespread customer adoption that would mark level 6 or 7. Level 6 requires products delivered at scale with rapidly increasing adoption. Here, most quantum-secure network implementations are **pilots or limited launches**, not yet rolled out across entire nations or to most customers. For example, Singtel’s and Sparkle’s quantum-safe networks are in trial phases[6][27], and while Cisco’s feature is available, only a small fraction of users have likely enabled post-quantum modes so far. We have no evidence of *broad* production deployment (e.g. thousands of quantum-safe links carrying everyday traffic) – adoption is cautious and just beginning (even U.S. agencies have only inventorying plans at this stage[17]). Additionally, **interoperability standards and certifications are still being finalized** (e.g. ITU/ETSI QKD specs, PQC in TLS/IPSec standards are emerging but not

uniformly implemented). The cost and complexity, while improved, are not yet “low friction” – specialized hardware (QKD devices, new chips) remains expensive and integration efforts are ongoing. These gaps mean the technology hasn’t achieved the market penetration or internal financing characteristic of level 6. In short, the concept is proven and attracting serious investment (level 5), but **full-scale commercialization and ubiquitous deployment are still on the horizon** (needed for level 6).

**C) Sub-component maturity breakdown:** This ART spans two main technology threads – **post-quantum cryptography (PQC)** and **quantum key distribution (QKD)** – plus supporting network control features. Each is at a slightly different stage, but they converge toward the same functionality (secure comms in a quantum era):

- *Post-Quantum Cryptography integration:* **Maturity ~5.** PQC algorithms have been standardized[20] and are being built into products: e.g. Cisco’s PQC VPN, Thales’s PQC SIM, and early adoption in protocols (TLS 1.3, IPsec)[11][25]. Multiple vendors and governments are driving this, with aggressive timelines (US and EU aiming for widespread adoption by 2035[14]). This suggests a transition from PoC to pre-commercial and pilot deployments, aligning with level 5 (active competition to implement and deploy).

- *Quantum Key Distribution and quantum networks:* **Maturity ~4.** QKD technology itself is proven (even deployed in niche uses), and recent field trials (UK, Germany, Singapore) show it can operate over metro/regional distances with high reliability[28][2]. Specialized firms (ID Quantique, Toshiba, etc.) do sell QKD systems, but these remain limited in scale and costlier than classical solutions. Integrated **quantum-secure network prototypes using QKD** (e.g. Nokia’s HellasQCI trial) are at proof-of-concept stage[9]; wider roll-out will depend on cost reduction and standardization. So QKD-enhanced networks lag slightly behind pure-PQC solutions in readiness – roughly at advanced field trial stage (level 4).

- *Network control, monitoring, and agility:* **Maturity ~4–5.** Software frameworks for crypto agility and threat monitoring are being tested: e.g. Nokia’s key orchestrator with automated failover from QKD to classical keys[10], and GSMA’s industry guidelines for quantum risk management[13]. These indicate concept validation (level 4) leaning toward level 5 as they get incorporated into pilot deployments.

Given that **the overall secure network solution can fulfill its core purpose with post-quantum cryptography alone** (QKD, while beneficial for certain high-security links, is an augmenting component), the maturity of the *bundle* is weighted more by the PQC integration track. PQC-backed network security is entering early commercialization, which justifies an aggregate score of **5**. In other words, the foundational capability – quantum-resilient encryption for network traffic – is approaching market readiness (level 5), even though some auxiliary elements (like widespread QKD or full metadata-hiding techniques) are still in prototype form. As those catch up, the ART as a whole will progress to the next level; for now, the evidence firmly places it at a mid-to-late developmental stage, **beyond proof-of-concept but not yet broadly deployed**.

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## ART 01.008 Integrated Sensing and Communication (ISAC)

### 47. ART extraction

48. *Primary capability – “Integrated Sensing and Communication” (ISAC):* Simultaneous high-speed wireless data communication and radar-like sensing using the **same radio**

**network infrastructure.** The network's radio signals carry user data *and* probe the environment, allowing devices and base stations to act as distributed sensors while still providing connectivity.

49. *Key sub-components / variants:*

- **Joint waveforms & hardware reuse:** Unified radio waveforms and transceiver hardware that encode data and also measure signal reflections[1][2]. Co-designed **OFDM/communication signals for radar sensing** avoid separate sensors[1].
- **Network synchronization & MIMO arrays:** Tightly coordinated **multi-antenna** nodes (massive MIMO, distributed arrays) and precise timing enable coherent sensing across multiple transmitters/receivers[3][4]. Supports **monostatic, bistatic, multistatic** sensing modes and distributed aperture for higher resolution.
- **Sensor fusion & ML:** Advanced signal processing and **machine learning** fuse measurements from many nodes to infer object distance, velocity, and coarse shape, improving robustness over single sensors[5][6].
- **Standardization & spectrum sharing:** Integration into **5G/6G standards**, with spectrum management and regulatory frameworks for dual-use signals[7][8]. (E.g. studies in 3GPP Release-19 define ISAC requirements[9]; IEEE 802.11bf adds Wi-Fi sensing in license-exempt bands[10][11].)
- **Application variants:** *Short-range indoor:* e.g. Wi-Fi APs detecting motion in smart homes[12][13]. *Wide-area cellular:* 6G base stations acting as “**radar**” **networks** to track drones, vehicles, intruders, etc[14][15]. *High-frequency ISAC:* sub-THz links for ultra-high-resolution imaging and data together[16][17].

50. *Maturity indicators:* Evidence of **feasibility** (lab prototypes, field trials demonstrating comm & sensing concurrently), **standards progress** (3GPP study items, IEEE 802.11bf adoption[10][11]), **industry investment** (multiple major vendors and consortia launching ISAC programs[18]), and **early deployments** (proof-of-concept systems in real environments, or initial product features like Wi-Fi motion sensing). Key signs include **field trials** (e.g. 5G networks used as radar in airports[19]), **PoC demos** showing both data & sensing with one radio[1], **standardized features** in upcoming wireless releases[7][20], and even **commercial offerings** of integrated sensing capabilities (e.g. home routers with Wi-Fi-based motion detection[12][13]).

51. **Evidence (10–20 recent, reliable sources)**

52. **6G ISAC PoC on mmWave (Thorsten Wild et al., EuMW focus session)** – *Peer-reviewed conference paper (preprint)* – May 2023[1]. **Demonstrates a proof-of-concept ISAC system** using commercial 5G mmWave hardware with added sensing algorithms. It achieved **simultaneous high data-rate communication and OFDM radar sensing in the same band**, successfully detecting a pedestrian target. This result shows that future cellular networks can practically incorporate radar-like sensing without separate sensors[1]. (*Plausibility: Confirms feasibility on real 5G hardware; Maturity: early PoC resolving key integration challenges.*)
53. **Ericsson: “Sensing in 6G – Use cases and architecture” (R. Keller et al., Ericsson Tech. Review)** – *Industry technology article* – Oct 2025[7][21]. Reports that **3GPP is adding initial sensing features in 5G-Advanced** and envisions **fully integrated sensing in 6G**, enabling mobile networks to “actively sense” surroundings[7]. Describes Ericsson’s proposed end-to-end 6G architecture with sensing-capable base stations and core network functions. Identifies

use cases like **drone detection, collision avoidance for vehicles, and blockage tracking**, and notes significant market interest. (*Plausibility: Endorsed by a top vendor; Maturity: Standardization work underway now (Release 18/19)*[\[21\]](#).)

54. **Ropitault et al., “IEEE 802.11bf: Widespread Adoption of Wi-Fi Sensing” (NIST)** – *Peer-reviewed standards magazine* – May 2023[\[10\]](#)[\[11\]](#). Reviews the in-progress **IEEE 802.11bf amendment (target 2025)** that formalizes Wi-Fi sensing. The draft defines how ordinary Wi-Fi devices (2.4/5/6 GHz) can perform **bistatic and multistatic motion sensing** by sharing CSI (channel state) measurements. Example applications include presence detection and environment monitoring via Wi-Fi signals[\[10\]](#)[\[11\]](#). (*Plausibility: Validates that existing WLAN signals can double as sensors; Maturity: Task Group BF formed due to industry demand, standard nearing completion.*)
  
55. **ETSI Industry Specification Group on ISAC (press release)** – *Standards body announcement* – Nov 2023[\[22\]](#)[\[8\]](#). Announces **formation of a dedicated ISAC working group** with 87 participating organizations (incl. InterDigital, Apple, Huawei, etc.) to coordinate **pre-standard 6G ISAC research**[\[22\]](#). The group’s mission is to develop use cases, requirements, and evaluation methods, feeding into **3GPP Release 20+ and ITU-R IMT-2030** frameworks[\[8\]](#). Use cases span critical infrastructure security (intruder detection), smart cities, health (fall detection), and environmental monitoring[\[14\]](#). (*Maturity: Broad, multi-region industry engagement signals a concerted push toward 6G implementation.*)
  
56. **SESAR “NewSense” project (ENAC & partners)** – *EU research project report (completed)* – Oct 2022[\[19\]](#)[\[23\]](#). Developed and tested a **5G-signal-based radar surveillance system** for airport runways. The team added a 5G-based positioning function and used **reflected 5G base station signals to detect non-cooperative targets**, complementing a low-cost mmWave radar[\[24\]](#). Field trials at a Toulouse airfield showed the 5G-based sensing achieving **360° coverage with super-resolution and up to ~2 km range**, while the mmWave radar covered a few hundred meters ( $\pm 65^\circ$  FOV)[\[19\]](#)[\[23\]](#). This suggests a **cost-effective alternative** to expensive dedicated radars for smaller airports. (*Plausibility: Validated dual-use of 5G signals in a real environment; Maturity: Early field trial proving feasibility and economic advantage.*)
  
57. **Rohde & Schwarz – ISAC test solution & partnerships** – *Vendor technical doc / press* – 2023[\[25\]](#)[\[26\]](#). The test-equipment leader R&S developed a **laboratory platform for ISAC**, combining a commercial radar echo simulator with 5G/6G radio frontends[\[25\]](#). This setup generates **virtual targets** and measures a device’s simultaneous sensing/communication performance, enabling repeatable R&D testing. The solution earned a “*Most Innovative Mobile Tech*” award at MWC 2023[\[27\]](#). R&S also announced collaboration with **China Mobile Research Institute** to research and validate ISAC technologies[\[26\]](#). (*Maturity: Existence of specialized test gear and operator partnerships shows the tech is far enough along to require performance verification and attract telecom industry investment.*)
  
58. **6G Flagship (Univ. Oulu) D-band ISAC demo** – *Academic demo award (IEEE JC&S 2026)* – Jan 2026[\[16\]](#)[\[17\]](#). A research team in Finland built an **integrated 144 GHz (“D-band”) radio link** that delivered multi-Gbps communication *and* real-time **radio tomography imaging** simultaneously[\[16\]](#). Uniquely, the system used a single continuous link (fixed LoS) for sensing without any mechanical scanning, reconstructing 3D images of objects while transmitting data[\[28\]](#)[\[17\]](#). The demo ran remotely (controlled from Oulu) and was **noted for its technical maturity and robustness**, winning the Best Demo Paper award at IEEE JC&S 2026[\[29\]](#)[\[30\]](#). (*Plausibility: Demonstrates high-frequency ISAC working in practice; Maturity: A polished prototype achieving simultaneous comm+sensing in sub-THz, indicating rapid progress in the research community.*)



59. **Wang et al., “Terahertz ISAC with 220 GHz portable device” (Nature Comm.)** – *Peer-reviewed experimental paper* – Nov 2025[31][32]. Reports a **compact 220 GHz ISAC prototype** built with a phased-array transceiver using fully shared hardware for sensing and communication. The device can electronically scan  $\pm 30^\circ$  and was tested with a moving user terminal[31]. It achieves **millimeter-level imaging resolution** via an OFDM-based compressed sensing algorithm, *without* needing the slow raster-scanning typical of THz imagers[31][32]. This prototype delivered high-speed data links and high-resolution radar imaging concurrently, establishing a practical framework for unified THz comm+sensing devices. (*Plausibility: Confirms that very high-frequency (sub-THz) radios can be dual-purpose; Maturity: Key THz components and algorithms demonstrated, although still a research prototype.*)
60. **Comcast Xfinity “WiFi Motion” deployment (H. Nasir, Tom’s Hardware)** – *Tech news / product evidence* – Jul 2025[12][13]. Describes a **new feature in consumer Wi-Fi routers** that uses standard Wi-Fi signals for motion detection. Comcast enabled “WiFi Motion” on Xfinity routers, which analyzes perturbations in signal strength between the router and connected devices to **sense movement in the home**[12]. It can even detect small motions (like an arm wave) and distinguish a pet from a person, sending alerts via an app[33]. Crucially, this requires **no new sensors – only software updates** leveraging existing Wi-Fi radios. (*Maturity: Real-world product rollout – integrated comm-sensing has moved from lab to a value-added service for consumers, albeit with simpler sensing capability.*)
61. **3GPP Release 19 ISAC study (SA1 Stage 1)** – *Standards technical report (TR 22.837)* – Approved Sep 2023[9]. The 3GPP SA1 working group (services) completed a **feasibility study on Integrated Sensing and Communication** as part of Release 19. The study (100% concluded by 2023) defined initial **requirements and use cases for ISAC** in future 6G networks[9]. This Stage-1 work item, code-named FS\_Sensing, lays out how networks might incorporate sensing functions and what performance metrics and scenarios (e.g. accuracy, range, types of objects) must be supported. (*Maturity: Indicates that cellular standards development has formally begun addressing ISAC, a precursor to concrete specs in subsequent releases.*)

## 62. Maturity score (1–7) and reasoning

### Proposed Score: 4 (Proof of Concept demonstrated, clear path to commercialization)

**A) Justification for score 4:** The collected evidence shows that integrated sensing-communication has moved beyond theory and isolated lab demos into **system-level prototypes and initial trials**, but is not yet a mainstream deployed capability in cellular networks. Multiple prototypes (mmWave and THz) have **demonstrated key functionality** – e.g. using 5G/6G hardware to detect humans[1], or imaging objects via a live high-frequency link[34] – proving that the once-theoretical integration is technically **feasible (ruling out Levels 1–2)**. A number of **Proof-of-Concept systems** have been built and tested in relevant environments: for instance, the NewSense field trial showed a 5G-based radar functioning on an airfield with km-range coverage[19], and the Nature Comm. device achieved joint 220 GHz sensing/comm in a compact form[31]. These successes indicate that **previous blocking issues (waveform design, hardware sharing, etc.) have been solved in principle**, consistent with Level 3. Moreover, early **commercial forays** are underway – notably, **Wi-Fi sensing features are already shipping to customers** (Comcast’s router update in 2025)[12]. This suggests that at least in niche applications, integrated sensing meets real-world requirements and is being monetized, which is characteristic of Level 4 (PoC viability and

initial market introduction). The technology's appeal is also evidenced by **major industry participation**: dozens of companies and standards bodies (3GPP, IEEE, ETSI) are investing in ISAC R&D and roadmaps[18][9], implying strong commercial motivation and a race to refine the concept – a dynamic that begins to approach Level 5.

**B) Why not a higher score:** Despite rapid progress, **fully integrated sensing-communication networks are not yet delivering broad services to end-users**, which rules out Levels 6–7. There is **no multi-vendor commercial product (beyond Wi-Fi motion detection) that offers high-resolution ISAC** – current telecom deployments (5G) do *not* include radar-grade sensing, and 6G standards are still in exploratory phases[7][8]. Level 5 would require multiple well-capitalized vendors on the cusp of production prototypes; while competition is heating up (Ericsson, Nokia, Apple, Huawei all active[35]), their efforts remain in the research or pre-standard trial stage, not final product development. For example, the **flagship demos and trials are impressive but isolated** – a cohesive ISAC infrastructure (with privacy/security frameworks, cost optimization, regulatory clearance) has yet to be proven at scale. **Key evidence missing for Level 5** includes public demonstrations of near-commercial **prototypes in operational networks** or announcements of dedicated ISAC hardware lines ready for manufacture. In short, the **core promise (e.g. city-wide 6G sensing networks)** is still several years and one 6G cycle away from realization, keeping the maturity in the advanced PoC stage (4).

**C) Sub-component maturity breakdown:**

- **Wi-Fi (WLAN) sensing integration:** *Maturity*  $\approx$  6. Wi-Fi-based motion sensing is already **delivered to consumers** by dozens of service providers (Cognitive Systems' WiFi Motion technology) and recently by Comcast[12]. Routers and mesh systems can act as home occupancy sensors with just software updates[33]. This shows economies of scale (leveraging existing Wi-Fi chips) and growing client adoption, although the sensing functionality is relatively basic (motion, presence).

- **Cellular (5G/6G) network ISAC:** *Maturity*  $\approx$  3–4. Significant **experimental milestones** have been reached – e.g. a Nokia-led PoC detected pedestrians via 5G mmWave[1], and academic teams demonstrated integrated comms & imaging in sub-THz bands[34]. There's a clear path to **standardization (3GPP Rel-19+ studies complete)[9]** and vendors plan incremental feature rollout by 5G-Advanced/6G[20]. However, current prototypes are mostly in labs or testbeds; **no carrier-grade product** or large-scale pilot has fully validated cost, durability, and performance trade-offs in the field.

- **High-frequency (mmWave/sub-THz) ISAC devices:** *Maturity*  $\approx$  3. Research prototypes (often lab-bench setups) have shown **remarkable performance** – e.g. millimeter-accurate imaging at 220 GHz[31] – breaking technical barriers. Yet, these are early-stage demonstrators; practical challenges like output power, miniaturization, and robust mobile operation remain before commercial prototypes (Level 4) emerge.

**Overall:** The **bundled ART functionality is essentially the same – using one wireless system for two purposes – but spans different scales and timelines**. We therefore weigh the maturity by the **core envisioned impact**, which lies in cellular/wide-area networks. Even though Wi-Fi sensing is more mature, its scope is narrower. Taking an average, the evidence supports **Level 4**: integrated sensing & communication is proven in concept with initial viable implementations, and standardization plus industry momentum are actively pushing it

toward production in the coming years, but full commercialization (Level 5+) is not yet attained.

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## Group 2 - Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 Compute-in-Memory & Neuromorphic Chips

1. **ART extraction**
2. *Primary capability* – **Energy-efficient AI computing by merging memory and processing:** Compute-in-memory and neuromorphic chips perform computations directly where data is stored (e.g. in-memory matrix multiplies) or using neuron-like event-driven circuits, drastically reducing data movement and idle power. This promises much higher throughput-per-watt and lower latency for data-intensive tasks than conventional CPU/GPU architectures[1][2].
3. *Key components/variants* – **(a) Analog in-memory arrays:** Non-volatile memory devices (e.g. RRAM/memristors, phase-change, MRAM) in crossbar circuits that perform matrix operations in-place via Ohm's and Kirchhoff's laws[3][4]. **(b) Neuromorphic spiking cores:** Networks of transistor "neurons" that communicate via sparse, asynchronous spikes (events), implementing brain-inspired computing (e.g. Intel Loihi, IBM TrueNorth, BrainChip Akida)[5][6]. **(c) Digital near-memory integration:** Memory chips (HBM, DRAM, etc.) augmented with logic (PIM/PNM) to process data within or close to memory banks, improving bandwidth and efficiency[7][8]. **(d) Interface & software stack:** These specialized chips are being designed as accelerators (chips or chipllets) with standard I/O and programming frameworks (e.g. Intel Lava) to integrate alongside CPUs/GPUs[2][9].
4. *Maturity indicators* – **Prototype demonstrations solving AI tasks** (e.g. in-memory analog chips running neural nets with high accuracy[10] or spiking chips handling vision/speech in real-time[6]). **Energy/performance benchmarks beating conventional hardware** (e.g. TOPS/W, latency)[11][12]. **Multiple actors and funding:** major industry R&D (Intel, Samsung, IBM) and startups producing test chips or early products[13][6]. **Pilot deployments or products:** e.g. neuromorphic chips available in developer kits or used in concept devices[14][15]. **Progress on challenges** (device variability, noise, software tools): evidence of

improved analog precision, yields, and toolchains enabling scale-up[16][17]. Successful **integration in standard fabrication** (e.g. analog memory on CMOS at advanced nodes) and plans for commercialization.

5. **Evidence (10–20 recent, reliable sources)**
6. **NeuRRAM RRAM Compute-in-Memory Chip (Nature, 08/2022):** *Chen, Wong et al. – Peer-reviewed paper.* Demonstrated a **48-core analog compute-in-memory ASIC with 3 million RRAM devices monolithically integrated on 130 nm CMOS**, achieving on-chip inference for multiple neural nets with software-comparable accuracy. The NeuRRAM chip delivered **1.6×–2.3× lower energy-delay product and 7–13× higher compute density** than prior RRAM prototypes[18], showing that in-memory analog computing can significantly improve efficiency without sacrificing accuracy[19][20]. (*Plausibility:* Validates analog AI computation on real silicon. *Maturity:* It's a complete lab prototype running diverse AI models, a key PoC.)
7. **64×64 MRAM In-Memory Computing Array (Nature, 01/2022):** *Jung et al. (Samsung Advanced Institute of Tech.) – Peer-reviewed paper.* Researchers built a **28 nm 64×64 magnetoresistive RAM crossbar** with an innovative “resistance summation” analog MAC architecture to overcome low device resistances. The chip achieved **93.23% accuracy on MNIST digit classification** (vs 95.24% digital baseline) and **93.4% on face detection**[21][10] – matching software-level performance when scaled to deeper networks[10]. *Significance:* This was **the first demonstration of in-memory analog computing with commercial-ready MRAM**, showing viability of a *non-volatile memory already in volume production* for AI computing[22][23]. (*Plausibility:* Achieved high accuracy on real AI tasks. *Maturity:* Used foundry-friendly tech, indicating a path to product.)
8. **IBM “HERMES” Analog AI Chip (Nature Electronics, 08/2023):** *Abu Sebastian et al. (IBM Research) – Peer-reviewed paper (summary in EE Times).* Describes **IBM’s 64-core in-memory inference chip with ~4 million phase-change memory (PCM) synapses on-chip**, aimed at deep neural network acceleration[24]. The HERMES prototype reached **16.1–63.1 TOPS throughput at 2.5–9.8 TOPS/W**[11]. While its energy efficiency was slightly lower than some RRAM-based accelerators, it achieved the **highest throughput-density to date – >1.8× higher** than any prior resistive-memory AI chip[25], and **achieved best accuracy on CIFAR-10** among in-memory accelerators[26]. This shows that large-scale analog chips can operate at performance levels approaching today’s digital accelerators. (*Plausibility:* High throughput neural network inference demonstrated. *Maturity:* Big industry player validating analog AI; comparing against other designs signals a competitive race.)
9. **2,048-Cell MoS<sub>2</sub> Memtransistor Crossbar (Nat. Commun., 10/2025):** *S. Das et al. (Penn State) – Peer-reviewed paper.* Demonstrated a **wafer-scale in-memory compute array using two-dimensional MoS<sub>2</sub>-based three-terminal memory transistors (“memtransistors”)**. They achieved **>92% device yield** across 2048-cell arrays, extremely low write energy (~0.2 fJ per device), and 10<sup>5</sup> read endurance[27][28]. The memtransistor’s tunable analog conductance (via gate voltage) allowed on-the-fly confidence modulation to resolve ambiguous inputs, improving inferencing without retraining[29][17]. The array successfully classified MNIST digits in hardware. *Why it matters:* This addresses analog variability by introducing gate-control and shows **thousands of analog devices can be reliably integrated**, a step toward larger in-memory networks. (*Plausibility:* New device tech achieving high yield and function. *Maturity:* Still experimental materials, but points to overcoming scaling limits.)
10. **BrainChip Akida Neuromorphic Processor in EV (EE Times, 01/2022):** *S. Ward-Foxton – Industry news.* Mercedes-Benz tested BrainChip’s Akida spiking neural network chip in its **Vision EQXX electric concept car** for ultra-low-power keyword spotting[30][6]. The

neuromorphic approach was **5–10× more energy-efficient** than conventional voice recognition, helping maximize EV battery range[6]. Mercedes stated that although neuromorphic tech “is still in its infancy,” such systems “**will be available on the market in just a few years**” and could radically cut AI energy use when scaled throughout a vehicle[31]. *Notably*, BrainChip’s Akida chip was made available on Mini-PCIe boards for integration, moving beyond demos to a product for early customers[14][32]. (*Plausibility*: Confirms spiking chips can perform real in-cabin AI tasks. *Maturity*: An actual neuromorphic chip deployed in a prototype car and offered as a product, indicating initial market entry.)

11. **SynSense “Speck” Event-Driven Vision SoC (SynSense, 06/2023):** *SynSense Inc. – Vendor technical announcement.* SynSense (Zurich/China startup) launched **Speck™, the world’s first fully event-driven neuromorphic vision SoC** combining a 128×128 pixel dynamic vision sensor with a multi-core spiking CNN processor on one chip[33]. The SoC performs always-on vision tasks (gesture, face detection, etc.) in **<10 mW and <200 ms latency**[34]. It is fully configurable with capacity of 0.32 M neurons. **Over 100 industry and academic users** are already working with SynSense’s neuromorphic hardware and software, and in 2023 the company began offering a \$199 Speck development kit for wider adoption[15]. *Significance*: This marks a **commercially available neuromorphic sensor-processor product** for ultra-low-power vision, and an active user ecosystem. (*Plausibility*: Custom spiking chips can handle real-world vision. *Maturity*: Early market traction – developer kits and dozens of pilot users signal progress toward commercial use-cases.)
12. **Samsung Memory Processing Prototypes (Samsung/Semiconductor blog, 01/2023):** *Samsung Electronics – Industry tech disclosure.* Samsung showcased its **Processing-in-Memory (PIM) and Processing-near-Memory (PNM) technologies**. A High Bandwidth Memory PIM (HBM-PIM) prototype (integrating compute into HBM2 stacks) demonstrated nearly **2× performance and ~50% energy reduction** on AI workloads versus a GPU without PIM[35]. Samsung also unveiled **CXL-PNM memory modules** for servers and an “AXDIMM” (compute-in-DIMM) with on-board AI engines, which delivered ~2× performance in database inference and 40% system energy savings in customer tests[36][37]. *Why important*: Major memory vendors are pushing memory-compute convergence into real systems – in 2022 Samsung **integrated HBM-PIM into an FPGA accelerator, boosting system performance ~2.5× and cutting energy 60%**[12][38]. This indicates a path to **near-term commercialization in data centers and mobile devices**, albeit using more digital/near-memory approaches initially. (*Plausibility*: Confirms data-movement is a real bottleneck and memory-side processing works. *Maturity*: Prototypes tested with industry partners (Xilinx, SAP); standardization efforts underway – an early stage toward productization.)
13. **High-Precision Analog Computing SoC (Science, 02/2024):** *W. Song, J. J. Yang et al. (USC & Tetramem) – Peer-reviewed paper (reported by USC).* Researchers demonstrated a **memristor-based computing System-on-Chip achieving digital-level precision** on analog hardware[39][40]. By coding one high-precision value across multiple low-precision RRAM devices with a novel error-compensating weighting scheme, they achieved “**arbitrarily high**” **precision analog computation** (up to 16-bit+) while retaining orders-of-magnitude efficiency gains[41][42]. This solution was validated on a fabricated **memristor NPU chip (11-bit per device precision) built in a standard commercial fab**[43][16]. *Impact*: It overcomes the longstanding analog accuracy barrier, showing that analog in-memory accelerators can be scaled to higher precision and manufactured in modern foundries. The work, partially done at startup Tetramem, “**signals the potential for widespread commercialization of analog computing solutions**” combining high efficiency with accuracy[16]. (*Plausibility*: Solves analog precision and variability via architecture – a critical feasibility milestone. *Maturity*: The chips were made with industry partners and indicate readiness to transition from lab to fab.)

14. **Neuromorphic Computing Outlook (Nature Commun., 04/2025): D. R. Muir & S. Sheik – Perspective/roadmap.** A broad review of recent advances concludes that **neuromorphic and in-memory computing designs are on the cusp of commercial maturity**[2] after decades of R&D. Key enablers include *digital-friendly neuromorphic designs* (replacing earlier analog neuron circuits) and *gradient-trained deep spiking networks* that ease software development[44]. The authors note **multiple ongoing projects and prototype devices** (Intel Loihi 2, IBM’s memristive chips, BrainChip Akida, SpiNNaker2, SynSense Dynap, etc.) and highlight that **the remaining hurdles are being addressed** – e.g. standardized programming models and scaling to larger applications[45][5]. They predict ultra-low-power neuromorphic processors will soon find wide use in battery-powered gadgets, edge IoT, and wearables[46]. (*Significance:* Authoritative confirmation that the field has moved from theory to practical engineering. *Maturity:* Implies that a wave of **competitive product development** is underway and that solving software and deployment issues will “clear the way to commercial success”[46].)
15. **TSMC/ITRI 10 ns SOT-MRAM Array (ISSCC 2024 report): AllPCB Tech – Industry summary (09/2023).** Reports that TSMC and Taiwan’s ITRI demonstrated a **spin-orbit torque MRAM prototype** (an advanced memory for compute-in-memory) with **~10 ns operation speed** and significantly lower power than prior STT-MRAM devices[47]. This progress in emerging memory technology indicates that **faster, more energy-efficient non-volatile memories** will be available for tightly integrated computing. *Relevance:* High-speed, low-energy NVM like SOT-MRAM could overcome the latency and endurance limits in current in-memory accelerators, aiding commercialization (e.g. enabling on-chip memory computing at cache-like speeds). (*Plausibility:* Shows hardware improvements at the device level. *Maturity:* Involvement of a leading foundry (TSMC) and demonstration on 28 nm suggests these new memory devices are nearing readiness for product integration.)
16. **Maturity score (1–7) and reasoning**  
**Final Score: 5** (Prototype proven, entering competitive development phase)

**A) Why not lower:** The core principles have moved well beyond theory (levels 1–2) – multiple **physical prototypes now exist** (analog crossbar chips, spiking neuromorphic ASICs) demonstrating functionality that clearly exceeds conventional von Neumann efficiency[18][6]. Key previously-blocking problems (e.g. analog inaccuracy) have seen **concrete solutions in hardware**[41][42], and at least one neuromorphic chip is **commercially available in developer kits**[15] – evidence surpassing a mere lab demo (level 3). Several prototypes (e.g. IBM HERMES, Samsung MRAM CIM) are effectively **PoCs meeting performance goals** (energy per operation, accuracy close to digital baselines) that hint at viable products (approaching level 4)[10][25].

**B) Why not higher:** The technology is **not yet widely deployed in end-user products or large-volume production**. While early products exist (BrainChip Akida boards, SynSense Speck kits), these serve niche or evaluation markets rather than mass adoption – indicating we haven’t reached level 6’s “products delivered in increasing amounts.” The **ecosystem is still nascent**: software toolchains and programming standards are only now coalescing[44], and integration into mainstream computing platforms remains limited to pilot collaborations (e.g. Mercedes concept car, Samsung’s tests with Xilinx/SAP)[31][12]. To reach level 6, we would expect multiple competing products shipping and clear signs of scaling production, which are not fully evident yet (e.g., **no multiple vendors selling high-volume neuromorphic accelerators**—instead we see mainly prototypes and single-source chips). The **next missing evidence** for level 6 is a **significant uptick in real-world deployment** – for instance,

neuromorphic co-processors designed into consumer devices or edge servers in volume, and production lines ramping up with economies of scale. Also needed is a broader **market pull** (growing customer demand) – market forecasts are optimistic (tens of billions by 2029)[48], but actual orders are only starting. In short, progress is rapid and several well-funded players are in the race (characteristic of level 5), but sustained commercial delivery and competition (level 6) are just on the horizon.

**C) Sub-score assessment:** This ART spans **two converging threads** – analog *compute-in-memory* and *neuromorphic spiking processors*. The **compute-in-memory** side (memristor/PCM/MRAM accelerators) is around **level 4**: laboratory PoCs like NeuRRAM and HERMES have proven functionality and even solved key technical hurdles[18][25], but they remain prototypes; no mass-market product is out yet (production and software integration challenges remain). The **neuromorphic/spiking side** is closer to **level 5**: multiple startups and large companies are actively developing chips, at least one **commercial neuromorphic chip (Akida)** is shipping in small volumes[14], and big industry names (Intel, Samsung) are investing heavily – signaling competitive development and fast-paced progress. Since these sub-technologies ultimately target *similar applications (edge AI acceleration, low-power pattern recognition)* and are often viewed as complementary (or even combinable in one system), their maturity can be aggregated. Here we lean toward the higher end (5) because **the presence of early products and multi-actor competition** indicates momentum beyond isolated lab demos. In summary, **score 5** reflects that the science is proven and functional prototypes are transitioning to pilot deployments, with numerous actors racing to deliver the first broadly adopted products – the field is **poised on the threshold of commercialization**, but full-scale product uptake is still forthcoming.

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## ART 02.010 Novel transistor technologies and materials beyond silicon CMOS

### 63. ART extraction

**A. Primary capability:** Enable digital computing components that far exceed silicon

CMOS limits in *energy efficiency, switching speed, and integration density*. These novel transistors operate at much lower power (even approaching reversible, near-zero dissipation), can be *stacked in 3D* or built into specialized subsystems (e.g. cryogenic logic), and maintain standard digital interfaces while unlocking new computing regimes (always-on ultra-low-power sensing, compute-in-memory, etc.).

#### **B. Key sub-components/variants:**

64. **Carbon nanotube FETs (CNFETs):** 1D carbon nanotube channels offering ballistic transport and  $\sim 10\times$  energy-efficiency gains over silicon, with potential for back-end-of-line (BEOL) integration[1][2].
65. **Two-dimensional (2D) material transistors:** Atomically-thin semiconductors (e.g.  $\text{MoS}_2$ ,  $\text{WSe}_2$ ) enabling extreme scaling (monolayer channels) and low off-current; can be grown or transferred onto wafers and even on flexible substrates.
66. **Spin-based logic devices: Magneto-electric** or spin-orbit devices (e.g. MESO) that use magnetization states for non-volatile logic at few 100 mV switching; promise attojoule-class operations via *voltage-controlled* magnetism[3][4].
67. **Tunnel/Single-electron transistors:** Steep-slope devices using quantum tunneling or Coulomb blockade to switch below the 60 mV/decade limit of CMOS; e.g. band-to-band tunnel FETs achieving sub-10 mV/dec slopes[5][6], or single-electron devices for ultra-low-power logic (often at cryo temps or via special structures).
68. **Reversible and superconducting logic:** Adiabatic superconducting circuits (e.g. AQFP, RSFQ) that can *recycle bit energy* and approach Landauer's limit of  $kT \ln 2$  dissipation[7][8]. Superconducting Josephson junction devices (operating at  $\sim 4$  K) switch picosecond pulses with  $\sim 10^4$ – $10^5\times$  lower energy than CMOS, enabling high-speed logic with minimal heat (at the cost of cryogenics).

**C. Maturity indicators (evidence sought):** Demonstrations of working **prototype devices and circuits** beyond theory – e.g. **lab prototypes** of transistors or logic gates with record performance (steep subthreshold swing, THz speeds, non-volatility, etc.), **integrated circuits** (ring oscillators, processors, memory arrays) built with these technologies, **wafer-scale fabrication yields** and uniformity reports, **scaling to larger arrays or 3D stacks**, involvement of **major industry consortia or roadmaps** (showing commitment to commercialization), and any **proof-of-concept system** (such as a specialized co-processor or sensor node using these transistors). Evidence of **compatibility with existing design flows or fabs** (e.g. 300 mm wafer processes, monolithic 3D integration in foundries) and of addressing reliability, variability, or cost challenges would also indicate progress toward viability.

69. **Evidence (10–20 recent, reliable sources)**
70. **Wafer-scale carbon-nanotube transistor arrays (2025)** – Yang Liu et al., *Nature Communications*, 12/2025. **(Peer-reviewed)** Demonstrates **4-inch wafer** fabrication of CNFETs with  $>98\%$  yield and high uniformity. Using solution-sorted semiconducting CNTs, they built memory-like charge-trap transistors and showed consistent performance across 300 devices (variation  $<6\%$ ). This indicates that CNT devices can be made at wafer scale with CMOS-compatible methods[9][10] – a key step toward large-scale integration. (Plausibility: high; Maturity: prototype wafer-level process)
71. **Monolithic 3D integration of CNT circuits in a foundry (2024)** – Andrew C. Yu (MIT), *PhD Thesis*, 2024. **(Technical report)** Established a **back-end-of-line (BEOL) carbon nanotube CMOS** process *inside a commercial 300 mm foundry*. Developed techniques for transferring and fabricating CNT-FETs atop silicon layers, achieving **monolithic 3D integration** of CNT logic on CMOS with improved reliability[11][12]. This shows that CNT transistors can be integrated

with existing silicon flows, paving the way for stackable logic-memory chips. (Plausibility: high; Maturity: lab/demo integration in fab)

72. **High-mobility 2D MoS<sub>2</sub> films and 2D ICs (2025)** – Ning Xi et al., *Nature Comm.*, 2025. **(Peer-reviewed)** Reported a **room-temperature processed MoS<sub>2</sub> monolayer film** (no high-temp steps) with carrier mobility up to 68 cm<sup>2</sup>/V·s, exceeding CVD-grown film mobility[13]. Achieved uniform TFT performance across an 8-inch wafer and built logic circuits: inverters, OLED drivers, and ring oscillators. The **5-stage ring oscillator reached >300 kHz** – the fastest for solution-processed 2D electronics (previous ~1 kHz)[14]. This evidences both performance and scalability improvements in 2D-material transistors. (Plausibility: high; Maturity: lab IC prototypes on wafer)
  
73. **Medium-scale flexible MoS<sub>2</sub> circuits (2024)** – Y. Peng et al., *Nature Communications*, 12/2024. **(Peer-reviewed)** Demonstrates **flexible integrated circuits** using monolayer MoS<sub>2</sub> TFTs. By improving fabrication, they achieved >90% device yield and built logic modules (NAND, XOR, latches) and a 112-transistor **clock divider** on plastic[15][16]. The circuits operate with full rail-to-rail logic swings. This exemplifies a complex IC (hundreds of devices) on 2D semiconductors, highlighting progress in device uniformity and circuit functionality at ambient conditions. (Plausibility: high; Maturity: prototype IC for niche (flexible) apps)
  
74. **300 mm wafer integration of 2D FETs (2023)** – C. J. Lockhart et al. (imec/Intel), *IEEE IEDM 2023 & imec report*, 12/2023. **(Industry roadmap/report)** imec and Intel **fabricated WSe<sub>2</sub> p-FETs on a 300 mm silicon wafer**, using a flow similar to MoS<sub>2</sub> n-FETs[17]. They analyzed grain size effects and reliability on these wafer-scale 2D transistors. This first 300 mm demonstration shows that 2D materials can be processed in an industrial fab environment, a crucial milestone for eventual high-volume manufacturing[17][18]. (Plausibility: high; Maturity: early fab-level demo, no product yet)
  
75. **Direct 2D material growth on chips (2023)** – MIT News (A. Zewe), 4/2023. **(University news, covers peer-reviewed work)** Developed a low-temperature CVD process to “**grow**” **monolayer MoS<sub>2</sub> on fully fabricated 8-inch CMOS wafers** without damaging them[19][20]. The method yields uniform 2D films in <1 hour (vs >1 day traditionally) and avoids manual transfer. This suggests 2D semiconductors can be directly integrated atop silicon circuits for high-density 3D chips[20][21]. It underscores engineering progress toward commercial integration of 2D transistors for denser, heterogeneous chips. (Plausibility: high; Maturity: process innovation at pilot scale)
  
76. **Sub-thermionic 2D/silicon tunnel FET (2022)** – J. Miao et al., *Nature Electronics*, 10/2022. **(Peer-reviewed)** Demonstrated a **heterojunction tunnel transistor** using a 2D InSe semiconducting layer on silicon, achieving **ultra-steep switching**: a 6.4 mV/decade subthreshold slope (average 34 mV/dec over 4 decades) and I<sub>ON</sub>/OFF ≈ 10<sup>6</sup>[22][5]. On-state current was 0.3 μA/μm @ V<sub>D</sub> = -1 V – low, but a clear proof that band-to-band tunneling in 2D materials can overcome the CMOS 60 mV/dec limit at room temperature. This validates the scientific feasibility of ultra-low-voltage logic devices. (Plausibility: high; Maturity: device concept proven in lab, needs higher drive current)
  
77. **Voltage-controlled spin logic (MESO) device (2024)** – M. Salamanca-Riba et al., *Nature Communications*, 2024. **(Peer-reviewed)** Researchers built a **magneto-electric spin-orbit (MESO) nanodevice**, the first experimental MESO implementation. A BiFeO<sub>3</sub> multiferroic was used to switch a coupled ferromagnet with <5 V pulses, and a Pt/CoFe spin-Hall structure read out the magnetization electrically[3][23]. They showed reversible 180° magnetization switching by purely electrical means and distinct output voltages for the two magnetic states. This confirms the MESO principle (voltage-driven, non-volatile logic at potentially ~attojoule



energies) in a prototype device[3][24]. (Plausibility: medium; Maturity: fundamental device demo, one bit)

78. **48,000-Josephson-junction superconducting circuit (2022)** – J. Strong et al., *Nature Electronics*, 3/2022 & *TechXplore*, 4/2022. **(Peer-reviewed & news)** Northrop Grumman built a **Reciprocal Quantum Logic (RQL) test chip** with 48k Josephson junctions operating at 3.5 GHz[25][26]. They implemented a novel metamaterial clock distribution network to deliver uniform AC power across a 3×3 mm<sup>2</sup> chip (<1 dB variation) at ~30% energy efficiency[27][28]. This demonstrates that **large-scale superconducting logic VLSI** is technically feasible, addressing a key bottleneck (clock/power delivery) for scaling up to millions of junctions. (Plausibility: high; Maturity: proof-of-concept computing fabric, still experimental and cryogenic)
79. **Reversible cryogenic logic near Landauer limit (2025)** – Q. Herr (imec), *arXiv preprint*, 4/2025. **(Preprint – simulation study)** Analyzes **adiabatic quantum-flux-parametron (AQFP)** superconducting logic with realistic variations. Shows that by copying inputs and using a “terminate” gate, logic operations can dissipate only ~7× the Landauer limit (kT ln2 per bit) even with 1% device parameter spread[7][29]. Idealized circuits can approach true reversible computing with energy dissipation proportional to information lost[30][31]. This suggests *in principle*, superconducting adiabatic circuits could perform complex logic with negligible heat – highlighting a path to ultra-efficient (level 1) computation if manufacturing challenges are solved. (Plausibility: medium; Maturity: theoretical validation, experimental verification pending)

#### 80. Maturity score (1–7) and reasoning

##### A. Final score: 3 (Laboratory prototype demonstrated).

**B. Justification:** The evidence shows that fundamental feasibility has been **proven in the lab** for all major variants – many have working prototypes solving previously blocking issues, but none are yet at a proof-of-concept *product* level. Level 3 corresponds to “a laboratory prototype demonstrated... key problems solved, functionality achieved, but production and durability issues remain.” This fits well:

- **Level 2 ruled out:** We have gone beyond mere principle demonstrations – e.g. CNT transistors are not only theory or one-off devices; a **16-bit microprocessor with 14k CNFETs** was built (2019) and recently **wafer-scale CNT device arrays with 98% yield** were shown[9]. Similarly, sub-thermal **TFETs** and **MESO spin devices** are experimentally realized[5][3]. These successes indicate progress past the initial “model verified in lab” stage; we are now engineering functional circuits, marking at least Level 3.
- **Why not Level 4?** Level 4 (proof-of-concept meeting *commercial* viability metrics) isn’t reached because none of these technologies yet meet **all the practical requirements** for commercialization in real products. For instance, **CNT chips** still face scaling and uniformity limits (the 16-bit CNFET CPU operated at kilohertz speeds on older nodes[2], and while manufacturing issues like metallic CNT removal are greatly improved[32][33], CNT CMOS is not yet beating silicon CMOS performance). **2D FETs** have been made on 300 mm wafers[17] and even stacked on CMOS[20], but device variability, contact resistance, and low drive currents persist[18]. No 2D or CNT logic has shown clear *cost or performance superiority* over incumbent tech in an actual application – a criterion for Level 4. **Spin logic (MESO)** is at a very early device stage (one-bit cells in lab) and **superconducting circuits** – despite large prototypes – remain impractical beyond niche uses due to cryogenic overhead (no commercial computer built from 50k JJ RQL yet). Essentially, each sub-tech is *motivated* by clear benefits

(e.g. steep slopes, non-volatility, no Joule heating), but **collectively** they are still solving integration and reliability challenges rather than approaching product rollout. There are not yet “production prototypes” or multiple companies racing to commercialize general-purpose CNT or 2D logic – development is mostly in consortia and research labs (industry roadmaps target ~2030+ for deployment[34]). Thus Level 4 – which requires a demonstrated viable product prototype or clear commercial path – is premature.

**C. Sub-score assessment by variant:** *(We consider the bundle’s application as extending digital logic – so we will average the maturity, as different approaches address similar needs in different ways.)*

- **Carbon nanotube FETs:** *Maturity ~3.* Demonstrated in complex circuits (a microprocessor, analog sensor interfaces)[2], and recently integrated in 3D with CMOS[11]. Key material issues (purity, alignment) largely solved, but needs higher speed and industry adoption.
- **2D material transistors:** *Maturity ~3.* Shown to work in medium-scale circuits[15] and scaled to 300 mm wafers[17]. However, performance (drive current) and device variability need improvement; no commercial 2D logic products yet.
- **Spin-based (MESO) logic:** *Maturity ~2.* Only basic devices and small gates in lab[3]; significant work remains to integrate these at scale or room temperature. Backed by Intel research, but no prototype circuits beyond few devices.
- **Tunnel/steep-slope devices:** *Maturity ~2–3.* Steep TFETs have been made with record swings[5], but on-currents are low and no large-scale integration yet (some TFET CMOS demonstrators exist, but not outperforming MOSFETs in practice). Single-electron transistors are mostly at physics experiment stage.
- **Superconducting & reversible logic:** *Maturity ~3–4 (in niche).* Superconducting digital tech (RSFQ/AQFP) has functioning prototypes – e.g. a 64-bit SFQ processor (demonstrated under DARPA’s program) and the 48k-JJ circuit[27]. These show fast progress (approaching Level 4 for certain niche computing like quantum annealers or specific accelerators). But as a general CMOS replacement, they are held back by infrastructure (cooling) and have not entered mainstream products. Reversible computing remains theoretical, though experiments indicate it’s within reach of superconducting tech[7][29] (yet no practical reversible CPU exists).

**Aggregation:** Since these approaches aim at the *same functionality* (improving digital logic performance/efficiency) and could be combined in future chips, we consider the **average maturity ~3**. The *overall ART* is at **lab prototype stage**: we have convincing demonstrations that break CMOS limits (proving plausibility), but **no commercial-ready device** yet. To reach Level 4, we would need, for example, a prototype processor or sensor node built with beyond-CMOS transistors that clearly outperforms a silicon equivalent *and* is close to manufacturable. Evidence missing for Level 4 includes: **high-volume reliability data, standard EDA integration, cost analysis, and commitments to productize** (e.g. a foundry announcing a post-CMOS node). Current efforts are promising but still in the R&D pipeline, justifying the maturity score of **3**.

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## ART 02.011 Quantum Computing Platforms

### 1. ART extraction

**A) Primary capability** – Quantum computing platforms promise **massively parallel computation via quantum superposition/entanglement**, exploring vast solution spaces faster than classical supercomputers for certain problems (e.g. combinatorial optimization, high-dimensional pattern search, quantum system simulations). They leverage interference among many quantum states to perform calculations that scale beyond classical capabilities. These platforms also **integrate quantum processors with classical infrastructure**, functioning as specialized accelerators accessible through standard software interfaces (e.g. cloud APIs) so that users can run quantum algorithms remotely on complex problems that are infeasible to brute-force classically.

**B) Key sub-components or variants** – Multiple hardware approaches are being pursued for qubit implementation, including:

- **Superconducting qubits (circuit QED):** nano-fabricated Josephson junction circuits operating at ~10–20 mK in dilution refrigerators, controlled by microwave pulses (e.g. IBM, Google devices). This approach offers fast gate speeds and is currently the most mature in qubit count (tens to hundreds of qubits).
  - **Trapped-ion qubits:** individual ions confined in electromagnetic traps (ultra-high vacuum) and manipulated with laser or RF pulses. These qubits have long coherence and high fidelity (extremely low error rates) and flexible connectivity (e.g. IonQ, Quantinuum systems).
  - **Photonic qubits:** single photons or squeezed light states traveling through optical circuits of beam splitters, phase shifters, and detectors. Photonic processors operate at room temperature and naturally interface with fiber networks (e.g. Xanadu's photonic chips), and have demonstrated specialized sampling tasks leveraging many-mode interference.
  - **Topological qubits:** emerging approach encoding qubits in exotic quantum states (e.g. Majorana zero modes in topological superconductors) that are inherently protected from certain errors. This is pursued by research teams (e.g. Microsoft Station Q) with the goal of greatly improved stability, though it remains at a nascent experimental stage.
  - **Semiconductor spin qubits:** electron or nuclear spins in quantum-dot devices on silicon or GaAs chips, controlled by gate electrodes similarly to transistors. This leverages mainstream CMOS fabrication for potential scalability (e.g. Intel and academic groups have 2–6 qubit prototypes), though currently with smaller qubit counts and challenging control crosstalk.
- (Additionally, all platform variants require)\* a classical control stack\*\*** (high-speed electronics, cryogenics, lasers, etc.) to initialize, manipulate, and read out qubits with precise timing. The quantum processor is tightly integrated with classical CPUs/FPGA controllers for real-time feedback, error correction circuits, and a software layer (quantum compilers, schedulers, etc.) that translates high-level programs into low-level pulses.

**C) Maturity indicators** – Evidence of progress toward a viable quantum computing platform would include:

- **Demonstrations of quantum advantage:** clear experimental proof that a quantum

processor can solve a well-defined task faster than the best classical algorithms on the world's fastest supercomputers. (E.g. random circuit sampling or boson sampling experiments showing orders-of-magnitude speedups.) Such results bolster plausibility that these machines indeed access a computational regime beyond classical reach.

- **Scaling of qubit count and quality:** prototypes moving from few-qubit demos to devices with tens or hundreds of qubits while maintaining high coherence times and high gate fidelities. Key metrics include two-qubit gate error rates below the ~1% (or even ~0.1%) level, and system-level measures like quantum volume or circuit depth achieved. Increasing qubit connectivity (or modular linking of processors) and improved fabrication yields are also important for scalability.

- **Quantum error correction milestones:** evidence that logical (error-corrected) qubits can outperform physical qubits. For instance, demonstrations of encoding a logical qubit in many physical qubits and achieving a lower error rate than a single qubit, or creation of multiple logical qubits with basic operations. Successful error correction is a strong sign that the platform can eventually scale to fault-tolerant, large computations.

- **Prototype integration and field trials:** quantum computers operating outside of a single lab setting – e.g. deployed in data center environments or integrated with supercomputing facilities. Early **cloud services** (such as IBM Quantum or Amazon Braket) giving remote access to quantum hardware, or on-premises installations (in national labs or industry R&D centers), indicate progress toward practical use and reliability (cooling, control electronics, uptime) in real-world conditions.

- **Growing ecosystem & investment:** multiple well-funded companies and government programs racing to build better quantum processors, indicating that the technology has moved beyond a lone research curiosity. Evidence of substantial private and public R&D investment, startup commercialization (some companies going public or selling services), and collaborations (consortia, roadmaps, standardization efforts) all point to increasing maturity and confidence in eventual payoff.

- **Initial end-user applications or partnerships:** instances where quantum computers (even with their current limitations) are applied to non-trivial problems in science or industry via pilot projects. For example, using a quantum processor to explore drug molecule interactions, optimization in finance, or secure communications, in partnership with domain experts. Also, dedicated facilities (e.g. a quantum computer installed for healthcare research) suggest that early adopters see enough promise to invest in on-site hardware and workforce training.

## 2. Evidence (10–20 recent, reliable sources)

3. **IBM Unveils 433-Qubit Osprey Chip** – Charles Q. Choi (*IEEE Spectrum*) – Nov 2022. (**Peer-reviewed tech magazine news**) – IBM demonstrated a 433-qubit superconducting processor (“Osprey”) – more than **3× the qubit count of its 127-qubit predecessor** – suggesting they remain on track for a >1000-qubit device the following year<sup>[1][2]</sup>. To achieve this scale, IBM introduced a multi-layer wiring and cryogenic packaging design that protects fragile qubits and significantly increases control signal density. Notably, the new system can **control >400 qubits per rack of electronics (versus ~40 qubits per rack previously)** thanks to custom cryo-CMOS controllers<sup>[3]</sup>, highlighting engineering progress in scaling up quantum processors. (*This indicates the feasibility of building large quantum machines and a roadmap toward “quantum-centric supercomputers.”*)



4. **Suppressing quantum errors by scaling a surface code logical qubit** – *Google Quantum AI (Nature)* – Feb 2023. **(Peer-reviewed research)** – Google’s team showed the first **experiment where a larger quantum error-correcting code outperformed a smaller code**, a critical proof of concept for fault-tolerance. Using a **72-qubit superconducting chip**, they implemented a distance-5 surface code (49 physical qubits) and measured a logical error rate of **~2.9% per cycle**, slightly better than the ~3.0% per cycle for a distance-3 code (17 qubits) on the same device[4]. In other words, adding qubits *reduced* the error – a milestone indicating their physical qubit fidelity is above the threshold required for error correction[5]. *This result demonstrates plausibly that quantum computers can be scaled with manageable error rates, as the logical qubit’s performance improved when more qubits were used for encoding, something essential for building larger, reliable quantum processors.*
5. **Accelerating Towards Fault Tolerance: Unlocking 99.99% Two-Qubit Gate Fidelities** – *IonQ Inc., technical blog* – Oct 2025. **(Preprint/tech report by industry)** – Trapped-ion startup IonQ announced it has achieved **99.99% two-qubit gate fidelity** (“four nines”) on its latest system[6] – the highest reported to date. This landmark crosses a key error threshold for practical quantum error correction, and IonQ did so with a novel technique avoiding slow ground-state cooling, thus maintaining speed[6][7]. Such ultra-high fidelity gates reduce logical error rates by orders of magnitude, directly supporting the feasibility of scaling to larger, fault-tolerant quantum computers. *(This provides strong evidence of technical plausibility – a solution to what was a blocking error-rate problem – and indicates maturity as IonQ and others now target system scaling with these reliable gates.)*
6. **Quantinuum 56-Qubit System Breaks Benchmark** – *Quantinuum (press release)* – June 2024. **(Industry press, experimental result)** – Quantinuum (formed by Honeywell & Cambridge Quantum) unveiled a **56-qubit trapped-ion quantum computer (H2-1)** that achieved a **random circuit sampling task 100× faster** than Google’s 2019 “supremacy” experiment[8]. Crucially, this device combines relatively high qubit count with **“three nines” fidelity (99.9% two-qubit gate fidelity across all pairs)**[9] – a first in any quantum system – enabling record system-level performance. They also demonstrated the creation of **4 logical qubits with error correction** on this machine[9], showing that both scale and error rates have progressed to where fault-tolerant techniques are beginning to work. *(This illustrates rapid progress in the ion-trap approach, with a competitive, well-capitalized actor achieving both quantum advantage and steps toward error-corrected qubits in a commercial device.)*
7. **Xanadu’s Borealis Photonic Quantum Advantage** – *L. Madsen et al., Nature & Photonics Spectra summary* – June 2022. **(Peer-reviewed experiment + industry news)** – Canadian startup Xanadu demonstrated **quantum computational advantage** using a photonic processor called *Borealis* with **216 squeezed-light qubits**. The machine generated outputs from a Gaussian boson sampling problem in **36 μs, whereas the best classical supercomputer would take an estimated 9,000 years**[10] – a  $\sim 10^7$  speedup. Importantly, Borealis is fully programmable in its interferometer configuration and was made **publicly accessible via cloud** (Xanadu Cloud/AWS), making it the **first photonic quantum computer to achieve advantage available to outside users**[11][12]. *This provides evidence that photonic approaches, though less mature in general-purpose algorithms, are scientifically feasible and can be integrated into cloud platforms, supporting the ART’s plausibility (through a specialized task) and hinting at a future where such photonic modules might be part of quantum data centers.*
8. **Eight-Qubit Topological Quantum Processor (Majorana qubits)** – *Microsoft & UCSB (Nature paper via Phys.org)* – Feb 2025. **(Peer-reviewed & institutional press)** – A team from Microsoft and UC Santa Barbara announced the first-ever **topological quantum computing device**: an 8-qubit chip using **Majorana zero modes** in a superconducting heterostructure[13]. This

proof-of-concept “Majorana 1” processor demonstrated the creation and control of Majorana-based qubits, effectively **observing a new topological superconducting phase** that shows the predicted stability (distinct lifetimes for topological qubit states)[14]. While only a small prototype (described as an “embryo” of a quantum computer), it marks a *major scientific milestone* – proving the topological qubit approach is experimentally real and can perform quantum operations quickly and accurately[14]. *This evidence underscores the plausibility of eventually achieving inherently fault-tolerant qubits; however, the topological platform is clearly behind other approaches in maturity (still at lab demonstration stage, though backed by a major tech company’s long-term effort).*

9. **Full control of a six-qubit quantum processor in silicon** – S. Philips et al., QuTech/Delft (Nature) – Sept 2022. **(Peer-reviewed experiment)** – Researchers at QuTech (Netherlands) built a **6-qubit quantum chip in silicon** (using electron spins in quantum dots) and achieved **universal quantum logic with low error rates** on all qubits[15][16]. This is a record number of silicon spin qubits operated together; they implemented high-fidelity single- and two-qubit gates and improved state preparation and readout techniques, all in one device. Notably, they maintained performance as qubit count increased – **a major step toward fault-tolerant quantum computers using silicon fabrication**[17]. *This evidence shows the feasibility of an alternate, CMOS-compatible qubit technology and demonstrates that key hurdles (crosstalk, calibration, etc.) can be overcome for a multi-qubit silicon device. It also diversifies the quantum hardware ecosystem, indicating a broader race across platforms (industry + academia) to realize scalable qubits.*
10. **Jülich integrates a quantum computer into an HPC center** – FZ Jülich/QSolid (DataCenter Dynamics news) – Nov 2025. **(Industry news, deployment evidence)** – In Germany, a **10-qubit superconducting quantum prototype** developed by the QSolid consortium was **integrated into the Jülich supercomputing center’s infrastructure (JUNIQ)**[18]. In a late-2025 field test, the quantum machine was made available via the center’s cloud portal to external users for two weeks[19]. This represents one of the first instances of a quantum computer operating as part of a high-performance computing facility, allowing hybrid quantum-classical workflows. *This evidence demonstrates growing maturity: quantum hardware is leaving isolated labs and being treated as an operational resource in a data center environment, with collaborations (26 institutions in QSolid) focusing on system integration and user access. It also reflects government-backed efforts (EU/Germany) to build domestic quantum technology and link it with existing computing infrastructure.*
11. **IBM Delivers Quantum System One to Cleveland Clinic** – Cleveland Clinic Newsroom – March 2023. **(Industry press, deployment evidence)** – IBM and Cleveland Clinic unveiled the **first on-site, private-sector quantum computer**, an **IBM Quantum System One installed at a client location**[20]. This 127-qubit system is dedicated to healthcare research – the **first quantum computer in the world focused on a single industry application (biomedical)**[20]. The deployment is part of a 10-year Cleveland Clinic–IBM partnership to accelerate drug discovery and genomics via quantum computing. *This source indicates a significant maturity milestone: a quantum computer has moved from a vendor’s lab to a customer’s facility as a delivered product/service (albeit IBM-maintained). While still very expensive and early-stage, it shows that quantum computers are being treated as valuable tools for domain research, and that institutions are investing in quantum capabilities in anticipation of future advantages.*
12. **USTC’s Zuchongzhi-3: 105-Qubit Quantum Processor** – Pan et al., Physical Review Letters & USTC News – Mar 2025. **(Peer-reviewed physics result)** – A Chinese research team (USTC) announced Zuchongzhi-3, a **105-qubit superconducting processor** integrating 182 couplers, which performed quantum random circuit sampling **10<sup>15</sup> times faster than the fastest supercomputer**[21]. This greatly exceeded Google’s prior experiments and established the

strongest claimed quantum advantage to date in a superconducting system. The chip achieved **coherence times ~72  $\mu$ s and high fidelities (~99.9% single-qubit and 99.62% two-qubit gates)**[22], enabling an 83-qubit, 32-layer random circuit sampling that outpaced the best classical simulation by *15 orders of magnitude*. The team also reported implementing a **distance-7 surface code** on this device as a test toward quantum error correction, with plans to scale to distance-9 and -11[23]. *This provides evidence of both scientific and engineering maturity: USTC has reached 100+ qubit scales with performance near error-correction thresholds, and they are now focusing on error mitigation. It also highlights global competition – multiple countries’ teams (China, US, EU) have built cutting-edge quantum processors – a hallmark of a maturing field.*

### 13. Maturity score (1–7) and reasoning

#### Proposed Maturity Score: 5 (out of 7).

**A) Justification:** Quantum computing platforms as described are **beyond proof-of-concept (Level 3)** and even beyond a single functional prototype demonstration (Level 4); they are now in the **early competitive development stage (Level 5)**. Multiple well-funded players (IBM, Google, Amazon, Intel, Microsoft, IonQ, Quantinuum, etc.) are **actively building and iterating on prototypes**, and there is a **clear race to scale up qubits and reduce errors**, backed by significant investment and rapid technical progress. The evidence above shows that **key feasibility hurdles have been overcome** – e.g. high-fidelity operations (99.9%+ gates[9][6]), some algorithms beating classical performance[8][10], and integration of quantum hardware into cloud and research workflows[20][19]. This means the field is no longer just exploratory science (Levels 1–3), but is moving toward engineering for scalability and real-world use (Level 5). Crucially, **multiple quantum computing firms now offer devices as a service** to external users, and even deliver systems to partners, indicating that we are *post-“proof of concept”* – consistent with Level 5 where well-capitalized actors compete to develop production-worthy prototypes. Recent roadmaps (IBM aiming for 1000+ qubits by 2025, etc.) and the formation of large consortia (EU Quantum Flagship, US National QIS programs) further underscore this fast-paced progress and commitment to commercialization.

**B) Why not a higher score?** The technology is *not yet at Level 6*, because **quantum computers are not broadly delivered products with growing customer demand** – they remain costly, specialized installations primarily used in research or as cloud-based demonstrations. For Level 6, we would expect routine delivery of quantum computers, significant cost reduction, and expanding practical applications. In reality, today’s quantum systems still have limited qubit counts (tens to a few hundred, often with no error correction), very high operating costs (cryogenics, vacuum, etc.), and they can only solve certain niche problems that are carefully chosen. There is **no wide adoption in industry yet** – rather, early adopters are testing the waters via partnerships and pilot projects. Additionally, fully error-corrected, large-scale quantum computers (needed for many envisioned applications) have *not* been realized; the evidence shows progress in error correction but logical qubits are still error-prone and overhead is massive[4][9]. Thus, the **platform is not at the product maturation stage** where one could be deployed like classical computers with “increasing amounts” and ROI – it’s best seen as entering the late-prototype/early-adoption phase.

**C) Sub-component analysis:** The overall ART “Quantum Computing Platforms” encompasses several hardware approaches at slightly different stages, but their **functional goal is the**



**same (accelerating computation via quantum mechanics)**, so we assess maturity in aggregate by the leading edge. The **most advanced implementations (superconducting and trapped-ion)** merit a Score 5: for example, IBM and Google’s superconducting qubits have achieved quantum advantage experiments and are rapidly scaling devices[1][22], and IonQ/Quantinuum’s ion-trap systems boast record fidelities and have commercial cloud access[6][8]. These platforms have moved from lab experiments to multi-qubit prototypes used by external users, aligning with the “production prototype under intense development” description of Level 5. **Photonic quantum computers** have demonstrated a specialized advantage (boson sampling) and are available via cloud (Xanadu), but have not shown general-purpose algorithms or error correction – they are slightly earlier in maturity (around Level 4) yet do not fundamentally change the overall score since photonics targets similar use-cases and is racing forward as well[12][10]. **Emerging approaches like topological qubits** are far behind (Level 2–3, still proving basic viability[13]), but these serve as long-term bets and are not required for near-term quantum computing success given progress in more mature modalities. Considering all threads, the field’s center of gravity is solidly at Level 5 – multiple prototypes exist solving previously intractable tasks and attracting competition – but **has not yet reached Level 6** where quantum computers are a practical commodity delivered to many customers. Therefore, **Score 5** best represents the current maturity: *a disruptive technology in the late-prototype stage with active competition and clear momentum toward commercialization, but still awaiting its first broadly practical products and scalable manufacturing breakthroughs.*

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## ART 02.012 Photonic and Optical Computing

### 17. ART extraction

18. *Primary capability* – **Light-based computation and data movement:** Using photons instead of electrons to perform computing operations and chip-to-chip interconnect, aiming for **vastly higher bandwidth and lower energy/heat** than electronic circuits[1][2]. This allows processing more data with less latency and within tighter power/cooling limits than conventional electronics.

19. *Key sub-components & variants:*

- **Chip-scale photonic processors/cores:** Specialized optical units (e.g. matrix-multiplication “tensor cores”) performing neural-network computations or optimizations via interference, modulation, and wavelength multiplexing[1][3]. Often hybrid designs: photonics handle large parallel linear operations while electronics provide control and non-linear functions.
- **Ultra-dense optical interconnects:** Integrated photonic links (waveguides, fiber, modulators) connecting CPUs, accelerators, and memory with extremely high bandwidth (>1–4 Tb/s) at low latency and distance-independent energy cost[2][4]. This includes *in-package optical I/O chiplets* and co-packaged optics for next-gen data centers, enabling disaggregated memory and processor pools.
- **Hybrid electro-optic modules:** Packaging of photonic chips with CMOS control/logIC. Electronics handle programmability, storage, and precise logic; optical components accelerate data-heavy operations and communications. Examples include 3D-integrated packages with multiple photonic and electronic dies interconnected for AI acceleration[5].

20. *Maturity indicators (evidence to look for):*

- **Lab demonstrations of core feasibility:** e.g. optical matrix-multiplies, photonic neural nets or optical Ising solvers outperforming electronic baselines, with metrics like TOPS/W or latency showing a clear advantage[6][7].
- **Integrated prototypes meeting application needs:** Complete photonic computing systems solving real AI tasks (image recognition, NLP, etc.) with accuracy close to digital and reasonable precision (4–8 bits analog)[8]. Prototype optical interconnects moving real data between chips in HPC setups[4].
- **Transition toward productization:** Proof-of-concept **optical processors and interconnects operating in practical environments**, e.g. installed in supercomputers or edge devices, or demonstrated in standard form factors (PCIe cards, chip packages)[2]. Signs of **well-funded startups and industry players** (multiple companies, large investments, partnerships) racing to commercialize optical computing components.
- **Manufacturing and integration progress:** Advances in photonic chip fabrication (silicon photonics, new materials) enabling scale and reliability – e.g. foundry-compatible processes for on-chip lasers or non-volatile optical memory[9]. Roadmaps from industry consortia or labs outlining clear performance targets and volume deployment within a decade[10].
- **Early deployments and shipments:** Evidence of optical computing hardware being **delivered to pilot customers** or integrated into existing systems, with improving economies of scale. For example, optical I/O modules shipping with FPGAs or AI systems, and photonic co-processors available via cloud or as appliances (even if in limited beta).

21. **Evidence (10–20 recent, reliable sources)**

22. **Photonic AI processor runs real AI models (Nature, 2025)** – Sufi R. Ahmed et al. (*Lightmatter Inc.*), peer-reviewed article, Apr 2025. A silicon photonic processor (6-chip 3D-integrated package with ~50 billion transistors and 1 million photonic components) was demonstrated to **run state-of-the-art neural networks (ResNet image classifier, BERT language model, DeepMind’s Atari RL)** with accuracy **approaching 32-bit digital electronics**[8][5]. It achieved 65.5 trillion ops/sec at ~80 W (1.6 W optical power) – a major milestone proving that photonics can handle complex AI workloads with performance and precision near conventional GPUs, marking a “substantial step towards post-transistor computing”[8].
23. **64×64 photonic computing chip beats GPU in latency (Nature, 2025)** – Shiyue Hua et al. (*Lightelligence & Stanford*), peer-reviewed article, Aug 2025. This work built a **highly integrated 64×64 optical matrix accelerator** (~16,000 photonic components on-chip) for solving an Ising optimization (MaxCut) problem. It attained **~7.6-bit analog computation accuracy** and achieved the solution **in 2.7 μs, over 300× faster latency than a high-end GPU (798 μs)** on the same task[6][11]. This validates that large-scale silicon photonic circuits can be reliably fabricated and can outperform electronic computation in speed for specific workloads, using **commercial silicon photonics technology** and hybrid electronic control[1].

24. **“Taichi” photonic chiplet – 160 TOPS/W AI engine (Science, 2024)** – Zhihao Xu et al. (Tsinghua University), peer-reviewed article, Apr 2024. A Chinese research team demonstrated “Taichi”, a **large-scale photonic neural network chiplet** that achieved **160 Tera-OPS per Watt energy efficiency** and **~879 Tera-MACs/mm<sup>2</sup> area density**, exceeding state-of-art electronic AI chips by 2–3 orders of magnitude in those metrics[12]. Uniquely, it implemented an optical network with **billions of neurons** (via diffraction and interference in a 64×64 input/output optical array) and successfully performed complex tasks: e.g. **1,623-category image classification (91.9% accuracy)** and **100-class mini-ImageNet classification (87.7% accuracy)** – the first time an optical chip tackled thousand-class vision tasks[13][12]. This massive scalability and efficiency showcase the plausibility of photonic processors to go beyond simple demos toward “beyond-billion-neuron” AI models in the future.
25. **All-optical neural network with on-chip training (Nat. Photonics, 2024)** – Farzin Ashtiani et al. (Univ. of Pennsylvania), peer-reviewed article, Dec 2024. Demonstrated a **single-chip photonic deep neural network** that not only performs inference but also supports *in situ* training (forward-only training method). The silicon photonic chip, containing dozens of programmable interferometers, achieved **92.5% accuracy on classification tasks** and could execute an inference in **only 410 picoseconds** optical latency[14]. This result shows that integrated photonic circuits can reach competitive accuracy on real datasets and operate at **nanosecond-scale inference speeds**, albeit currently on smaller-scale networks – a promising path to ultrafast, low-energy AI inference.
26. **Optical AI accelerator for wireless edge (Science Advances, 2025)** – Dirk Englund’s group (MIT), peer-reviewed article reported via MIT News, Jun 2025. Researchers built a photonic hardware accelerator aimed at 6G wireless signal processing. The **optical chip classifies radio signals in nanoseconds**, achieving about **100× faster throughput than the best digital signal processor**, while still reaching ~95% classification accuracy[7]. The device is also smaller, lighter, and more energy-efficient than conventional AI edge hardware[7]. This *edge photonic processor* illustrates the feasibility of deploying optical computing beyond the lab – in this case to enable real-time spectrum management or potentially autonomous vehicle sensors – where its **speed-of-light parallelism yields tangible system-level benefits**.
27. **Analog optical computing for AI and optimization (Nature, 2025)** – Kirill Kalinin et al. (Microsoft Research Cambridge et al.), peer-reviewed article, Sep 2025. This work introduces an **analog optical computer (AOC)** that combines **free-space 3D optics with analog electronic feedback** to solve both neural network inference and combinatorial optimization without digital conversions. The system uses a **fast 20 ns optical/electronic loop** where optical components handle large matrix-vector multiplications and electronics apply nonlinearities and feedback[3]. In prototypes, it successfully performed image classification, medical image reconstruction, and even a financial transaction optimization problem on the same hardware[15]. Built largely from scalable, “consumer-grade” components, this AOC achieved significant speed-ups and highlights a co-design approach (algorithm and hardware) to overcome noise and precision issues in analog photonic computing[15][3]. Its demonstration of a *single platform tackling AI and NP-hard optimization* underscores the versatility and plausibility of optical analog computing for future ultra-efficient processors.

28. **4 Tb/s optical I/O chiplets in FPGA (Ayar Labs & Intel, 2023)** – *Ayar Labs press release, Nov 2023 (Supercomputing '23 showcase)*. Ayar Labs demonstrated an **Intel Agilex FPGA with two “TeraPHY” optical I/O chiplets integrated**, delivering an aggregate **4 Tbps bidirectional bandwidth** (2×4 Tb/s) via 64 optical channels per chiplet[2]. The optical FPGA achieved **5× the I/O bandwidth of conventional electric links, with <5 pJ/bit energy and only ~5 ns latency** per optical hop[2]. This is a concrete industry result showing that in-package photonic interconnects can drastically boost throughput while reducing latency and power. Notably, the optical links operated error-free over fibers and were powered by compact multi-wavelength semiconductor laser modules – proving maturity in the **packaging and integration** of photonics with standard electronic chips for HPC/AI use. (The company noted that optical I/O “has the maturity and manufacturability” for upcoming high-performance systems[16].)
29. **Intel’s co-packaged optical interconnect demo (Intel, 2024)** – *Intel Integrated Photonics Group, technical press release, OFC Mar 2024*. Intel reported the **first fully integrated optical compute interconnect (OCI) chiplet** co-packaged with a CPU, running live data[17]. The prototype optical I/O chiplet carried **64 channels × 32 Gbps each (≈2.0 Tb/s per direction)** and supported links up to 100 m fiber length[4]. This breakthrough enables future CPUs/GPUs with optical I/O for memory pooling and resource disaggregation, far exceeding the reach and bandwidth density limits of copper—“boosting bandwidth, reducing power consumption and increasing reach” for AI systems[18][4]. Intel’s demo underscores that major industry players are actively de-risking the manufacturing (co-packaging, alignment, etc.) and proving out reliability of optical interconnects in realistic environments, a critical step toward commercialization in data centers.
30. **Heterogeneous photonic integration with non-volatile memory (Nat. Commun., 2024)** – *Maoliang Wei et al. (Zhejiang Univ. & Westlake Univ., China), peer-reviewed article, Mar 2024*. This study tackled a key fabrication challenge: integrating new materials for optical computing on a CMOS photonics platform. The team developed a foundry-compatible process (“zero-change” backend integration) to add **chalcogenide phase-change materials (PCMs)** into silicon photonic chips[19][20]. They successfully incorporated two PCMs (Sb<sub>2</sub>Se<sub>3</sub> and GSST) to create **non-volatile optical tuning devices** that require **no power to hold state**. Using these, they realized compact optical switches and attenuators with multi-bit precision – e.g. microring filters with **>5-bit intensity control and broadband attenuators with >7-bit depth**, as well as a 48% reduction in power for trimming a Mach-Zehnder switch thanks to non-volatile phase correction[9]. This is important evidence of progress in **optical memory and reconfigurability**: it shows that high-precision optical weights or settings can be built and *monolithically fabricated* at scale, addressing bottlenecks of power-hungry tuning and enabling programmable photonic circuits for computing.
31. **Silicon photonics roadmap highlights computing era (Perspective, 2024)** – *Sudip Shekhar, Wim Bogaerts et al., Nature Communications perspective, Jan 2024*. Leading researchers outline the next generation of silicon photonics, noting that after revolutionizing datacenter transceivers, the field is now entering an era of **Large-Scale Integration (LSI)** with **500–10,000+ photonic components per chip**[10]. They cite emerging applications like **photonic computing, switching, and LiDAR** as drivers for this complexity, and point out that even **VLSI prototypes (>10k components) have been demonstrated** in labs[10]. Crucial challenges identified include integrating on-chip light sources, improving photonic packaging, and co-designing



electronics–photonics for better yield and performance[21][22]. This authoritative roadmap confirms strong academic and industry interest in optical computing, and that the community is systematically addressing the **fabrication and integration bottlenecks** (laser integration, CMOS-foundry compatibility, packaging) to move from millions of units (transceivers) to “*billions of units shipped*” in photonics over the coming decade[23] – a scale which would imply mainstream adoption of technologies like photonic computing accelerators and optical I/O.

### 32. Maturity score (1–7) and reasoning

**Proposed Maturity Score: 5** (out of 7).

**Justification:** Photonic/optical computing has advanced beyond fundamental lab demos (levels 2–3) to **full system prototypes and early commercial-stage development**, but has not yet reached widespread product deployment. The evidence shows multiple **functioning proof-of-concept systems (level 4)** – for example, *photonic AI chips performing real tasks with competitive accuracy and speed*[8][7], and *integrated optical interconnects meeting performance targets in realistic settings*[4]. These prototypes clearly achieve benefits (orders-of-magnitude speed or efficiency gains) beyond what traditional electronics offer, satisfying key functionality needed for commercialization (e.g. analog optical accelerators attaining nearly digital precision, or optical links delivering 5× bandwidth at fraction of power)[6][2]. Importantly, the field now features **several well-capitalized actors and active competition**: multiple startups (Lightmatter, Lightelligence, Ayar Labs, etc.) and large firms (Intel and others) are racing to develop production versions of optical computing hardware, supported by significant funding and partnerships. This corresponds to level 5, where **post-PoC development is rapid and moving toward product prototypes**. For instance, Lightmatter’s 6-chip processor and Lightelligence’s 64×64 optical accelerator, both published in 2025, indicate that **production-worthy designs are in late-stage testing**[8][1]. Likewise, optical I/O solutions are **already being showcased in standard platforms (FPGA, CPU packages)** and slated for integration into next-gen data center hardware[24][17], with some initial shipments to early customers reported. This momentum goes beyond isolated lab research, underscoring that the technology is on the cusp of commercialization.

*Why not a 6 or 7?* Full commercial rollout (level 6–7) is *not yet* achieved. While prototypes exist, **broad customer delivery and scaling are just beginning**. There is no evidence yet of optical computing hardware shipping in volume or being widely adopted in production data centers – current deployments are limited to pilot installations or specific demo units. Key manufacturing and cost challenges remain (e.g. mass-producing photonic chips with high yield, integrating lasers economically, developing a software ecosystem), and no **off-the-shelf optical general-purpose processor** is commercially available as of 2025. In short, the technology has proven its merit (ruling out levels 1–3 decisively) and attracted serious investment (well beyond level 4), but **needs further engineering and scaling effort to move into routine, large-scale use**. Reaching level 6 will require demonstrating reliable volume production and delivering devices to many customers with decreasing costs – likely a few years away.

*Sub-component outlook:* Within this photonic computing bundle, **optical interconnects** may be slightly more mature than photonic processors. High-bandwidth optical I/O is already **sampling to industry partners** and on a roadmaps for near-term integration in AI systems[18][24]. One could argue optical interconnect tech is approaching level 6 (initial

products delivered, e.g. co-packaged optics for switches). Meanwhile, **photonic computing accelerators** (for AI/ML, etc.) are at a solid proof-of-concept stage, around level 4–5, with functional prototypes but only limited early-user access. Considering the combined impact, we assign an overall **score 5**, reflecting that *most pieces of the photonic computing stack have left the lab and are in the late prototype/early-product-development phase*. This score acknowledges the significant recent progress (multiple demonstrations solving real problems, multi-actor investment), while recognizing that the **technology as a whole has yet to fully cross into widespread productization**, which will be the hallmark of level 6.

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## ART 02.013 Next-Gen Memory & Storage

### 81. ART extraction

82. **Primary capability:** Enable vastly higher-density and longer-lasting data storage, allowing computers to keep more data “live” in non-volatile memory. This includes storage media that retain data with power off, endure far more write cycles than today’s flash, and even perform data processing directly where data is stored (minimizing data movement).

### 83. Key sub-components/variants:

- *Resistive & magnetoresistive memories (ReRAM, MRAM):* Non-volatile RAM using resistive changes or magnetic tunneling to store bits, aiming to combine DRAM-like speed with NAND-like persistence.
- *Advanced NAND flash:* Continued scaling of flash memory (3D structures with more layers, multi-bit cells) for higher density and I/O performance (e.g. 200+ layer TLC/QLC NAND).
- *DNA-based storage:* Encoding digital data in synthetic DNA strands for extreme density and millennial longevity; primarily for “cold” archives due to high latency.
- *Molecular/DNA computing:* Performing in-storage operations (like search or pattern matching) via biochemical reactions on DNA or other molecular data stores.
- *Processing-in-memory/storage:* Architectures that integrate compute logic into memory or storage devices (e.g. in-memory computing, computational storage drives) to process data in-place.

84. **Maturity indicators:** Evidence of **lab prototypes and demos** (e.g. storing/retrieving real data in DNA, or resistive memory arrays meeting endurance targets); **proof-of-concept integrations** (e.g. memory devices embedded in standard chips, or storage drives with in-situ processing); **field trials or initial products** (e.g. new NVM used in commercial systems); **multiple industry players investing** (competing startups, foundry offerings, alliances); and **roadmaps or standards efforts** (signaling path to manufacturing scale and market adoption).

### 85. Evidence (10–20 recent, reliable sources)

86. **DNA storage search demo (iPRES 2023)** – L. Provencher et al., Univ. of Illinois (conference short paper, 2023). Demonstrated DNA-based data storage and in-memory search: encoded images and full literary texts into DNA and successfully queried a specific word across multiple stored works[1]. This shows the feasibility of **molecular storage** combined with simple **DNA-based computing**, retrieving data subsets without reading the entire archive – a key step toward in-storage processing.

87. **Massively parallel DNA storage search (Catalog, 2022)** – Catalog Technologies (press release via GlobeNewswire), 12/2022. Reported a breakthrough in DNA computing: encoded ~17,000 words of Shakespeare into DNA “in a few minutes” on a



microfluidic DNA writer, then performed a chemical **keyword search** that retrieved all occurrences of a query word[2]. Notably, the search time stayed constant even when scaling to 200k words and is projected to remain ~constant up to 100 million words[3]. This underscores DNA storage's **massive parallelism** – searching an exabyte-scale archive via chemistry – and demonstrates a proof-of-concept for **DNA as both storage and compute medium** (albeit with slow absolute speeds).

88. **SNIA DNA Data Storage Tech Review (2025)** – *DNA Data Storage Alliance (industry report, SNIA, 2025)*. *Authoritative status review*: Confirms that **throughput and automation** are the main hurdles for DNA storage. Current write speeds are on the order of 0.001 MB/s (~100 MB/day), vastly slower than tape or SSD, but **advances in DNA synthesis parallelism are on track**. In 2022, Twist Bioscience unveiled a chip with ~100 million synthesis spots (writing ~1 GB per run), and projections foresee **100 billion parallel synthesis features by ~2027**, reaching “commercially relevant” data rates[4]. This roadmap – backed by the IARPA program – bolsters the plausibility of DNA archives, while emphasizing that significant manufacturing innovation (e.g. array chips, automation of fluid handling) is required.
89. **Infineon & TSMC embed RRAM in MCUs (2022)** – *Infineon & TSMC (joint market news, 11/2022)*. *Industry prototype announcement*: The next-gen Infineon AURIX™ TC4x automotive microcontrollers will use TSMC's embedded **Resistive RAM (RRAM)** technology at 28 nm, replacing embedded flash[5]. RRAM was chosen for its scalability beyond 28 nm and its reliability: it allows byte-level writes (no bulky erase cycles) and offers **endurance and retention on par with flash** memory[6]. Early samples of the 28 nm RRAM-based chips were slated for customer delivery by end of 2023[7]. This marks a significant step toward commercialization of **ReRAM**, with a top-tier chipmaker and foundry validating it for safety-critical, high-volume applications (automotive), thereby demonstrating both technical feasibility and industry commitment.
90. **Review – Emerging NVM in industry (Hellenbrand et al. 2024)** – *Cambridge University (peer-reviewed in MRS Communications, accepted 10/2024)*. *Survey of industrial progress*: Finds that **STT-MRAM and oxide ReRAM are the frontrunners** among emerging non-volatile memories for embedded use, with several implementations “very advanced” and aiming to **replace embedded flash**[8]. In contrast, Phase-Change Memory and FeRAM are “less available” as commercial products[8]. The review collates concrete performance achievements: e.g., **Everspin's 1 Gb STT-MRAM** has  $10^{10}$  cycle endurance and is qualified in 28 nm and 22 nm nodes, and **Avalanche Technology's MRAM** reached  $>10^{14}$  cycles and  $10^3$ -year retention at 85 °C in 22 nm chips[9][10]. It also notes that multiple foundries (GlobalFoundries, TSMC, Samsung) now offer embedded MRAM/RRAM options. This broad evidence base shows that the **materials and device challenges (endurance, retention, scaling) are largely solved** for MRAM/ReRAM, and these memories have entered the pilot production and product integration phase.
91. **IBM adopts MRAM in enterprise storage (2024)** – *Everspin Technologies & IBM (press release, 05/2024)*. *Product integration evidence*: IBM's latest FlashCore Module 4 (high-end SSD for IBM FlashSystem arrays) incorporates Everspin's **1 Gb STT-MRAM** as a persistent write buffer[11]. The MRAM, with a DDR4 interface, delivers **2.7 GB/s read/write throughput** with “instant non-volatility,” ensuring no data loss on power failure[12]. IBM's adoption of MRAM – displacing supercapacitor-backed DRAM in the

array's design – underscores that emerging memory has matured enough for **mission-critical, shipped products**. It provides real-world validation of MRAM's speed/endurance advantages for low-latency storage and indicates scaling to gigabit-class densities.

92. **Samsung SmartSSD (2nd Gen, 2022)** – *Samsung Electronics & AMD (press release, 07/2022). Computational storage in action:* Introduces Samsung's second-generation SmartSSD, a SATA SSD with an integrated Xilinx (AMD) FPGA. This **in-situ processing** drive can offload data-intensive tasks (e.g. database scans, video transcoding) to the storage device itself. In tests, it cut query processing time by >50%, with **70% lower energy and 97% lower host CPU usage** compared to a conventional SSD performing the same task[13]. Notably, Samsung confirms the **1st-gen SmartSSD (2020)** has already been delivered to customers (e.g. video platform providers) and proven its value (CES 2021 Innovation Award)[14]. The 2nd-gen's improved onboard ARM cores and customer-programmable IP demonstrate increasing maturity. This is evidence that **compute-storage convergence** is leaving the lab: major vendors are standardizing it (Samsung is working with SNIA and NVMe bodies[15]) and customers are testing real workloads, validating the concept's practicality.
93. **Micron 232-layer 3D NAND in production (2022)** – *Micron Technology (press release, 07/2022). Advancing the incumbent tech:* Micron began **volume production** of the world's first 232-layer NAND flash in 2022, heralding it as a "watershed moment" proving that 3D NAND can scale beyond 200 layers in manufacturing[16][17]. This sixth-generation NAND achieves the industry's highest bit density and boosts per-chip read/write bandwidth by >75%/100% over the prior 176-layer node[18]. It also introduces architecture innovations (e.g. first six-plane NAND) for better parallelism. By shipping this flash in consumer SSDs and announcing data-center deployments, Micron demonstrated **continued viability of flash scaling**. This directly addresses the ART's motivation ("growth of digital data straining conventional storage") by extending NAND's density and energy efficiency within acceptable cost – an important *near-term* component of a next-gen memory hierarchy.
94. **Weebit Nano & SkyWater deliver ReRAM silicon (2022–23)** – *Weebit Nano & SkyWater Tech (joint announcement, 11/2022; follow-up news, 06/2023). Foundry qualification of ReRAM:* Startup Weebit and US foundry SkyWater **produced the first silicon wafers with embedded ReRAM** in late 2022, using a mature 130 nm CMOS process[19][20]. This was the *first ever* ReRAM integration in a production fab, achieved with standard tools and flows – a major milestone toward commercialization[21]. By mid-2023, the 256 Kb ReRAM macros (on demo chips with a RISC-V MCU and periphery) were fully qualified for reliability and offered to customers for SoC designs[22][23]. This evidence shows that **resistive memory IP is becoming fab-ready** for embedded use, enabling third-party chip designers to adopt it. It also highlights growing *competitive activity*: besides Infineon/TSMC, a second supplier (SkyWater/Weebit) is entering the market, which will help drive down risk and cost of ReRAM technology.

95. **Maturity score (1–7) and reasoning**

**Score: 5 (Proof-of-Concept to early prototyping stage).**

**A) Justification of score:** The collected evidence indicates that **multiple threads of "next-gen memory" have progressed beyond lab demonstrations (Level 3) into proof-of-concept prototypes (Level 4) and are now entering the production prototyping and early product phase (Level 5)**. In particular, **non-volatile memories like MRAM and ReRAM have working**

**prototypes meeting commercial requirements** – for example, embedded RRAM in 28 nm MCUs and 1 Gb STT-MRAM in shipping IBM storage systems – and **several well-funded actors (Infineon, Samsung, foundries, startups)** are actively investing in their development[6][11]. This clearly surpasses Level 3/4: the core technical feasibility has been proven (high endurance, retention, etc.), and the motivation for commercialization is validated by real use-cases (e.g. MRAM eliminating backup capacitors in storage[24]).

**Standardization efforts and competition** (multiple foundry IP offerings, industry alliances like the DNA Storage Alliance, SNIA computational storage group) further confirm a Level 5 scenario – progress is rapid and stakeholders are coordinating to ready these technologies for market[15][4].

Crucially, **the ART is a bundle** spanning very mature to still-nascent elements. On one end, advanced 3D NAND flash is *already* in volume production (a solid Level 7 for that component)[16], and novel storage-class memory like 3D XPoint had briefly reached market (Optane, 2017–2022) before economic factors led to its discontinuation. On the other end, **molecular/DNA storage is still at lab prototype stage** – automated DNA write/read cycles have been demonstrated[25], and even in-memory DNA search has been shown[2], but **throughput and cost are orders of magnitude from viability**, corresponding to roughly Level 2–3. The overall “next-gen memory stack” vision assumes integrating these layers, so its full realization depends on the **least mature link (DNA)** catching up in coming years.

Given this mix, a *Level 5* assessment reflects a **weighted average** of sub-technologies. **Persistent RAM (MRAM/ReRAM)** is nearing Level 6 (initial products and scaling plans) but not yet ubiquitous; **computational storage and in-memory processing** have seen proof-of-concept deployments (SmartSSD, PIM-enabled memory) in niche markets – again around Level 5. Meanwhile, **DNA storage/computing is at Level 3** at best, still needing a breakthrough in speed and cost to reach PoC viability[26][4]. As a whole, the field is best characterized as “*transiting from PoC to prototype*”, with strong momentum but not yet a broadly market-ready solution set. This rules out lower scores: the concept is far beyond theoretical (Level 1) or initial lab proof (Level 2) – we have functional devices and compelling demonstrations in multiple domains. At the same time, it is **not** at Level 6 because, aside from conventional flash, we don’t see wide customer uptake or economies of scale for most of these new memories yet (e.g., no **mass adoption of MRAM in consumer devices** so far, and DNA storage is not productized). Key evidence still missing for Level 6–7 would be: large-scale manufacturing ramp-ups, clear cost-per-bit competitiveness, and multiple vendors shipping interchangeable products (signifying a mature market). Over the next decade, we would expect to see precisely those developments as prototypes turn into commercial memory offerings.

#### **B) Sub-component breakdown:**

- **MRAM (magnetoresistive RAM):** *Maturity* ~6. Proven in logic-qualified processes (14–28 nm) with **billion-cycle endurance** and used as embedded NVM by foundries[27]. Everspin’s standalone MRAMs are shipping (the **IBM module use** is strong Level 6 evidence of “products delivered to customers”)[24]. MRAM enjoys **multiple suppliers (Everspin, Samsung, TSMC, etc.) and growing adoption**, pushing it toward early Level 6.
- **ReRAM (resistive RAM) & Phase-Change Memory:** *Maturity* ~4–5. They have cleared major technical hurdles (high-temperature retention, switching endurance) in research[28][29], and **first commercial integrations are underway** (Infineon’s RRAM MCU sampling in 2023,

Weebit/SkyWater’s qualified ReRAM IP)[7][20]. However, *volume production* and broad competition are just beginning – implying late Level 4 to Level 5. (Notably, Intel/Micron’s PCM-based 3D XPoint reached Level 6 in 2020 but was a single-supplier product and was discontinued, so PCM’s current commercial presence is limited.)

- **Advanced 3D NAND Flash: Maturity ~7.** This is in full mass production worldwide; multiple firms (Micron, Samsung, SK Hynix) compete on layer count and cell design. The **232-layer node** debut in 2022[16] and roadmap to 300+ layers show continued scaling. It’s a mature market with **economies of scale and rising demand**, characteristic of Level 7. (It’s included here as the baseline “bulk storage” layer that next-gen memories will augment, not replace, in the near term.)

- **DNA-based storage & computing: Maturity ~2–3.** Fundamental studies have validated the concept (e.g. kilobyte–megabyte data archives retrieved successfully, DNA logic operations performed in vitro)[25][2] – so it’s beyond mere theory. An **automated DNA storage device** was built in 2019[25], and recent demos by both academia and startups show improved integration (parallel synthesis, search-in-storage)[2][3]. Still, **no proof yet that it meets real-world speed or cost requirements** – current write/read is millions of times slower than magnetic/solid-state media, and costs are in the \$1000s per megabyte. This sub-area remains at early experimental stage (Level 2–3), needing significant engineering breakthroughs (which are expected over a 10–20 year horizon, per the ART description).

- **Compute-in-memory / computational storage: Maturity ~5.** Initial products exist (Samsung’s SmartSSD, AI-enabled memory like HBM-PIM samples) and **enterprise trials are validating the performance gains**[13]. Multiple big players (Samsung, AMD, Huawei, etc.) are investing, and standards groups are involved – indicating a transition from one-off demos to broader prototyping. The concept is proven beneficial (e.g. SmartSSD’s 50% query speedup[13]), but it’s not yet mainstream in data centers (no Level 6 scale deployment yet).

We assign an overall **Level 5** because the **functionality of the “next-gen memory” vision relies on combining these layers**, and at this point, some critical layers (and their integration software) are only in the proof-of-concept phase. In other words, the **value proposition spans diverse use-cases (fast cache, persistent main memory, archival store, in-situ processing)** that won’t be fully realized until *each* piece achieves product maturity. Thus, averaging the sub-scores (from ~3 for DNA to ~7 for NAND) yields a mid-level maturity. We chose Level 5 to reflect that **several of the technologies are in late R&D with clear commercial momentum**, even though the *complete revolutionary stack* will materialize over the coming decade. This score is supported by evidence of rapid progress and growing industry commitment, while also acknowledging that **further development and scaling investment** are needed to reach the next level (e.g. widespread adoption and cost reduction to challenge incumbent memories).

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## ART 02.014 Molecular Computing

### 1. ART extraction

**A) Primary capability:** This ART envisions **molecular computing** platforms that perform information processing using chemical/biological reactions (e.g. DNA strand interactions) instead of electronic circuits. The key capability is **in-situ computation at the molecular scale** – encoding, storing, and transforming information via molecular concentrations, sequences, and reactions. This would allow **embedded logic within chemical or biological environments** (e.g. inside fluids, cells, or materials) where conventional silicon electronics cannot easily operate.



## B) Key sub-components/variants:

- **DNA/RNA strand-displacement circuits:** Dynamic networks of nucleic-acid strands and enzymes implementing logic gates and cascades in solution[1][2]. Variants include DNA-based neural networks and classifiers that perform pattern recognition and learning tasks purely with molecules[3][4].
- **Molecular logic in living cells:** Engineered genetic or protein circuits inside living cells or synthetic biomaterials that process multiple molecular inputs and produce functional outputs. Examples include protein-based logic gates in cells that respond to chemical signals with different actions (e.g. change cell orientation or gene expression)[5][6].
- **Microfluidic/”lab-on-chip” molecular processors:** Miniaturized devices (fluidic chips, reactors) that integrate molecular computing reactions with physical infrastructure. These use channels, compartments, and surface-bound components (like DNA origami “registers”) to execute multi-step computations faster and with automation[7][8].
- **Parallel DNA computing for data storage/search:** Techniques that leverage DNA’s massive parallelism to compute on data stored in DNA databases. For instance, DNA-based search algorithms can retrieve matches from DNA memory archives in parallel, scaling almost independently of data size[9][10].
- **Network-based biocomputation (molecular motor circuits):** An alternative model using biological nanomotors (proteins) and nanofabricated networks. Here, molecules like motor-propelled filaments explore physical channel networks to solve computational problems in parallel (e.g. pathfinding for NP-complete problems)[11][12].
- **Design automation and programming tools:** High-level languages, AI-assisted design platforms, and standard “molecular instruction sets” that allow researchers to **program molecular logic** without manual trial-and-error. Recent advances include automated DNA circuit design using AI/ML models trained on large libraries of circuit variants[13][14] and tools for error-correcting molecular encodings.

**C) Maturity indicators:** Evidence of maturity would include: **Multi-layer prototypes and proof-of-concept demonstrations** (e.g. multi-step logic circuits, molecular classifiers) in labs; **field trials or real-world applied demos** (such as diagnostic tests or control systems using molecular logic); **integration into usable devices** (microfluidic chips or kits performing molecular computation autonomously); **well-funded development efforts or startups** (competition among companies, dedicated consortia); **standardization of tools and workflows** (automated design software, repeatable processes); and signs of **progress toward practical performance** (e.g. improved speed, error correction, cost reduction, scalability to real data sizes) such that the technology moves from one-off experiments to robust prototypes.

## 2. Evidence (10–20 recent, reliable sources)

- **RNA Strand-Displacement Logic Circuits (Science Advances 2022)** – Schaffter & Strychalski (NIST) – Peer-reviewed paper (Mar 2022).  
*Demonstrated the largest and most complex molecular logic circuits to date using DNA/RNA strand displacement. Achieved multi-layer cascaded logic and signal amplification in a test-tube system, with circuit behavior accurately predicted by a simple model[1][2]. This showcases the feasibility of designing scalable molecular logic gates and suggests a path to circuits operable in living cells (by using RNA transcription to generate DNA strands in situ). It*

*proves the underlying computing principle in chemistry and addresses a key challenge of multi-step signal processing in molecular systems.*

- **DNA Neural Network with Supervised Learning (Nature 2025)** – Kevin Cherry & Lulu Qian (Caltech) – Peer-reviewed article (Sept 2025).  
*Showed that DNA molecules can autonomously perform supervised machine learning. A DNA-based neural network was trained to classify 100-bit binary patterns entirely in vitro, with molecular “weights” stored as DNA concentrations[3][4]. The system learned to correctly categorize new inputs after training, demonstrating pattern recognition and adaptive behavior emerging from DNA reactions. This result greatly expands plausibility by proving complex computational algorithms (like neural network learning) can be implemented in a wet molecular system, albeit at laboratory scale.*
- **Protein Logic Gate in Live Cells (Science Advances 2023)** – Jiaxing Chen et al. (Penn State) – Peer-reviewed paper (May 2023).  
*Engineered a protein-based “nano-computer” inside mammalian cells that processes two biochemical inputs with order-dependent outputs[5]. The device used a fusion of sensor proteins to detect a drug (rapamycin) and light; it produced different cellular responses (changing cell orientation to two distinct angles) depending on input sequence[5][6]. This noncommutative logic gate in live cells is a proof-of-concept for embedded decision-making in cell therapies, showing that cells can be programmed with multi-input logic (beyond simple AND/OR gates) to trigger specific behaviors. It also highlights progress in biocompatibility – the molecular circuit functioned in real time in a biological environment.*
- **DNA Computing for Data Search (Catalog Press Release 2022)** – Catalog Technologies Inc. – Vendor technical news (Dec 2022).  
*Catalog (a US startup) demonstrated a DNA-based computing platform that can search through DNA-stored data in parallel. Using their automated DNA writer “Shannon,” they encoded ~17,000 words of text into synthetic DNA in minutes and then performed a massively parallel search to retrieve all occurrences of a query word[9]. They scaled up to 200,000 words (eight entire books) and still found query matches with the same few chemical steps[10]. This shows unprecedented parallelism: search time was almost independent of database size, leveraging chemistry to do in one step what would require indexing in digital systems. Importantly, Catalog plans to scale to 100 million-word datasets and is developing a **rack-sized DNA computing platform** for enterprise use[10][15]. This indicates fast-paced progress toward practical deployment, with external partnerships and funding supporting a path to commercialization.\**
- **Microfluidic DNA Computing Chip (PLOS One 2023 / RIT News 2024)** – Amlan Ganguly et al. (RIT & Univ. of Minnesota) – Peer-reviewed + University report (Oct 2023, reported Jan 2024).  
*Developed a microfluidic integrated circuit for DNA computing that performs artificial neural network operations on DNA-encoded data[16]. This lab-on-chip device uses DNA strand concentrations to represent numbers and executes operations like addition and multiplication via DNA reactions[17]. The prototype ANN processor (implemented in a mini fluidic chip with embedded nanosensors) produced the correct outputs for simple neural-network computations, and it is being scaled up for visualization and testing[18][19]. This work marries molecular computing with hardware, aiming for standardized, reprogrammable DNA computing units. It demonstrates feasibility of compact, self-contained molecular computers and addresses integration and readout challenges by bridging biology with established chip fabrication techniques.*
- **Bitkom “Future Computing” Roadmap – DNA Computing Section (Germany 11/2023)** – C.F. Strnadl (Software AG) – Industry/consortium report (Nov 2023).

An authoritative tech outlook assessing DNA computing as experimental but advancing. It notes DNA/RNA computing can offer massive parallelism and high energy efficiency, but today it remains at TRL ~3–4 (lab proof-of-concept) and has not yet been validated outside controlled lab settings[20]. Key limitations are highlighted: molecular logic operations are slow, often requiring hours (vs. microseconds in silicon) due to chemical kinetics[21]; processes are labor-intensive and currently require automation to scale (manual pipetting and semi-automated equipment are still common)[22]; and costs are prohibitively high, needing  $\sim 10^6$ -fold reduction to become economical[23]. This report underscores that while scientific feasibility is proven, significant engineering breakthroughs (speed, error-correction, automation, cost) are needed for real-world deployment.

- **Digital DNA Classifier for Diagnostics (Advanced Materials 2025)** – Linghao Zhang et al. (BUCT, China) – Peer-reviewed paper (Mar 2025).  
 Demonstrated a multi-input molecular diagnostic classifier using a “Digital DNA Strand Displacement” (DDSD) scheme[24]. The DNA circuit could analyze multiple biomarkers and achieved 96% accuracy in distinguishing bacterial vs viral infections from clinical blood samples, and 100% accuracy in identifying specific pathogen types, surpassing prior molecular diagnostic methods[24][25]. The DDSD approach uses DNA polymerase-driven strand release to greatly reduce the number of DNA strands required, improving robustness. They also built cascaded DNA circuits handling up to 14 different signal levels (valences) with improved error suppression via DNA nanostructures[26]. This is a real-world-oriented validation – showing that molecular computing can interface with messy biological samples and provide medically relevant decisions. It represents a major step toward practical molecular computing applications (rapid infection diagnostics), albeit as a lab prototype.
- **Molecular-Motor Biocomputer Scaling (ACS Nano Au 2022)** – Pradheebha Surendiran et al. (EU Bio4Comp consortium) – Peer-reviewed paper (Oct 2022).  
 Achieved a  $128\times$  scale-up in network-based biocomputation, an approach where protein filaments (e.g. microtubules) explore nanofabricated channel networks to solve combinatorial problems in parallel[11][12]. They solved multiple instances of the NP-complete Exact Cover problem using a chip-sized network of channels and thousands of molecular motors running simultaneously. This work (part of an EU project) shows that an alternative molecular computing paradigm can tackle significantly larger problems than before, using highly energy-efficient parallel exploration. It indicates progress in fabrication and error control (the nanoscale rail networks were engineered to reliably guide molecules). While still experimental, it suggests that biological nano-machines can be harnessed for computing tasks that are hard for traditional computers, validating another branch of molecular computing beyond DNA chemistry.
- **Fast, Rewritable DNA Computing via Origami Registers (ACS Central Science 2024)** – Qian Zhang, Chunhai Fan et al. (Shanghai Jiao Tong Univ.) – Peer-reviewed paper, summarized by ACS (Dec 2024).  
 Reported a new “liquid computing” architecture with DNA origami registers that dramatically speeds up sequential DNA logic operations. By attaching a DNA-based logic register to a solid surface (a glass chip) and using it to hold and release intermediate DNA strands, the team eliminated manual transfer between reaction steps. They demonstrated that all steps of a multi-step DNA computation could occur in one pot within  $\sim 90$  minutes, versus many hours previously[8][7]. The register is reusable/resettable, enabling write–read–erase cycles similar to electronic memory[7][27]. They also integrated a signal amplifier to overcome diffusion limits, ensuring components find each other quickly. This result is a breakthrough in speed and automation: it lays groundwork for scalable, automated DNA circuit execution and real-time



operation, addressing two major bottlenecks (slow kinetics and tedious workflows) in molecular computing.

- **AI-Assisted Design of Genetic Circuits (Nature 2026)** – Caleb Bashor et al. (Rice Univ.) – Peer-reviewed paper, reported by Rice News (Jan 2026). Demonstrated the first use of machine learning to automate molecular circuit design. The team developed a platform (“CLASSIC”) that can generate and test hundreds of thousands of DNA circuit variants in human cells in parallel, creating massive datasets for training AI models[13]. With this, they showed that an ML model can learn the complex rules of genetic circuits and accurately predict new circuit designs that achieve desired outputs (tested in living human cell cultures)[14][28]. This greatly accelerates the design-build cycle: instead of hand-crafting circuits, researchers can leverage AI to navigate the huge design space. The study reported that ML-designed circuits performed better and more reliably than those designed by trial-and-error or simple models[28]. This is a strong indicator of maturity in the engineering tools ecosystem around molecular computing – moving toward data-driven, standardized design processes needed for scaling up complexity.

### 3. Maturity score (1–7) and reasoning

#### Overall Maturity Score: 3 (Laboratory Prototype demonstrated)

**A) Justification:** Molecular computing as a whole is **beyond mere theory (levels 1–2)** – multiple experiments over the last few years show real, working prototypes of molecular logic circuits and even complex functionalities like classification and learning in chemical systems. For example, **multi-layer DNA logic and neural network behavior have been achieved in vitro**[1][3], and molecular circuits have been embedded in living cells to control behaviors[5]. These successes indicate that fundamental feasibility issues (can molecules compute?) have been resolved, satisfying and surpassing level 2. We are squarely in the **laboratory prototype stage**: distinct prototypes tackle specific tasks (e.g. DNA data search[9], disease diagnostics[24], in-cell logic gates[5]), and crucial previously-blocking problems have been addressed one by one. For instance, the slow, sequential processing of DNA circuits has been accelerated by new designs (90-minute one-pot computation instead of multi-hour manual steps)[8][7], and error-prone complex circuits have been stabilized by novel architectures (DDSD, origami registers)[24][7]. These meet the rubric for level 3: **necessary functionality has been achieved in prototypes**, and key hurdles (multi-step cascades, scaling of parallelism, basic interfacing to real signals) have been proven solvable in principle.

However, **the technology is not yet at level 4 (validated PoC for commercialization)**. The current prototypes, while impressive, **do not fully meet practical deployment requirements** for broad use. Evidence for this gap includes:

- **Operating conditions & reliability:** Molecular computers still require controlled lab environments (temperature, cleanliness, specialized reagents). No evidence yet shows a **field-ready device** robust to outside conditions – e.g., the Bitkom report explicitly states DNA computing has *not been validated in any relevant real-world environment*[20].
- **Speed and throughput:** While speed has improved, it’s still orders of magnitude slower than electronics for general tasks. Even the “high-speed” DNA chip executes logic in minutes[7], whereas digital circuits do it in nanoseconds. The **intrinsic reaction rates (mass-action kinetics)** impose a ceiling that keeps many applications out of reach[21]. There is no evidence

yet of a molecular computer matching or exceeding conventional computing speeds except in very niche massively parallel searches[9][10].

- **Automation and integration:** Prototypes often involve manual steps or bespoke setups. Efforts like one-pot processing and surface-bound circuits are addressing this, but **true automation (like a push-button molecular CPU)** is nascent. The need for automation is emphasized as an unsolved challenge[22], and while startups like Catalog are building integrated machines, those are essentially advanced lab instruments at this stage, not widely-deployable products.
- **Cost and scalability:** All evidence points to **high costs and low throughput** currently. The Bitkom roadmap estimates DNA computing needs a million-fold cost reduction to be competitive[23]. Even though Catalog's approach scales well computationally, it still involves significant DNA synthesis and sequencing overhead. No **commodity manufacturing process** exists yet for molecular computing hardware – current implementations rely on expensive custom syntheses, enzymes, or nanofabrication. This means they are far from meeting cost or volume requirements of a commercial product (level 4 expects a viable path to production, which we don't yet see).
- **Actors and competition:** We do see the **beginnings of well-capitalized efforts** (e.g. Catalog's \$35M funding, Microsoft and academic partnerships, EU consortia). But the landscape is still limited – only a few specialized startups and labs are in the race, not (yet) a broad industry with multiple competing vendors. This suggests we have not reached level 5 where “several market actors” are pushing products. The field is still largely R&D-driven, with collaboration between academia and niche firms, indicating level 3–4 rather than 5+.

**B) Sub-score considerations:** The ART encompasses a **bundle of sub-technologies**, all under the umbrella of molecular computing:

- *DNA/RNA strand displacement computing (in vitro):* Maturity  $\approx$  **3.5**. Academically advanced with complex demos (neural nets[3], multi-layer logic[29]) and even early applied prototypes (diagnostics classifiers[24]). However, it remains lab-bound; no commercial device yet. (Scoring mid-Level 3; approaching 4 in specific niches like DNA data search where a prototype system exists[10].)
- *In vivo/Synthetic biology circuits:* Maturity  $\approx$  **2–3**. Fundamental logic gates in cells have been shown (e.g. protein logic gate with two outputs[5], CRISPR-based regulators in other studies). These are promising for future cell therapies, but still **early experimental** – complexity is low (a few inputs) and not productized. (Edge of level 2 and 3: basic functionality is shown, but far from a deployable therapy yet.)
- *Microfluidic and hardware-integrated molecular computers:* Maturity  $\approx$  **3**. Recent breakthroughs (DNA computing chip, DNA origami register on chip) show that integration and automation is possible[16][7]. They have built **lab prototypes** of “molecular computing devices,” meeting the definition of proof-of-concept hardware. None are market-ready, but they prove that physical packaging of molecular logic is achievable after long being a concern.
- *Parallel DNA computing for big data (e.g. storage+compute):* Maturity  $\approx$  **3–4**. Here, **exceeded classical capabilities** in some aspect (parallel search on unstructured data[9]). A company (Catalog) is actively engineering a platform, and even engaging with pilot customers. This sub-thread is closest to commercial: by showing a useful function (search) and planning a **scaled prototype** for enterprises, it edges into level 4 territory. Yet, until a working product or service is actually delivered and proven viable, we keep it at high-3.

- *Network-based biocomputation (molecular motors)*: Maturity  $\approx$  **2–3**. Progress is significant scientifically (solved larger math problems than before<sup>[11]</sup>), but this approach is highly experimental and not as directly tied to a near-term product. It's a visionary alternative with unknown scalability to practical computing tasks. (Solidly level 2 for now, with a lab demo marking level 3 for the concept.)

Given these sub-scores, the **aggregate score  $\sim$ 3** is appropriate. We weighted the more mainstream DNA computing developments a bit higher than fringe approaches. The DNA/RNA-based chemical computing – which is the core of the ART description – is around level 3: robust lab demonstrations, clear use-case interest, but **not yet a validated product or widely adopted tool**. Meanwhile, no sub-component has clearly achieved level 4 across functionality, cost, and reliability requirements, though some are close in one dimension (e.g. functionality for Catalog's search, or reliability within a lab setting).

**C) What's needed for Level 4:** To reach the next level, we would expect to see a **functional prototype system that convincingly works outside the research lab** – for example, a molecular computing device applied in a real operational setting (hospital, environmental field sensor, industrial bioreactor control) demonstrating practical value. This would require **improving speed and stability**, integrating error-correction so the device can run for long durations, and a form factor suitable for deployment. Cost and throughput would need to improve such that using the molecular approach is competitive for at least one application domain (perhaps DNA data search in an archival data center, or cell-based biosensors that operate autonomously). We would also expect by level 4 that **investors and industry show stronger commitment**, possibly a startup delivering a beta product or a government program running field trials. Those indicators have not fully materialized yet – current evidence shows continued research advancements but also acknowledges the significant gaps to commercialization<sup>[23][22]</sup>. Thus, the score remains at **3 – a proven concept with working prototypes, still awaiting the transition to practical, real-world validated technology**.

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## Group 3 – Artificial Intelligence & Learning Systems

### ART 03.015 Causal Learning & Reasoning

#### 1. ART extraction

- **A) Primary capability (what the ART claims)**
- Build **explicit, machine-usable causal models** (cause–effect, intervention structure) rather than purely correlational predictors.
- Answer **intervention and counterfactual queries** (“what if,” “why,” “what caused this,” “what happens if we change X?”) with traceable causal pathways and uncertainty.
- Operate as **deployable software components** (libraries/frameworks/services) that integrate data + assumptions/domain knowledge and plug into larger decision-support/AI reasoning stacks.
- **B) Key sub-components / variants (bundle sub-threads)**
- **Causal effect estimation** (ATE/CATE, uplift, policy impact) from experiments and observational data (with assumptions).

- **Causal discovery / structure learning** (learning graphs/DAGs/MAGs; handling latent confounders; time-series and dynamical systems).
- **Causal representation learning** (recovering latent causal variables from high-dimensional observations; identifiability with interventions).
- **Causal generative modeling** (SCM-grounded generative models enabling controllable counterfactual generation).
- **Operational causal diagnosis / root-cause analysis** in complex systems (e.g., monitoring/logs, AIOps-like settings; human-in-the-loop refinement).
- **Benchmarking and evaluation infrastructure** (shared datasets, reproducible evaluation, standard metrics and protocols).
- **LLM-assisted causal reasoning** (LLMs proposing causal graphs/arguments, assisting setup, or learning causal structure/inference under controlled conditions).
- **C) Maturity indicators (what would count as evidence)**
  - **Working software artifacts** where users can specify causal assumptions/graphs, fit mechanisms, and answer causal queries with documented APIs and reproducibility.
  - **Competitive performance on benchmarks** with known ground truth (graphs/interventions), including **time-series and dynamical** settings and realistic confounding/noise regimes.
  - **Scalability evidence** (runtime/complexity results, distributed implementations, large variable counts, large sample sizes).
  - **Applied/production evidence**: deployed workflows in real organizations (e.g., large-scale observational studies, RCA/diagnosis pipelines), or systems evaluated on real operational data with measurable gains.
  - **Cross-actor ecosystem**: multiple well-capitalized actors + open-source communities pushing interoperable tooling, benchmarks, and methods (a sign of accelerating maturity).
  - **Known gaps** explicitly documented: robustness to hidden confounding, causal misspecification, dataset shift, and limits of purely observational discovery.

## 2. Evidence (10–20 recent, reliable sources)

### 1) DoWhy-GCM: An Extension of DoWhy for Causal Inference in Graphical Causal Models

- Authors/org: Patrick Blöbaum[1] et al.; Amazon Web Services[2]

- Venue/type: *Journal of Machine Learning Research (JMLR)* (peer-reviewed; open-source software track/MLOSS-style paper)

- Publication date: **May 2024** (Published 5/24)

- Link: <https://www.jmlr.org/papers/volume25/22-1258/22-1258.pdf>

- Why it matters: Demonstrates a **usable causal modeling library** that goes beyond effect estimation to queries like **root-cause attribution, distribution shift attribution, and causal structure diagnosis**, aligning directly with the ART’s “why/what-if” tooling vision. [3]

### 2) CausalBench: A Flexible Benchmark Framework for Causal Analysis and Machine Learning

- Authors/org: Ahmet Kapkic[4] et al.

- Venue/type: *ACM CIKM 2024* (peer-reviewed conference paper; benchmarking infrastructure)

- Publication date: **October 2024** (CIKM '24, Oct 21–25, 2024)
- Link: <https://arxiv.org/html/2409.08419v1>
- Why it matters: Provides an **evaluation platform** (datasets/models/metrics + reproducibility/versioning concepts) targeting the ecosystem need for **standardized causal ML benchmarking**, a key maturity accelerator for moving from research to dependable engineering practice. [5]

### 3) **Balancing Approach for Causal Inference at Scale**

- Authors/org: Sicheng Lin[6] et al.; includes deployment context at Snap Inc.[7]
- Venue/type: *ACM SIGKDD (KDD '23)* (peer-reviewed conference paper; large-scale causal inference systems)
- Publication date: **August 2023** (KDD '23, Aug 6–10, 2023)
- Link: <https://arxiv.org/pdf/2302.05549>
- Why it matters: Shows **scalable causal effect estimation** engineering (including runtime scaling to large datasets; single-node timing up to 1M rows and distributed runs on 10M-scale) and explicitly describes **productionizing** a workflow for observational impact estimation—strong maturity evidence for the “causal decision-support in practice” slice of the ART. [8]

### 4) **Deep Learning-Based Causal Inference for Large-Scale Combinatorial Experiments: Theory and Empirical Evidence**

- Authors/org: Zikun Ye[9] et al.
- Venue/type: *Management Science* (peer-reviewed journal; “Articles in Advance”)
- Publication date: **October 2025** (Published online 15 Oct 2025)
- Link: <https://rphilipzhang.github.io/rphilipzhang/DeDL-nonblind.pdf>
- Why it matters: Provides peer-reviewed evidence that causal/experimental inference problems in modern platforms can be treated in **large-scale, high-dimensional “combinatorial experiment” regimes** with deep-learning-based estimators—supporting plausibility and indicating advanced applied maturity in experimentation-heavy domains. [10]

### 5) **Disentangled Causal Graph Learning for Online Unsupervised Root Cause Analysis (CORAL)**

- Authors/org: Dongjie Wang[11] et al.
- Venue/type: Preprint (*arXiv*) with strong experimental detail (online RCA via causal graphs)
- Publication date: **May 2023** (Submitted 18 May 2023; later revisions noted)
- Link: <https://arxiv.org/abs/2305.10638>
- Why it matters: Presents an **online** causal-graph-based RCA framework with (i) near-real-time trigger detection, (ii) incremental causal graph updates, and (iii) root-cause localization, evaluated on **three real-world datasets**—evidence that causal reasoning components can operate as continuously-updated decision aids, not just offline analysis. [12]

### 6) **From Logs to Causal Inference: Diagnosing Large Systems (LOGos prototype)**

- Authors/org: Markos Markakis[13] et al.
- Venue/type: *Proceedings of the VLDB Endowment (PVLDB)* (peer-reviewed systems/data management paper)
- Publication date: **2024** (PVLDB 18(2):158–172, 2024)
- Link: <https://www.vldb.org/pvldb/vol18/p158-markakis.pdf>
- Why it matters: Demonstrates a **human-in-the-loop causal inference workflow over messy production logs**, including measured gains (e.g., ranker precision improvements over



baselines and reduced causal judgments) and a data prep pipeline with scaling behavior—concrete progress toward “embedded causal diagnosis” in operations settings. [14]

#### 7) **Causal Modelling: Tools for the high-tech industry**

- Authors/org: Emile van Gerwen[15] (with Johan Lukkien); TNO[16]
- Venue/type: Authoritative applied research report (not peer-reviewed journal, but a national applied research organization report)
- Publication date: **May 2025** (26 May 2025)
- Link: <https://publications.tno.nl/publication/34644344/Ajrn12zb/TNO-2025-P11200.pdf>
- Why it matters: Provides a **practitioner-oriented synthesis** of causal modeling for industrial decision support (including terminology, modeling choices, and tool discussions), reflecting institutional-level effort to translate causal methods into engineering practice—useful maturity evidence for real-world adoption pathways. [17]

#### 8) **Deep learning of causal structures in high dimensions under data limitations**

- Authors/org: Kai Lagemann[18] et al.
- Venue/type: *Nature Machine Intelligence* (peer-reviewed journal article)
- Publication date: **October 2023** (Published 26 Oct 2023)
- Link: <https://www.nature.com/articles/s42256-023-00744-z>
- Why it matters: Supplies high-quality evidence that causal structure learning can be combined with deep learning and prior knowledge to identify causal relationships across **thousands of variables**, supporting feasibility claims for some “large-scale causal world model” components (at least for specific domains and assumptions). [19]

#### 9) **Scalable Differentiable Causal Discovery in the Presence of Latent Confounders with Skeleton Posterior (Extended Version) (SPOT)**

- Authors/org: Pingchuan Ma[20] et al.
- Venue/type: Preprint (*arXiv*) aligned with KDD-style scalable causal discovery; focuses on MAG learning under latent confounding
- Publication date: **June 2024** (Submitted 15 Jun 2024)
- Link: <https://arxiv.org/abs/2406.10537>
- Why it matters: Addresses a core maturity blocker—**latent confounding** and scaling beyond small variable counts—explicitly stating prior limits (e.g., difficulty scaling MAG learning beyond ~50 variables) and proposing a framework intended to improve scalability and accuracy via skeleton posterior guidance. [21]

#### 10) **causalAssembly: Generating Realistic Production Data for Benchmarking Causal Discovery**

- Authors/org: Konstantin Göbler[22] et al.
- Venue/type: PMLR proceedings paper (peer-reviewed; UAI 2024 proceedings volume context)
- Publication date: **2024**
- Link: <https://proceedings.mlr.press/v236/gobler24a/gobler24a.pdf>
- Why it matters: Uses a real manufacturing assembly-line dataset plus domain knowledge to generate semisynthetic data **Markov w.r.t. a ground-truth graph** and benchmark multiple causal discovery methods—directly supporting maturity indicators around **realistic evaluation** and industrial relevance. [23]

### 11) **CausalTime: Realistically Generated Time-series for Benchmarking of Causal Discovery**

- Authors/org: Yuxiao Cheng[24] et al.
- Venue/type: *ICLR 2024* (peer-reviewed conference; OpenReview record)
- Publication date: **January 2024** (OpenReview published 16 Jan 2024)
- Link: <https://openreview.net/forum?id=iad1yyyGme>
- Why it matters: Tackles a practical maturity barrier—lack of ground-truth causal graphs for real time series—by generating **realistic time series with “ground truth” graphs** for benchmarking, enabling faster iteration toward deployable time-series causal discovery methods. [25]

### 12) **CausalDynamics: A large-scale benchmark for structural discovery of dynamical causal models**

- Authors/org: Benjamin Herdeanu[26] et al.
- Venue/type: *NeurIPS 2025 Datasets & Benchmarks Track* (peer-reviewed track artifact via OpenReview)
- Publication date: **September 2025** (Published 18 Sept 2025)
- Link: <https://openreview.net/forum?id=ck7euvU7V3>
- Why it matters: Provides a large-scale benchmark for dynamical causal discovery, including many graphs derived from coupled differential equations and climate models, evaluating robustness to **noise/confounding/lagged dynamics**—critical for moving “causal world models” beyond toy settings. [27]

### 13) **Interventional Causal Representation Learning**

- Authors/org: Kartik Ahuja[28] et al.
- Venue/type: *ICML 2023* (peer-reviewed conference; PMLR proceedings)
- Publication date: **July 2023** (23–29 Jul 2023)
- Link: <https://proceedings.mlr.press/v202/ahuja23a.html>
- Why it matters: Establishes identifiability results showing that **interventional data can enable recovery of latent causal factors** under fairly general settings, supporting the plausibility of learning causal representations that underpin counterfactual simulation modules. [29]

### 14) **Learning Linear Causal Representations from Interventions under General Nonlinear Mixing**

- Authors/org: Simon Buchholz[30] et al.
- Venue/type: *NeurIPS 2023* (peer-reviewed conference paper)
- Publication date: **December 2023**
- Link: [https://proceedings.neurips.cc/paper\\_files/paper/2023/file/8e5de4cb639ef718f44060dc257cb04f-Paper-Conference.pdf](https://proceedings.neurips.cc/paper_files/paper/2023/file/8e5de4cb639ef718f44060dc257cb04f-Paper-Conference.pdf)
- Why it matters: Pushes the theory/practice boundary on causal representation learning by providing **identifiability guarantees** under unknown interventions and nonlinear mixing, directly supporting the ART’s claim that hybrid learning can infer underlying mechanisms—not just correlations. [31]

### 15) **From Identifiable Causal Representations to Controllable Counterfactual Generation: A Survey on Causal Generative Modeling**

- Authors/org: Aneesh Komanduri[32] et al.



- Venue/type: Survey with journal reference (*Transactions on Machine Learning Research (TMLR)*; label: survey / review)
- Publication date: **May 2024** (arXiv revised May 23 2024; journal reference 2024)
- Link: <https://arxiv.org/abs/2310.11011>
- Why it matters: Systematizes methods that combine SCM concepts with deep generative models for **counterfactual generation and causal representation learning**, clarifying what is feasible today and what remains open—useful for plausibility assessment and maturity gap identification. [33]

#### 16) **Causal Reasoning and Large Language Models: Opening a New Frontier for Causality**

- Authors/org: Emre Kıcıman[34] et al.; Microsoft Research[35]
- Venue/type: *Transactions on Machine Learning Research (TMLR)* (peer-reviewed; OpenReview record)
- Publication date: **August 2024** (Published 14 Aug 2024; later certified for ICLR 2025 journal track)
- Link: <https://openreview.net/forum?id=mqoxLkX210>
- Why it matters: Provides benchmarked evidence that LLM-based methods can produce correct causal arguments and perform strongly on select causal tasks (pairwise causal discovery, counterfactual reasoning, event causality) while also documenting failure modes—directly relevant to the ART’s “LLMs calling causal solvers / helping causal setup” pathway. [36]

#### 17) **Causal Discovery and Inference through Next-Token Prediction**

- Authors/org: Eivinas Butkus[37] and Nikolaus Kriegeskorte
- Venue/type: *NeurIPS 2025* (peer-reviewed conference venue listing via OpenReview; research paper)
- Publication date: **September 2025** (Published 18 Sept 2025)
- Link: <https://openreview.net/forum?id=MMYTA3v66p>
- Why it matters: Claims (with experiments and mechanistic probes) that a GPT-style transformer can **discover linear-Gaussian SCM instances** and **answer counterfactual queries**, supporting plausibility of integrating foundation models with causal inference capabilities—while still limited to controlled SCM regimes. [38]

#### 18) **CounterBench: A Benchmark for Counterfactuals Reasoning in Large Language Models**

- Authors/org: Yuefei Chen[39] et al.
- Venue/type: Preprint (*arXiv*; benchmark dataset and evaluation)
- Publication date: **February 2025** (Submitted 16 Feb 2025)
- Link: <https://arxiv.org/abs/2502.11008>
- Why it matters: Introduces a 1K-question benchmark designed around **formal-rule counterfactual inference** and reports that many LLMs perform near random guessing; also proposes an iterative reasoning/backtracking method that improves results—strong evidence that “causal reasoning in LLMs” remains a maturity constraint and needs tool-like scaffolding. [40]

#### 19) **ExpliCa: Evaluating Explicit Causal Reasoning in Large Language Models**

- Authors/org: Martina Miliani[41] et al.
- Venue/type: *Findings of ACL 2025* (peer-reviewed proceedings track; dataset + evaluation)
- Publication date: **July 2025** (ACL 2025, July 27–Aug 1, 2025)

- Link: <https://aclanthology.org/2025.findings-acl.891.pdf>

- Why it matters: Adds a linguistically focused causal reasoning dataset (causal + temporal relations, different connective orders) and finds that even strong models struggle to reach high accuracy and often conflate temporal with causal relations—evidence that natural-language causal interfaces need robust causal backends, not just fluent text generation. [42]

### 3. Maturity score (1–7) and reasoning

- **A) Final maturity score: 4**
- **B) Justification mapped to the rubric**
- **What evidence rules out levels 1–3 (the “only theory / only lab demo” range):**
  - There are multiple **functionally usable software artifacts** and prototype systems that operationalize causal modeling and causal querying beyond basic effect estimation, e.g., DoWhy-GCM enabling diverse causal queries “with just a few lines of code.” [3]
  - There is strong evidence of **scaled, engineering-oriented causal inference** work aligned with real platform needs (distributed/large data, operational constraints), including an end-to-end observational study workflow described as productionized in a major company setting. [8]
  - There are peer-reviewed systems papers demonstrating causal inference in operational contexts (e.g., causal diagnosis from raw logs) with measurable performance/effort improvements and artifact availability—well beyond a purely conceptual stage. [14]  
Collectively, this places the ART above “lab principle” and “single prototype” maturity, because functional prototypes exist and are demonstrated on real or operationally-inspired data with measured outcomes.
- **Why this is not yet level 5 (and above) for the ART as a whole:**
  - The ART description implicitly targets **generalizable causal learning and reasoning services** spanning domains, including robust causal discovery under hidden confounding, dynamic world models, and trustworthy counterfactual answering integrated into broader reasoning systems. Evidence shows **active progress**, but also highlights that core components remain fragile or benchmark-constrained:
  - Causal discovery (especially with latent confounders and in dynamical/time-series regimes) is still heavily driven by research benchmarking and method development rather than broadly standardized, push-button production deployment. [43]
  - LLM-based causal reasoning remains inconsistent: formal counterfactual reasoning is often near random without specialized scaffolding, and explicit causal reasoning datasets show persistent errors and confusions. [44]
  - To justify level 5 for the ART *as a whole*, the missing evidence would include: broadly adopted **production-grade “causal reasoning modules”** (across multiple sectors) with clear scaling economics and standardized interfaces; robust validation playbooks for hidden confounding and causal misspecification; and repeated proof that causal discovery and counterfactual

modules maintain reliability under real-world drift and incomplete observability. The recent literature instead suggests tool proliferation + benchmarking, but not yet “production prototype finishing phase” across the full bundle. [45]

- **C) Sub-component maturity breakdown and aggregation**
- **Causal effect estimation & experimentation at scale → ~6**
  - Evidence: large-scale/industrial causal inference methods and workflows are described with distributed scaling and productionization; peer-reviewed journal work addresses large combinatorial experiments. [46]
- **Operational causal diagnosis / root-cause analysis systems → ~5**
  - Evidence: LOGos (PVLDB 2024) demonstrates a prototype causal workflow over real logs with measured improvements; DoWhy-GCM supports root-cause/distribution-shift causal queries as library features. [47]
- **Causal discovery at scale (latent confounders, time-series/dynamical) → ~4**
  - Evidence: SPOT directly targets scalability under latent confounding constraints; multiple benchmark frameworks (CausalTime, CausalDynamics) exist to stress-test methods in more realistic regimes, indicating PoC-quality infrastructure but not generalized deployment. [43]
- **Causal representation learning & causal generative modeling → ~3**
  - Evidence: peer-reviewed ICML/NeurIPS work provides identifiability results and implemented approaches under intervention assumptions, and surveys synthesize the field; however, these methods are not yet demonstrated as stable, general-purpose production components. [48]
- **LLM-assisted causal reasoning / causal setup assistance → ~3**
  - Evidence: TMLR work shows strong performance on several causal-argument tasks, but benchmark datasets indicate persistent failures in explicit and formal counterfactual reasoning; NeurIPS 2025 results show promise in controlled SCM settings. [49]
- **Aggregation to a single ART score:**
  - Because the ART’s benefits are split across multiple application areas and technical threads (scalable effect estimation vs. causal discovery vs. causal representation learning vs. LLM integration), an **average-based score** is most appropriate per the rubric guidance. Averaging the above rough sub-scores (6, 5, 4, 3, 3) yields approximately **4.2**, which conservatively maps to **ART maturity level 4** (“PoC exists and is functional, but broad production scaling and reliability across contexts is not yet demonstrated”). [50]

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[2] [5] [9] [18] [45] <https://arxiv.org/html/2409.08419v1>

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[20] [21] [39] [43] [2406.10537] Scalable Differentiable Causal Discovery in the Presence of Latent Confounders with Skeleton Posterior (Extended Version)

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[22] [28] [31] Learning Linear Causal Representations from Interventions under General Nonlinear Mixing | Empirical Inference – MPI-IS

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[38] Causal Discovery and Inference through Next-Token Prediction | OpenReview

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[40] [41] [44] CounterBench: A Benchmark for Counterfactuals Reasoning in Large Language Models

[https://arxiv.org/abs/2502.11008?utm\\_source=chatgpt.com](https://arxiv.org/abs/2502.11008?utm_source=chatgpt.com)

[42] aclanthology.org

<https://aclanthology.org/2025.findings-acl.891.pdf>

## ART 03.016 Federated & Privacy-Preserving Learning

### 96. ART extraction

**A. Primary capability:** Enables collaborative machine learning on sensitive, distributed datasets without pooling raw data centrally. Models are trained **at data sources** (e.g. user devices or different organizations) and only **privacy-safe updates** (not personal data) are shared, so useful patterns can be learned while preserving confidentiality. This allows AI to leverage fragmented data (that couldn't legally or safely be centralized) by "**bringing the code to the data**" instead of copying data into one place.

### B. Key sub-components/variants:

- **Federated learning algorithms:** Methods like Federated Averaging dispatch an initial model to participants, train locally, and aggregate updates on a server. Variants include **cross-device FL** (many low-powered devices like phones) vs **cross-silo FL** (fewer institutional nodes), as well as techniques like **split learning** and **swarm learning** (decentralized peer-to-peer training).
- **Secure aggregation protocols:** Cryptographic methods (secure multi-party computation, homomorphic encryption) that **encrypt or mask model updates** so that a server or eavesdropper cannot decipher any single participant's data. These ensure only aggregated results are available, preventing reverse-engineering of individual contributions.
- **Trusted execution environments (TEE):** Secure hardware enclaves (e.g. Intel SGX) that run the training code in an isolated, encrypted zone on each device or server. TEEs prevent even privileged insiders from inspecting the data or model updates during computation, adding a hardware layer of privacy assurance.
- **Differential privacy (DP):** Statistical noise injection techniques applied to model updates to **limit information leakage** about any individual data point. By adding carefully calibrated randomness, DP provides quantified privacy guarantees (e.g. an  $\epsilon$ -differential privacy budget) so that the global model or gradients do not reveal specifics of any one user's data.
- **Federation infrastructure & orchestration:** Systems for managing connectivity, scheduling, and aggregation across distributed nodes. This includes coordination servers, networking protocols, and federated learning frameworks (open-source platforms like TensorFlow Federated, PySyft, FATE, NVIDIA FLARE, etc.) that provide tools for deploying FL at scale. These handle heterogeneity in device capabilities, unreliable connections, and

orchestrate rounds of training and model fusion.

- **Privacy/utility balancing methods:** Specialized algorithms to tackle FL challenges such as non-IID data (imbalanced or silo-specific data distributions), communication efficiency (reducing bandwidth or rounds), and fairness. For example, personalization layers allow local tailoring of the global model, and adaptive optimization or data weighting can help when some nodes have scarce data. These ensure the federated approach remains effective even when data across partners is uneven or limited.

### C. Maturity indicators:

- **Peer-reviewed prototypes and field trials:** Evidence of federated learning working on real sensitive data (e.g. multi-hospital studies, cross-bank collaborations) with metrics close to conventional centralized training. For example, published case studies or challenge results where a federated model achieves accuracy comparable to a model trained on pooled data would indicate technical feasibility.

- **Production deployments and products:** Signs that major tech companies or industries have moved FL out of the lab. This could include **shipping features** (e.g. a smartphone app or IoT service that uses on-device federated updates), cloud services offering “federated learning” to clients, or open-source frameworks reaching version 1.0 and being adopted in industry. Multiple well-funded actors (Google, Apple, NVIDIA, Huawei, etc.) actively developing and offering FL solutions or incorporating privacy-preserving learning in their platforms would show competition and investment.

- **Scalability and performance benchmarks:** Reports that FL systems can handle large numbers of participants or large models with acceptable overhead. Maturity would be indicated by overcoming the initial performance penalties – e.g. algorithms or hardware that significantly reduce the extra communication, or protocols that handle millions of devices. Demonstrations of federated training on realistic scales (millions of users or very high-dimensional models) or integration of acceleration (efficient secure aggregation, use of GPUs in enclaves, etc.) suggest readiness for broad use.

- **Standards and consortium adoption:** Emergence of **standards, best practices, or regulatory endorsements**. For example, an IEEE or ISO standard for federated learning architecture, or guidelines from data protection authorities endorsing FL as a privacy measure. Industry consortia (in healthcare, finance, etc.) establishing FL networks, and references to FL in privacy regulations or government AI strategies would show the approach is recognized as a viable solution.

- **Commercial services and cost models:** If companies are offering federated learning as a service (with pricing), or if organizations budget for FL infrastructure as part of their AI deployments, it implies a mature value proposition. Evidence like cloud providers supporting FL APIs, startups selling FL-powered analytics, or surveys showing increased adoption in multiple sectors would indicate that federated, privacy-preserving learning is crossing into mainstream use.

#### 97. Evidence (10–20 recent, reliable sources)

98. **Federated Learning in Public Health: A Systematic Review of Decentralized, Equitable, and Secure Disease Prevention Approaches** — S. T. Shah et al., *Healthcare (MDPI)* – Oct 2025. This peer-reviewed review analyzed 19 studies (2020–2025) applying FL in public health settings. It found that **federated models across multiple institutions preserved privacy while improving generalizability** of disease detection models, enabling “near real-time intelligence” from diverse data that could not be centralized<sup>[1]</sup>. However, it notes ongoing



barriers like data heterogeneity, interoperability gaps, and unclear legal pathways, implying that **FL is promising for secure analytics but needs better standards and regulatory guidance** to reach routine use[2]. (Peer-reviewed paper)

99. **Fair evaluation of federated learning algorithms for automated breast density classification: Results of the 2022 ACR–NCI–NVIDIA FL challenge** — *K. Schmidt et al., Medical Image Analysis – July 2024*. In this international challenge, algorithms were trained on **simulated mammography data from 3 separate hospitals** without pooling patient images. The **winning federated model achieved performance (kappa ~0.65) comparable to a centrally-trained model**, demonstrating that FL can reach centralized accuracy in medical imaging[3][4]. Notably, the smallest data site hurt performance, highlighting the need for methods to handle imbalanced data. This result gives experimental proof that federated training can produce high-quality models in healthcare, validating the approach’s **plausibility and indicating progress toward practical viability**. (Peer-reviewed journal article)
100. **TechDispatch: Federated Learning** — *European Data Protection Supervisor (EDPS) – June 2025*. This EU regulatory bulletin discusses FL as a **privacy-preserving technology** aligned with data protection principles. It confirms that in FL, only model updates (gradients/weights) are shared while raw personal data stays local[5], reducing exposure and breach risk. However, the EDPS also warns of unresolved challenges: even model updates can leak sensitive information (through reverse engineering or **membership inference attacks**), so FL implementations must mitigate these risks[6]. The report’s balanced view — highlighting FL’s compliance benefits alongside its new threat vectors — underscores that the technique is **taken seriously by regulators** but must mature further (through robust privacy techniques and “data protection by design”) before being fully trusted. (Authoritative tech report by EU regulator)
101. **Federated learning frameworks: quality and interoperability for biomedical research** — *M. Chavero-Diez et al., NAR Genomics and Bioinformatics – Feb 2026*. This peer-reviewed article systematically reviewed current open-source FL frameworks (e.g. TensorFlow Federated, PySyft, FATE) for use in biomedical research. It found an **ecosystem of many FL platforms** with good availability and reusability, but **poor interoperability and sparse integration of advanced privacy tools**[7]. Most frameworks are designed for specific use-cases and mainly support basic horizontal FL; features like differential privacy or secure multi-party computation are often missing, and frameworks don’t easily work together. This suggests that while multiple actors have built FL infrastructure (a sign of interest and partial maturity), the **fragmentation and lack of built-in privacy enhancements may hinder scalability and wide adoption**. The paper calls for more flexible, privacy-aware framework design moving forward. (Peer-reviewed review, academia)
102. **Privacy-Preserving Federated Learning on AWS with NVIDIA FLARE** — *K. Kersten (NVIDIA) & U. Khalid et al. (AWS), AWS Partner Network Blog – Nov 2022*. This technical blog introduces **NVIDIA FLARE**, an open-source SDK for federated learning, and its deployment on AWS Cloud. FLARE evolved from NVIDIA’s Clara healthcare platform and **has already been used to build numerous AI applications in medical imaging**[8]. The post details FLARE’s architecture for secure collaboration, including components for provisioning federations and encrypted communication. Notably, **FLARE comes with built-in support for differential privacy and even homomorphic encryption filters** to protect data during training[9]. The availability of such a robust, enterprise-grade FL toolkit indicates a **commercial push toward scalable federated learning**. That AWS and NVIDIA jointly promote it shows industry validation, and its real-world use cases in healthcare illustrate growing maturity (moving from research to practical toolchains). (Vendor technical documentation / blog)

103. **Intel & Ping An: Break Down Data Silos with Hardware-enhanced Security (Case Study)** — *Intel & Ping An Technology (China) – Jan 2023*. This case study describes how Ping An (a major Chinese financial and healthcare tech company) integrated Intel’s SGX trusted execution environments into their federated learning platform. By running FL within SGX enclaves, Ping An **secured multi-source data collaboration across insurance, healthcare, voice, and IoV (telematics) applications**[10]. The document reports “*noteworthy results*” and positive user feedback in these domains, implying the approach is working in practice. A Ping An engineer is quoted emphasizing that **Intel SGX creates trusted hardware zones for each data source, ensuring privacy and boosting AI model training with multi-party data**[11]. This demonstrates a real-world deployment of federated learning enhanced by hardware security, indicating that at least some businesses have moved beyond prototypes to implementing FL for sensitive data analytics. (Vendor case study – cautious use as it’s a corporate publication, but concrete in reporting deployment and impact)
104. **Differentially private knowledge transfer for federated learning** — *T. Qi et al., Nature Communications – June 2023*. This peer-reviewed study addresses the performance penalty of strict privacy in FL. The authors propose “PrivateKT,” a method using a small public dataset to transfer knowledge, achieving markedly better utility under strong privacy. **In experiments, PrivateKT closed ~84% of the accuracy gap between a centrally-trained model and a federated model with rigorous differential privacy ( $\epsilon$  as low as 1)**[12]. This is significant evidence that the **technical feasibility of privacy-preserving learning is improving** – the accuracy trade-offs can be mitigated. It supports the plausibility of the ART by showing that even under legal-grade privacy constraints (DP), models can approach conventional performance. Such advances in algorithms are crucial for federated learning to become standard; they indicate the research community is actively solving remaining barriers (like privacy vs. accuracy). (Peer-reviewed research paper)
105. **Efficient Differentially Private Secure Aggregation for Federated Learning (USENIX Security ’22)** — *T. Stevens et al., 31st USENIX Security Symposium – Aug 2022*. This academic work (peer-reviewed) presents a new cryptographic protocol that combines secure aggregation with differential privacy, without needing a trusted third party. It leverages hardness of lattice problems (Learning with Errors) to protect gradients. The authors report that their protocol **outperforms prior art and scales to large numbers of clients while maintaining optimal model accuracy under DP**[13]. This evidence shows progress on the scalability and efficiency front: federated learning can be made **both secure and performant at scale** via advanced cryptography. It indicates that previously blocking issues (e.g. high overhead of secure aggregation, or too much noise from DP) are being addressed, a sign that the technology bundle is steadily moving from theoretical possibility toward practical deployment in larger networks. (Peer-reviewed conference paper)
106. **WeBank FATE Case Study – Accelerating Secure Computing for Federated Learning** — *WeBank AI & Intel, case study (PDF) – Nov 2022*. This joint report highlights outcomes from deployments of **FATE (Federated AI Technology Enabler)**, an open-source FL platform originally from China’s WeBank. Two real-world impacts are quantified: (a) In a healthcare scenario, **small hospitals using horizontal FL saw 10–20% higher diagnostic accuracy** for stroke prediction compared to using only their own data, while keeping patient data local[14]. A modeling of scale-up suggests that if 10% of China’s population were covered by such federated early-disease prediction, it could save ~¥200 million annually in healthcare costs[15]. (b) In finance, a federated credit scoring solution using data from multiple institutions improved the risk model’s effectiveness by **12%** and cut credit approval costs ~5–10%, all with privacy protections in place[16]. These concrete metrics from large-scale trials show that federated learning is not only feasible but **adds value in production settings**,



reducing key bottlenecks (data sharing barriers) and delivering economic benefits. The fact that WeBank's FL platform is **adopted by various organizations** and now part of Linux Foundation's ecosystem further underlines the growing maturity and industry uptake. (Vendor/consortium technical report)

107. **Advances in private training for production on-device language models (Gboard)** — Z. Xu & Y. Zhang, *Google Research Blog* – Feb 2024. Google details how its Gboard keyboard app now trains its predictive text models via federated learning with rigorous privacy. By 2024, **over 30 on-device language models across 7+ languages and 15+ countries are being trained with federated learning combined with formal differential privacy guarantees**[17]. The DP protection is strong ( $\delta=1e-10$  and  $\epsilon$  often  $<1-10$  range), making this the **largest production deployment of user-level DP + FL** to date[18]. They also mention techniques like secure aggregation (encryption of updates) and client-side data controls in use[19]. This source is compelling evidence of maturity: a tech giant has integrated the full federated, privacy-preserving stack (FL + DP + SecAgg) into a live product used by millions. It shows that the ART's approach is not only plausible but already **delivering value at scale (lower latency and privacy by design for users)**, and that the engineering hurdles (communication at scale, privacy accounting) have been overcome in at least one major domain (mobile AI). (Industry blog post, describing a deployed system with technical detail)
108. **Swarm learning for decentralized AI in cancer histopathology** — O. L. Saldanha et al., *Nature Medicine* – Apr 2022. This study demonstrated a variant of federated learning ("swarm learning" using a blockchain-based peer-to-peer approach) on a large medical dataset. **Five thousand patient pathology images from Northern Ireland, Germany, and the USA were used to train an AI model collaboratively without data sharing**[20]. The swarm-trained model predicted cancer genetic markers as accurately as a model trained on centrally merged data, and better than models trained in isolation at each hospital. This shows that even in highly regulated, multi-national settings, distributed learning can produce **high-quality models while avoiding legal barriers of data pooling**. The success across continents and the fact that performance kept up with conventional training underscore the **scientific feasibility and potential impact** of privacy-preserving learning in critical domains like cancer diagnosis. (Peer-reviewed article)

#### 109. **Maturity score (1–7) and reasoning**

##### **A. Final Maturity Score: 6** (Products delivered and scaling)

**B. Justification:** Federated and privacy-preserving learning has **progressed beyond lab prototypes (Levels 2–3)** and even beyond isolated proof-of-concepts. We see **functional production deployments** – for example, Google's Gboard shipping to millions of users with federated, differentially private training in place[18]. Such deployments prove that the key technical barriers (distributed optimization, basic privacy protection) have been solved to a degree that meets real-world requirements, ruling out lower maturity levels. Multiple well-funded actors are actively developing and adopting FL (Google, NVIDIA, Intel, WeBank, Apple, healthcare consortia), indicating **competition and investment consistent with Level 5**. The evidence of actual **products and services being delivered** pushes the score to **Level 6**: Gboard's ongoing global rollout, NVIDIA's FLARE platform being used in practice, and Ping An's industry applications show that federated learning is being implemented for end-users or clients today (often internally financed as part of bigger products). Furthermore, application areas are expanding (mobile keyboards, healthcare diagnostics, finance, IoT), and efforts are underway to reduce costs/overheads – e.g. new protocols to cut bandwidth or use hardware to secure data[10][13]. These are signs of scaling and maturing ecosystems.

**Why not Level 7?** The technology hasn't yet reached ubiquitous adoption or a state of **wide market competition in off-the-shelf FL products**. While there are multiple frameworks, we don't yet see many standalone federated learning products with a broad customer base and **independent demand**. Many deployments are either internal (Google, Apple using it for their own apps) or pilot collaborations in specialized fields (medicine, finance). Some critical challenges remain before full commoditization: e.g. seamless interoperability between frameworks[7], stronger guarantees against information leakage[6], and ease-of-use for organizations without deep ML expertise. In short, the field is at the stage of **early products and expanding pilots (6)**, but not yet a default component in every AI deployment (which would merit 7 when "competing products and rising demand" are clearly observable). Evidence like the EDPS report and framework reviews show that **integration and standardization are still in progress**, and not all privacy-preserving techniques are production-ready (for example, fully homomorphic encryption in FL is still experimental). Thus, it hasn't fully crossed into the "competitive growth" phase despite clear momentum.

**C. Sub-component breakdown:** The ART comprises a bundle of technologies that are maturing at slightly different paces, but they converge to enable the same overall functionality (privacy-preserving collaborative learning):

- *Core federated learning algorithms:* **Level 6**. The concept of training on distributed data is well-demonstrated and in use (e.g. federated optimization algorithms like FedAvg running on **millions of phones in production**[18]). Multiple tech companies and open-source projects have production-grade implementations, indicating a mature core.
- *Differential privacy in federated ML:* **Level 5–6**. Research of the last few years (e.g. DP-FTRL and PrivateKT) and Google's deployment show that formal DP can be applied at scale with acceptable performance[18][12]. At least one major deployment (Gboard) uses it, but outside of big tech, many FL applications still do not implement strong DP, suggesting uneven adoption (hence on the cusp of 6).
- *Secure aggregation & cryptographic protocols:* **Level 5**. Secure aggregation (basic encrypted averaging of updates) is already employed in practice (Google's system, for instance) and frameworks like NVIDIA FLARE include it[9]. Advanced cryptographic FL (MPC, homomorphic encryption) is more nascent – demonstrated in academia and some pilot projects, but not widely deployed due to complexity. This sub-tech is closer to Level 3–4 in isolation (lab demonstrations like the USENIX '22 protocol[13]), but simpler versions are in production use (hence averaging to ~5).
- *Trusted hardware enclaves:* **Level 4–5**. The use of TEEs for FL security has been proven (Ping An's implementation with Intel SGX[10]) and a few platforms support it, but it's not yet common across deployments. It's moving from prototype to early adoption in sensitive industries.
- *Ecosystem and standards:* **Level 5**. The field has multiple frameworks and consortium-driven platforms (indicating competition and interest), and regulators acknowledge FL as a promising PET (privacy-enhancing tech)[21]. Efforts like FATE (Linux Foundation) and IEEE standards show coordination, but full interoperability and plug-and-play ease aren't there yet[7].

Given these subcomponents serve one integrated purpose and the **highest-impact implementations (federated + DP)** are already at a high maturity, we assign the overall ART the score **6**. We weight the score toward the most developed aspects (since an organization can achieve the ART's goal today by using the mature pieces, even if not all approaches are

equally advanced). In summary, federated and privacy-preserving learning is **commercially deployed and scaling in certain domains (supporting Level 6)**, though some supporting techniques are still catching up, and broader adoption should follow as those gaps close.

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## ART 03.017 Trustworthy AI Systems

### 110. ART extraction

111. **Primary capability:** Enabling AI systems to operate **reliably and safely without constant human supervision** in high-stakes domains. This means AI that is *predictable, auditable, and aligned with explicit rules/values* even under stress, errors, or attacks. It would *reduce the need for human oversight* by providing understandable outputs (with explanations, confidence metrics) and automatic fail-safes.

### 112. Key components & variants:

- **Robust & Resilient AI algorithms:** Machine learning models (e.g. deep networks) trained or structured to *withstand adversarial inputs, distribution shifts, errors, and perturbations* without unpredictable failures. This includes adversarial training, certified robustness techniques, and redundancies for safety.
- **Formal verification & validation:** Methods to *formally prove or verify* certain properties of AI components (e.g. proving a neural network controller will not violate safety constraints within defined conditions). Also rigorous testing, simulation, and validation protocols to guarantee performance *within a specified operating envelope*.
- **Secure execution environments:** Deployment setups that use *trusted hardware or cryptographic techniques* to ensure the AI model and data cannot be tampered with or leaked. This ranges from trusted execution environments (enclaves) for AI inference to federated or privacy-preserving learning that maintain data confidentiality.
- **Monitoring and self-monitoring layers:** Integrated *sensing of the AI's own behavior and context* – e.g. runtime monitors for anomalies, bias detection, concept drift or performance degradation. The AI can flag when it is operating out of its trained domain or when uncertainties are high.
- **Explanations and transparency tools:** Mechanisms for the AI to provide *human-interpretable explanations, decision rationale, provenance of data used, and calibrated confidence scores* for its outputs. This helps users and auditors understand *why* the AI made a decision and whether to trust it.
- **Objective and constraint interfaces:** Clear interfaces for humans to *configure the AI's goals, rules, and escalation policies*. For instance, setting ethical constraints or fairness criteria that the AI must follow, and defining when the AI should hand control back to a human or go into a safe fallback mode.

- **Self-correction and fail-safe mechanisms:** The AI system can *automatically adjust or shut down* when it detects potential failures. For example, an autonomous vehicle's AI might revert to a safe-state or request human intervention if sensors malfunction or if an unrecognized scenario occurs.
  - **Lifecycle governance & traceability:** Tools and processes for *tracking training data provenance, model versions, and policy changes* over time. This includes audit logs, model “datasheets” or cards documenting performance and limitations, and pipelines that ensure updates to the AI are reviewed for compliance with safety and ethics guidelines.
113. **Maturity indicators:** Evidence would include **working prototypes and deployed systems** that embody these features. Key signs: (a) **Successful field trials or deployments** of AI in high-stakes settings (medicine, transportation, etc.) operating with minimal incidents under monitored conditions. (b) **Proof-of-concept demonstrations** of self-monitoring AI triggering safe fallbacks or handoffs in response to anomalies. (c) **Formal certification or verification results** for AI components (e.g. a neural network with mathematically proven safety bounds). (d) **Competition and investment** – multiple companies releasing “AI assurance” tools (for robustness, explainability, fairness) or integrating them into products, and industry standards/best-practice frameworks being published. (e) **Regulatory or enterprise adoption** – e.g. requirement of explainability or bias audits in procurement, showing these technologies are moving from lab to real-world requirement. (f) **Performance benchmarks** that show improvements: e.g. robust models that maintain high accuracy under attacks or across data shifts, or explainability tools that demonstrably improve user trust or debugging. (g) **Integration into ML platforms** – major AI providers offering built-in features for fairness, drift detection, secure model serving, etc., indicating commercial viability and scaling.
114. **Evidence (10–20 recent, reliable sources)**
115. **Adversarially Robust Models at Scale – Wang et al. (UCSC), CVPR 2024 (peer-reviewed) – June 2024. Finding:** Demonstrates a breakthrough in training large vision models with adversarial robustness. By adversarially training a Vision Transformer on a 1-billion-sample dataset, they achieved **71.0% robust accuracy on ImageNet ( $\ell_\infty$  norm attacks)** – a ~12% absolute improvement over prior state-of-the-art<sup>[1][2]</sup>. *Why it matters:* This shows that the *once “brittle” deep models can be made significantly more robust* to adversarial inputs when scaled and trained properly, indicating the scientific feasibility of robust AI required for trustworthy systems. It also proves out new techniques (like their AdvXL framework) to overcome previous scalability problems in robust training, a key step toward deployment in the wild.
116. **Microsoft Responsible AI Toolbox – Besmira Nushi et al., Microsoft Research blog (open-source toolkit) – Feb 2023. Finding:** Microsoft released an open-source Responsible AI Toolbox integrated with Azure ML, providing *interoperable tools for error analysis, fairness assessment, interpretability, and mitigation tracking*<sup>[3]</sup>. Notably, the toolbox includes a “Mitigations” library and a “Tracker” that lets users test bias mitigation techniques and *visualize model performance broken down by subgroups* to detect hidden failure modes<sup>[4]</sup>. *Why it matters:* It indicates *industry-grade tooling is now available to operationalize trustworthiness*. Practitioners can systematically debug models, enforce fairness metrics, and document improvements – suggesting that concerns like bias and explainability are being addressed at scale in real development pipelines (a sign of growing maturity beyond academic proofs-of-concept).



117. **Amazon SageMaker ML Lineage Tracking – Amazon Web Services documentation** (vendor technical doc) – Nov 2023. **Finding:** AWS’s production ML platform now offers automated *lineage tracking* for models: it records every step from data prep to training to deployment, tracking datasets, parameters, model artifacts, and versions[5][6]. This allows one to *reproduce models, audit their exact data sources, and prove compliance* with governance standards. *Why it matters:* High-stakes AI demands traceability. The existence of *built-in lineage and governance in a leading cloud ML service* shows that the industry recognizes the need for **accountability and auditability**. It’s evidence of *commercialization* of trustworthy AI practices – clients (like banks or healthcare) can meet regulatory requirements by using these tools, reducing the friction that previously blocked AI deployment due to lack of transparency.
118. **Autonomous Medical AI Deployment (IDx-DR) – Hunfeld et al., Scientific Reports (peer-reviewed)** – Jan 2026. **Finding:** A real-world clinical evaluation of an FDA-approved autonomous AI (IDx-DR for diabetic retinopathy) on 875 patients showed it could *safely handle a majority of cases*. The AI’s diagnostic system **successfully analyzed 63.4% of patient cases on its own**, flagging ~26% as “not analyzable” (poor image quality) for human follow-up[7]. For severe disease, its performance reached **94.4% sensitivity and 90.5% specificity** (versus expert ophthalmologists) when good-quality inputs were available[8]. *Why it matters:* This is *tangible proof of a trustworthy AI in practice*. The system had *built-in fail-safes* (it outputs “image insufficient” rather than risking a wrong diagnosis), and it provided high accuracy in detections – addressing safety and effectiveness in a high-stakes domain. It also shows that *regulators have begun approving such systems*, and they are being deployed to augment healthcare – a strong indicator that the technology (at least in constrained scopes) has passed proof-of-concept into real operation.
119. **NIST AI Risk Management Framework (RMF) – NIST report, National Institute of Standards and Technology** (U.S. Govt, standards roadmap) – Jan 2023. **Finding:** This authoritative framework defined **“trustworthy AI” characteristics** including validity, reliability, safety, *security/resilience*, explainability, privacy, and **fairness (bias management)**. For example, it specifies that *secure and resilient AI systems “withstand unexpected adverse events or changes...and degrade safely and gracefully when necessary.”*[9] Likewise, “Fair AI” is defined as having *harmful bias managed*, noting three sources of bias (systemic, statistical/computational, human) that must be addressed[10]. *Why it matters:* This shows a *broad consensus and clarity on what technical measures are needed* for trustworthiness. The RMF (while voluntary) is being adopted as a baseline – its detailed guidance (e.g. on testing for bias or ensuring fail-safe behavior) reflects that the field has matured to the point of *codifying best practices*. It also pushes developers toward measurable standards, accelerating development of tools for alignment, bias mitigation, and robust design (many of which we see emerging in other evidence here).
120. **Out-of-Distribution (OOD) Detection in AI – Mortier et al., Bioinformatics (peer-reviewed)** – 2025. **Finding:** Demonstrated that modern OOD detection methods can reliably *catch when new input data falls outside a model’s training distribution*. In testing on biomedical data, six different OOD algorithms were able to **accurately identify novel cell types** and *flag significant data shifts* in gene expression datasets[11]. *Why it matters:* An AI that monitors its own input for “unfamiliar” patterns is crucial for self-monitoring and safe deployment. This study provides experimental evidence that such mechanisms work: the AI *can detect when it might be entering an unknown regime* where its predictions could be invalid. It is a step toward the “*internal shift detection*” described in the ART: practically, systems like this could trigger an alert or fallback mode when conditions stray beyond what they were trained on – an essential component for trustworthy autonomy.

121. **Human Trust and Explanations Study – Nicolson et al., *npj Digital Medicine* (peer-reviewed) – Nov 2025. Finding:** In a clinician user study, adding explainable AI features had *mixed effects* on trust and performance. An explainable model for ultrasound imaging did *increase clinicians' confidence* in the AI, but **explanations had no significant effect on overall trust or reliance** on the AI's recommendations[12]. Some clinicians even performed worse with AI explanations than without. *Why it matters:* This is a reality-check that while explainability tools are available (and indeed being deployed), *they don't automatically solve the trust issue in practice*. Users may not uniformly benefit from them, highlighting a maturity gap: the technology for generating explanations exists (and is a pillar of trustworthy AI), but achieving *consistently improved human-AI trust and outcomes* may require further refinement of how explanations are presented or used. It underscores that *"trustworthy AI" is not just a checklist of features; it requires validation in human interactions*. The ongoing research here is evidence that we are in a formative stage of learning how best to integrate these tools for true value.
122. **Confidential Computing for AI – Elsie Jang, Confidential Computing Consortium Workshop report (technical blog) – Jan 2026. Finding:** Progress in secure AI execution is marked by hardware advances in 2023: **GPU-level Trusted Execution Environments (TEE)** became available, extending confidential computing to AI workloads[13]. (NVIDIA has been working on GPU enclaves since ~2019 for a client; Google's TPUs still lack support as of 2025.) These TEEs allow AI models to run inside encrypted, isolated memory regions on accelerators, protecting both model weights and user data during inference. *Why it matters:* Trustworthy AI isn't just about the model's logic – it's also about *securing the infrastructure* so the model cannot be manipulated or leak sensitive information. The fact that *confidential AI inference is now technically feasible on modern hardware* is a big enabler: for instance, a hospital could run an AI on patient data in the cloud with guarantees that no one (not even the cloud provider) can peek at the data or altered model. This development addresses the "unauthorized access" and "cryptographic infrastructure" element of the ART description, moving it from theory toward implementation.
123. **"Constitutional AI" for Value Alignment – Bai et al. (Anthropic), arXiv preprint (peer-reviewed at ICLR 2023) – Dec 2022. Finding:** Introduced a novel *self-alignment* method for AI models using a fixed set of human-provided principles (a "constitution"). The team trained a large language model to be harmless and helpful **without extensive human feedback**: the AI model was made to *generate critiques of its own outputs and improve them* following the given principles[14]. They then used a form of reinforcement learning where the *reward signal came from an AI evaluator (model-generated preferences) rather than human labels*, called "RL from AI Feedback (RLAIF)"[15]. The result was an assistant that *refused unsafe or unethical requests by citing its principles*, yet did so in a non-evasive, transparent manner (explaining its objections). *Why it matters:* This showcases a viable path to *embedding explicit rules and values into AI behavior* – essentially aligning the AI internally with human-defined ethics. It's significant because it achieved alignment with far fewer human interventions, hinting at scalable solutions for future, more powerful AI. This addresses the core of the ART: making AI behavior *controllable and value-driven by design*. The work is being deployed in real systems (Anthropic's Claude chatbot), indicating a transition from research to practical tooling for alignment.
124. **Neural Network Verification Competition (VNN-COMP 2023) – Brix et al., arXiv (report) – Dec 2023. Finding:** The 4th International Verification of Neural Networks Competition featured 7 teams and established common benchmarks for formally verifying properties of neural nets[16]. Notably, the community has standardized on exchange formats (ONNX for models and VNN-LIB for specs) and used an *automated evaluation pipeline* on

cloud instances to compare tools fairly[17]. Tools showed increasing capability to prove properties on diverse networks (e.g. robustness within certain input bounds, safety of control decisions, etc.). *Why it matters:* Formal verification of AI, once very nascent, is now *organized and progressing year-over-year*. The existence of such competitions signals that the field has moved from isolated academic ideas to a coordinated effort to push capabilities (e.g., handling larger networks or more complex specs each year). It's an indicator of plausibility that eventually, at least in well-specified scenarios, we will have **AI components with mathematically provable guarantees** – a cornerstone for high-assurance systems. This evidence shows the underlying methods are maturing, though they may still be computationally expensive or limited to smaller models today.

125. **Industry Investment in Trustworthy AI (AI Security) – Cisco acquisition of Robust Intelligence, reported by S&P Global – Aug 2024. Finding:** Cisco Systems acquired Robust Intelligence (a startup specializing in AI robustness and validation) for an estimated **\$350M**[18]. Robust Intelligence's platform provides automated "AI firewall" and stress-testing of models to catch vulnerabilities. The report notes this is one of the first major tech acquisitions in the AI assurance space, and it cites enterprise survey data: "*security for generative AI*" is the #1 emerging technology priority in security teams, with **23% of organizations already running pilot projects** and many more planning to in the next 1–2 years[19]. *Why it matters:* This is strong evidence of *commercial and competitive momentum* toward trustworthy AI solutions. Multiple well-capitalized actors are now in the fray – not only startups with dedicated products, but big incumbents like Cisco, IBM, Microsoft, Google investing via acquisitions or internal R&D. The market pull (driven by client demands and fear of AI failures) is validating that these technologies aren't just academic; they are becoming *standard components of AI deployments*. The acquisition also suggests that robust AI tools are nearing a level where they can be *packaged and integrated into enterprise workflows at scale*, heralding a new industry segment focused on AI risk management.

126. **Maturity score (1–7) and reasoning**

**Final Score: 5 (out of 7)** – *The overall technology bundle "Trustworthy AI Systems" is at a solid mid-to-late development stage. Many pieces have progressed beyond proof-of-concept (Level 3) and even pilot deployments (Level 4), entering an era of active productization and competition (Level 5). However, full integration and ubiquity are not yet achieved, and some sub-components remain less mature, keeping the bundle shy of Level 6.*

- **Why not lower:** We have **concrete evidence ruling out Levels 1–4**. The fundamental feasibility is long proven (Level 1/2) – e.g. we have lab validations for robust learning, bias mitigation, etc., and even formal verifications on small cases. We've also seen **laboratory prototypes solving key barriers (Level 3)**: for instance, the 2024 robust model that achieved 71% robust accuracy[1][2] removed a major blocker by showing large models can be trained to resist adversarial attacks. **Working prototypes in operational environments (Level 4)** are clearly present: the IDx-DR medical AI running autonomously in clinics is essentially a proof-of-concept deployed under real conditions (with regulatory approval)[7][8]. Likewise, multiple *comprehensive frameworks* (Microsoft's, IBM's, etc.) have been rolled out to practitioners to meet real-world needs for explainability and monitoring, indicating functionality meeting commercial requirements. These achievements show that *no single piece of the puzzle is purely theoretical anymore – each has seen practical demonstration*.
- **Why not higher: Level 6 (products in widespread delivery)** is on the horizon but *not fully realized across the board*. While some trustworthy AI features are included in products (e.g. cloud ML services offering bias tools, or autonomous AI diagnostics in healthcare), we can't



say the *complete vision* is delivered at scale yet. For example, **formal verification** of AI remains mostly a research endeavor – we don’t yet have neural networks routinely shipping with provable guarantees (they are *starting* to for narrow cases[17], but it’s not mainstream). Similarly, **true self-monitoring AI with broad self-correction** is still limited – as evidence, even though explainability tools exist, their effectiveness in fostering trust can vary and sometimes underperform expectations[12]. And importantly, today’s powerful AI models (like large language models) still exhibit occasional brittleness or unpredictable outputs, meaning *robustness and alignment are not “solved” problems* in practice, and further R&D is ongoing (sign of not yet Level 6 where issues are largely ironed out and products reliably meet stringent demands). Additionally, the need for high-quality data, policy governance, and the overhead noted in the ART description is indeed being encountered as a friction in scaling these solutions – organizations are grappling with implementing these layers, suggesting the technology hasn’t yet become plug-and-play universally.

- **Indicators of Level 5:** We see **multiple well-capitalized actors racing** to deliver Trustworthy-AI-enabling products. The Cisco–Robust Intelligence deal in 2024 is a prime example, showing that big players are investing heavily to obtain these capabilities[18]. Startups focusing on AI auditing, fairness, and safety have attracted significant funding, and big cloud providers have launched competing responsible-AI toolsets – a clear sign of a competitive market forming (a hallmark of Level 5). Moreover, *standards and regulations are coalescing* (e.g. NIST RMF, impending EU AI Act), effectively forcing the hand of vendors to build compliance features – this accelerates product development and deployment. We also see that many of these subsystems (*robustness, explainability, monitoring*) are being *integrated into enterprise workflows* now (via toolboxes and platforms), indicating that production prototypes are being actively trialed and refined in real deployments. Progress is indeed **fast-paced**, as the rubric describes for Level 5: the timeline from research to product has shortened (e.g., Anthropic’s 2022 alignment method was incorporated into a commercial chatbot the next year).
- **Sub-component breakdown:** If we score elements individually, **some elements are quite mature (Level 6)** – e.g. *Explainability and bias mitigation tools* are delivered as part of major cloud services and used in customer-facing AI solutions today. *Model monitoring and data lineage* (MLOps governance) are also well into Level 6 in enterprise AI deployments, as evidenced by widespread availability[5][6]. Meanwhile, **other elements linger around Level 3–4** – e.g. *formal verification of AI* is still mostly at prototype stage (lab competitions, initial aerospace trials) without industry-wide deployment, and *general AI self-correction or strong value alignment* remains at proof-of-concept (we have encouraging demos[14][15], but not yet a guarantee in every deployed AI). **Robust adversarial resilience** is roughly Level 4 – researchers have demonstrated it in principle at scale[1][2], and some robust models are used in security-sensitive fields, but it’s not yet standard for all AI systems. Considering this mix, the *overall bundle’s maturity is an aggregate in the Level 5 range*. The more developed aspects show that trustworthy AI *can* be productized, and the less developed ones are actively being worked on with strong incentives to catch up (especially as regulation creates urgency). We choose the **average-based score of 5**, reflecting that many (though not all) pieces have moved into the stage of intense engineering, commercialization efforts, and early adoption.

**In summary,** *Trustworthy AI Systems* as a unified vision is well past the exploratory stage – it’s becoming a competitive requirement and is being partially delivered in practice (hence above Level 4). But achieving the full, integrated ideal (where AI is universally safe, auditable, and self-monitoring by default) will require a bit more time and advancement, which is why we stop at **Level 5**. The ongoing evidence – from field deployments to corporate investments – strongly suggests that within the next few years we’ll see further convergence toward Level 6, as isolated trustworthy AI capabilities consolidate into standard product features and

industry norms. For now, however, the technology's **maturity is best characterized as “proven in parts, with active expansion toward comprehensive solutions.”**

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## ART 03.018 Automated Machine Learning (AutoML)

### 1. ART extraction

**A. Primary capability** – The ART promises a “*model and agent factory*” that can **automatically design, train, and deploy ML models and agents with minimal human input**. Key capabilities include: - **End-to-End Model Building**: Automatically selecting model architectures, hyperparameters, and training pipelines to produce high-performing predictive or generative models without manual tuning. - **Autonomous Agent Training**: Given simulators or interaction data, automatically training reinforcement learning (RL) agents through trial-and-error (including safe exploration and sim-to-real transfer) to achieve specified goals.

**B. Key sub-components / variants** – This technology bundle encompasses several threads: - **Neural Architecture Search (NAS) & Hyperparameter Optimization (HPO)**: Algorithms to automatically find optimal model architectures and training settings[1]. This extends to *AutoDL* for deep nets and *AutoRL* for policy networks[2]. - **Automated Data Preprocessing & Feature Engineering**: Pipelines that clean and transform raw data, engineer features, and handle data splits with minimal human guidance (currently partial in many AutoML tools[3]). - **AutoML for Reinforcement Learning (AutoRL)**: Methods to automate the design of RL training (reward shaping, environment generation, algorithm selection) – a nascent area tackling RL-specific challenges[4][5]. - **Continuous Model Monitoring & Adaptation**: Systems that monitor deployed models for performance drops or data drift and can trigger retraining or rollback to maintain robustness over time (often integrated in modern AutoML platforms[6]). - **Human-ML Interface (No-Code ML)**: User interfaces (dashboards, natural language prompts, APIs) enabling non-experts to request and deploy models/agents without coding, effectively democratizing model creation[7].

**C. Maturity indicators** – Evidence of maturity would include: - **Peer-Reviewed Demonstrations**: Proof-of-concept AutoML systems that **match or exceed expert-designed models** on benchmark tasks (accuracy, efficiency) and solve previously intractable design problems[8][9]. - **Production-Ready Frameworks & Products: Multiple competing AutoML platforms available commercially** (cloud services, enterprise software) with growing user adoption[10][11]. Indicators include **customer case studies** showing reduced development time or improved outcomes via AutoML[12]. - **Scaling and Self-Management**: AutoML solutions managing **large-scale workloads** (big data, complex models) and incorporating features like automated drift detection, safety constraints, or self-tuning in production[6]. Field trials or deployments of AutoML-driven agents (e.g. in robotics or finance) would further demonstrate maturity. - **Investment and Competition**: Significant **R&D investment by major tech companies and startups**, with dedicated conferences (e.g. an AutoML Conference since 2022) and an expanding market size, signaling that the technology is moving toward mainstream use[13].

## 2. Evidence (10–20 recent, reliable sources)

- Automated RL survey – Parker-Holder et al., JAIR (2022):** “*Automated Reinforcement Learning (AutoRL): A Survey and Open Problems.*” **Venue:** Journal of AI Research, vol. 74, 2022. **Findings:** Surveys how AutoML techniques are being extended to RL, noting that **AutoML has shown promise in automating RL training design**, with initial successes in domains from RNA sequence design to Go gameplay[4]. AutoRL is identified as an *emerging research area* addressing RL-specific challenges, underlining the plausibility of an “agent factory” but also that additional research is needed for full maturity[4][5].
- AutoML hyperparameter optimization – Vincent & Jidesh, Scientific Reports (3/2023):** “*An improved hyperparameter optimization framework for AutoML using evolutionary algorithms.*” **Venue:** Scientific Reports (Nature), Mar 2023. **Findings:** Proposes enhancements to Bayesian HPO in AutoML by integrating genetic algorithms, differential evolution, and CMA-ES for optimizing the acquisition function. In experiments on image classification, these evolutionary tweaks **significantly improved model performance compared to standard Bayesian optimization**[11], highlighting ongoing advances that make AutoML model tuning more efficient and effective (thus increasing the feasibility of fully automated model search).
- AutoML framework benchmark – Eldeeb et al., Expert Systems with Applications (6/2024):** “*AutoMLBench: A comprehensive experimental evaluation of automated machine learning frameworks.*” **Venue:** ESWA (peer-reviewed), June 2024. **Findings:** Benchmarked **six AutoML frameworks** (Auto-WEKA, Auto-sklearn, TPOT, Recipe, ATM, SmartML) on 100 diverse datasets[14]. It finds that these tools can reliably **produce models competitive with hand-tuned models**, given sufficient time budgets. Key insights include: small search spaces with top algorithms yield near-optimal results, meta-learning helps cold-start on short budgets, and **ensemble models consistently improve accuracy**[15]. This cross-framework study indicates a *maturing ecosystem* of AutoML solutions, with multiple implementations in active use and known design trade-offs (time vs. performance, etc.), supporting the technology’s plausibility and emerging standardization.
- AutoML for small data & usage trends – Conrad et al., Scientific Reports (11/2022):** “*Benchmarking AutoML for regression tasks on small tabular data in materials design.*” **Venue:** Scientific Reports (Nature), Nov 2022. **Findings:** Evaluated AutoML on small (~<1000 samples) science datasets. Concludes that **AutoML is highly competitive with manual model optimization even with limited training time**[16], often matching expert-tuned results, which underscores its practicality. Importantly, the paper notes **widespread adoption by practitioners**: a 2021 Kaggle survey found ~58% of data scientists use AutoML tools (and rising)[17]. However, it also observes that current AutoML tools mostly automate model/parameter selection, whereas **data preprocessing, feature engineering, and model interpretability remain only partially automated** in practice[3]. This mixed finding shows the field has *proven core capabilities* (model search/tuning) and active usage, while pointing out remaining gaps (full pipeline automation and self-explanation).
- AutoML & LLMs (vision paper) – Tornede et al., arXiv preprint (6/2023):** “*AutoML in the Age of Large Language Models: Current Challenges, Future Opportunities and Risks.*” **Venue:** arXiv preprint (under review), June 2023. **Findings:** An expert roadmap discussing how AutoML and large language models (LLMs) can mutually enhance each other. It states that **AutoML has achieved remarkable success over the last decade, evidenced by heavily-used open-source frameworks (Auto-sklearn, AutoGluon, etc.) and commercial tools**[18]. This underscores that the core AutoML idea is already validated and in wide use. At the same time, the authors note that *current AutoML methods are not yet equipped to fully automate the entire lifecycle of massive LLMs* due to extreme compute demands and multi-stage training

complexities[19]. This source reinforces that for typical problems AutoML is quite mature, while the frontier (applying it to state-of-the-art AI like billion-parameter models) is an ongoing challenge – aligning with the ART’s constraint that large data/compute requirements remain a bottleneck.

- **AutoML surpassing human-designed algorithms – Fawzi et al. (DeepMind), *Nature* (10/2022):** “*Discovering faster matrix multiplication algorithms with reinforcement learning.*” **Venue:** *Nature*, Oct 5, 2022. **Findings:** DeepMind’s “AlphaTensor” agent used AutoML-like search (via deep RL) to **automatically discover new matrix multiplication algorithms more efficient than any human-derived algorithm**[8]. Notably, it found a 4×4 matrix multiply method that improves on Strassen’s classical algorithm – the first such improvement in 50 years[20]. This dramatic result demonstrates the *scientific plausibility* of automated methods designing superior solutions in very complex search spaces. AlphaTensor is a specific case (algorithm design), but it epitomizes the ART’s claim that automated systems can “reach beyond human intuition”[21] – lending credibility to AutoML’s ability to explore model/agent design spaces at superhuman scale and thoroughness.
- **Automated algorithm deployed in practice – Mankowitz et al. (DeepMind), *Nature* (6/2023):** “*Faster sorting algorithms discovered using deep reinforcement learning.*” **Venue:** *Nature*, June 7, 2023. **Findings:** DeepMind’s “AlphaDev” system autonomously discovered improved sorting algorithms via reinforcement learning. **The AI-found algorithms outperformed long-standing human benchmarks and have been integrated into the LLVM C++ standard library**[22], replacing the prior sorting routine. This real-world deployment is a milestone: an automated design not only matched but *surpassed* human solutions and was trusted enough for production use. It underscores that automated machine learning/algorithm design is transitioning from lab demos to practical impact, signaling a high maturity for the underlying approach (at least in constrained domains). It also highlights the importance of guardrails: such systems were carefully verified (proofs of correctness were required)[22], echoing the ART’s note that governance and validation remain essential even as AutoML capabilities grow.
- **Industry AutoML platform (Google) – Encora Tech Blog (10/2023):** “*Unlock the Power of AutoML with Google’s Vertex AI.*” **Type:** Industry technical blog (Encora Inc.), Oct 2023. **Details:** Describes Google Cloud’s Vertex AI AutoML services. Emphasizes a **no-code interface that “puts the power of machine learning in the hands of non-experts,”** enabling users without ML expertise to build image, text, or tabular models via a few clicks[7]. It also notes that Vertex AI provides “**robust monitoring and management tools**” to ensure models continue to perform optimally as data evolves[6] – reflecting automated retraining/adjustment capabilities. This source exemplifies a *commercially delivered AutoML product*: it offers on-demand scalability, covers a wide range of use cases, and includes MLOps features like drift detection alerts. The existence of such platforms (from Google and others) indicates that AutoML for standard supervised tasks is already at a product stage, being actively used in industry to reduce specialist labor needs.
- **Market growth and case studies – Market report (ResearchAndMarkets via PRNewsWire, 5/2023):** “*Global Automated Machine Learning (AutoML) Market Report 2023: Increasing Need for Accurate Fraud Detection Drives Growth.*” **Type:** Market analysis report (press release summary), May 2023. **Details:** Estimates the **AutoML market at ~\$1.0 billion in 2023, projected to reach \$6.4 billion by 2028** (44.6% CAGR)[13], highlighting rapid growth. It attributes demand to industry needs like customer personalization and fraud detection in finance (BFSI sector being a major adopter)[23]. The report cites concrete **enterprise case studies**: e.g., *Consensus Corp.* cut model deployment time from “**3–4 weeks to 8 hours using**



**AutoML**\*\*[12], and PayPal used H2O Driverless AI to strengthen fraud detection[11]. Numerous vendors are named (Google, AWS, Microsoft, DataRobot, H2O.ai, etc.[24][25]), showing a competitive landscape. This evidence demonstrates that multiple well-capitalized actors are delivering AutoML tools to real customers, across various industries\*\*, and achieving notable efficiency gains – a strong indicator of advanced maturity (moving from experimental to widely operational).

*(Additional references above also support these points: e.g., AutoML competition wins by academic groups[26] and the formation of an annual AutoML Conference (since 2022) illustrate the field's momentum, though they are not individually listed.)*

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 6 (out of 7).

**B) Justification of score:** AutoML as a whole has **progressed into a product-delivery and scaling phase, albeit not yet fully ubiquitous**. The evidence shows that we have **moved beyond prototypes** – multiple independent AutoML frameworks and services are operational and competing, with **major tech companies and startups delivering products to customers (characteristic of Level 6–7)**. For example, Google's Vertex AI AutoML, Amazon's AutoGluon/SageMaker Autopilot, DataRobot, H2O Driverless AI, etc., are in active enterprise use, and the AutoML market is valued around \$1B with fast growth[13]. This widespread deployment and competition strongly *rule out lower maturity levels* (Levels 3–4, which correspond to mere prototypes or single pilots). Furthermore, **real-world impact has been demonstrated**: AutoML has enabled non-experts to achieve results comparable to expert data scientists[17][9], and even produced algorithmic solutions beyond human designs in certain cases[8][22] – evidence that meets or exceeds the expectations of Level 5 (PoC proven clearly beneficial).

However, a few factors stop us from assigning the maximum score of 7: **not all aspects of the ART vision are equally mature or widely adopted yet**. Notably, the **“agent factory” extension (AutoRL)** is still in early-stage research (labs have demonstrated automated RL tuning[4], but there is no off-the-shelf product that lets non-experts train arbitrary autonomous agents safely with full automation). Similarly, **full automation of the entire ML lifecycle (including data cleaning, feature engineering, and continuous self-evolution of models) is only partially realized** – current AutoML tools still require human oversight for data preparation or confirmation of model changes[3]. These gaps mean the field as a whole hasn't reached the breadth of deployment and *trusted autonomy* implied by Level 7 (which would require AutoML to be as routine and self-sustaining as, say, automated compilers or database systems in IT). Governance concerns (bias, safety) also present ongoing challenges[27][28], and their resolution will likely accompany the final push to Level 7.

In summary, **AutoML's core functionality for standard ML tasks is at a high maturity (even approaching Level 7 in those domains), while newer extensions (like automated reinforcement learning and fully self-managing pipelines) lag behind**. Given this mix, we assign an overall **Level 6**: - Level 6 is justified by evidence of products “being delivered to customers in increasing amounts” with expanding applications and internal financing. Indeed, multiple vendors are selling AutoML solutions, and adoption is rising across finance, healthcare, etc.[29][30]. Companies have invested heavily, indicating confidence in near-term returns. - *Why not Level 7?* Reaching 7 would require **broad, rising demand across**

**essentially all sectors and fierce competition solely driven by market forces**, with the technology largely “solved” except ongoing incremental improvements. **While demand is growing, AutoML is not yet a default approach everywhere** – some organizations still rely on manual ML due to trust or complexity issues[28]. Moreover, the cutting-edge functions (automating complex agent behaviors, handling any scenario with minimal human input) are not fully commoditized yet. The need for expert validation (to handle bias, explainability, data nuances) means AutoML hasn’t entirely replaced human ML engineers, especially for high-stakes or very novel tasks.

**C) Sub-component breakdown:** To support the aggregate score, we note sub-technology maturity: - *AutoML for supervised learning (model/feature selection, HPO, NAS)*: **Level 7**. Multiple **competing products** from well-capitalized companies are on the market, with a wide user base. Evidence: e.g., Google, Amazon, Microsoft cloud AutoML services and open-source libraries are widely used, and ~58% of data scientists report using AutoML tools[17]. These systems reliably deliver value (sometimes super-human model performance) in vision, NLP, and tabular tasks, indicating a near-full commercialization. - *AutoML for reinforcement learning (agents/policies)*: **Level 3–4**. Demonstrated in research prototypes and some benchmarks (lab successes like AutoRL tuning for games[31], AutoML-designed algorithms in controlled settings[22]), but **no general commercial AutoRL platform yet** for non-experts. It’s at the functional prototype stage (proof-of-concept algorithms exist, motivating investment, but production viability and safety are still being proven). - *Automated data pipeline & model management (MLOps automation)*: **Level 5**. Early versions are integrated into products (e.g., Vertex AI’s automated monitoring and pipeline triggers[6]). There are proofs-of-concept in industry that model retraining can be automated on drift detection. Yet, most deployments still require human oversight to validate retrained models or to set constraints. The functionality exists and clearly adds value (e.g. greatly reducing model maintenance time), and major actors are actively developing it, but it’s not entirely “fire-and-forget” yet.

Given these varied sub-scores, we weight by their importance to the overall ART vision. **The core value – automating model development – is at the highest maturity (driving the high score), while the less mature aspects are emerging but not dominant in usage.** Thus, averaging the bundle might yield a 5–6, but since the primary capability is already broadly realized, we lean to **Level 6**. This score captures that AutoML is **no longer speculative** – it’s a rapidly scaling technology with proven benefits – but also acknowledges that *the ultimate vision of a fully autonomous, self-evolving “AI factory” is just shy of fruition*, likely to be achieved as the newer components catch up in the coming years. The next jump to Level 7 would be warranted once we see truly autonomous end-to-end ML systems widely trusted in production (including automated agents and self-correcting models), a milestone on the horizon but not uniformly reached as of today.

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## ART 03.019 Collaborative Multi-Agent AI

### 1. ART extraction

**A. Primary capability:** *Collaborative multi-agent AI* enables many intelligent agents (software or robots) to work as a coordinated whole. They **share information and negotiate roles in real time** to achieve common goals, instead of operating in isolation. This promises **parallel, resilient task execution at large scales** – for



example, covering wide areas with swarms of sensors/robots, handling numerous small tasks simultaneously, and **continuing operation despite individual failures** (graceful degradation).

### B. Key sub-components / variants:

- **Distributed sensing & actuation:** Heterogeneous agents (from fixed IoT sensors to mobile robots and cloud services) form a network, **exchanging data over wireless links and APIs**. They maintain shared world models (e.g. common maps or task queues) that any agent can update and use.
- **Communication & networking:** Robust *ad hoc* mesh networks and protocols are needed to connect dozens or hundreds of agents. Systems must avoid radio interference and congestion when many devices communicate at once, often leveraging **decentralized networking** and local broadcast techniques for scalability.
- **Coordination algorithms:** A mix of pre-programmed rules and AI/ML (e.g. multi-agent reinforcement learning) governs cooperation. Agents dynamically allocate tasks, form sub-teams, plan paths, and adapt to changes **without a central controller micromanaging each unit**. They can negotiate roles or share intent through messages, and even use learned strategies from collective experience.
- **Human-swarm interface:** Dashboards, voice/text commands, and supervisory control tools allow humans to set high-level objectives, impose safety constraints, and override or adjust behaviors. Hierarchical control lets human operators intervene at different levels of detail (from whole swarm to individual agent) as needed.
- **Safety & fault-tolerance:** Mechanisms for fail-safe behavior are critical. Agents handle **uncertain sensing and dropouts** gracefully – e.g. defaulting to safe modes if data is lost, redistributing tasks if a unit goes offline. Redundancy and cross-validation (agents cross-check each other's observations) mitigate errors and increase reliability.
- **Variants by domain:** *Swarm robotics* (drones, autonomous vehicles, robots cooperating in physical tasks) vs. *distributed digital agents* (software bots/services coordinating in cyberspace) are two extremes, often combined. Some systems emphasize **swarms of inexpensive robots** for field operations (e.g. drone swarms, fleets of farm robots), others might involve **millions of micro-agents** in IoT networks or cloud simulations. All share the core challenge of scalable, distributed decision-making.

**C. Maturity indicators:** We expect evidence such as: **large-scale field trials or demos** (e.g. dozens of robots teaming up autonomously in real environments); **prototypes solving coordination challenges** (like consensus with limited comms, dynamic task allocation); **early commercial deployments** or pilot programs (e.g. robot swarms used in industry, warehouse fleets, agricultural robot teams); **competition among major players** (multiple well-funded companies or military programs racing to develop swarm systems); **standardization efforts or platforms** for multi-robot coordination; and eventually **shipping products** with multi-agent autonomy (with growing customer adoption and scaling production). Signs of progress include achieving reliable performance beyond single-robot limits (coverage, efficiency) and falling costs per agent enabling larger deployments. Field robustness (handling communication loss, complex environments) and integration into human workflows (use of supervisory UIs) are key hurdles being overcome in recent projects.

## 2. Evidence (10–20 recent, reliable sources)

3. **Swarm robotic cooperation advantages – Cai et al., Neurocomputing (Survey, peer-reviewed), 09/2024.** *Overview:* Surveys the state of multi-agent *robotic swarm* systems, highlighting that compared to a single robot, a swarm of agents can coordinate via information sharing to achieve a **wider monitoring range, flexible organization, and strong reconfiguration** (adaptability)[1]. It reviews key technologies for collaborative tasks (e.g. target search, task allocation, path planning) in multi-robot swarms and notes broad applications from environmental monitoring to rescue and military use. *Why relevant:* Confirms the fundamental plausibility and motivation for multi-agent AI – leveraging collective behavior yields capabilities (coverage, resilience) unattainable by lone agents, and these principles are being actively researched across domains.
4. **Decentralized multi-UAV team in DARPA challenge – Petrlík et al., Field Robotics (peer-reviewed), 01/2023.** *Finding:* Demonstrated a **fully autonomous, decentralized team of drones** that cooperatively explored a complex underground environment in the DARPA Subterranean Challenge finals[2]. The system used novel mapping techniques to enable multi-robot cooperation under very low-bandwidth communications[3], allowing the UAVs to share a compressed map and coordinate without constant contact. It proved robust in a harsh real-world setting (dark, GPS-denied tunnels), where the drones collectively searched for objects. *Why relevant:* This is a concrete proof-of-concept of collaborative multi-agent AI in the field – multiple robots formed an ad-hoc team, distributed themselves to map and search, and succeeded **without central control**. It validates the feasibility of key constraints mentioned (limited connectivity, need for on-board decision-making) and shows the technology working in a realistic mission scenario.
5. **AI-driven drone swarm (70-unit concept) – Edge Group (Halcon), Defense News (industry news), 02/2022.** *Revealed:* A UAE defense contractor unveiled the “Hunter 2-S” swarming drone system, capable of launching **36 drones (with plans for up to 70)** from a single vehicle[4][5]. The drones use an algorithm to communicate over a main channel and share information about targets, dividing into sub-groups to engage multiple targets collaboratively[6]. A first live demonstration launched one drone from a tube (wings deployed and it flew successfully), with full-system flight tests planned for 2023 and production slated by 2025[7]. *Why relevant:* This illustrates a near-term *pre-production prototype* of a coordinated multi-agent system. It shows industry investment in architectures for dozens of agents that coordinate targeting and maintain formations autonomously. The roadmap (demo → testing → production) and interest from armed forces indicate both technical feasibility and a drive toward real-world deployment, underscoring rapid maturity in multi-agent coordination (at least in specialized domains like defense).
6. **Multi-robot search & rescue trial – Deep Robotics (China), IoT World Today (trade news), 03/2023.** *Reported:* Five autonomous quadruped robots (Deep Robotics “Jueying X20” units) were successfully trialed as a team in a 3,000 m<sup>2</sup> simulated disaster environment[8]. In eight different search-and-rescue missions, the **team of five robots shared information over a wireless mesh** network and used an in-house multi-robot exploration algorithm to coordinate their coverage[9][10]. They split up to evenly cover the area, communicated only the most essential data (to reduce bandwidth use), and collaboratively located targets (e.g. victims or hazardous objects). Each robot had Lidar and cameras for sensing, and the cooperative strategy improved speed and accuracy of search outcomes. *Why relevant:* This demonstrates a *field trial* by an industry player showing that multi-agent robotics can perform a complex task (searching a building) more efficiently as a group. It validates the plausibility in a civilian context and shows attention to practical issues like limited bandwidth (they optimized communication by sharing only simple, useful info[9]). The trial’s success suggests the

approach is moving toward real deployment to augment or replace humans in hazardous response scenarios.

7. **AI negotiates in multi-agent strategy game – Meta (FAIR) CICERO, Science (peer-reviewed), 11/2022.** *Achievement:* Meta AI's CICERO is the first AI agent to reach **human-level performance in the 7-player board game Diplomacy**, which requires natural language negotiation and alliance formation[11]. CICERO combined a language model with strategic reasoning so it could coordinate plans with multiple human players via dialogue. In 40 online games, it doubled the average score of human participants and ranked in the top 10%[12]. Crucially, the AI engaged in convincing human-like negotiation – forming agreements and adjusting strategy when partners cooperated or betrayed. *Why relevant:* Diplomacy is a notoriously complex multi-agent setting (no single winner can succeed without collaboration). CICERO's success demonstrates the feasibility of *software agents that negotiate roles and joint strategies* with others in real time. It provides evidence that AI systems can coordinate and cooperate in open-ended environments, not just follow pre-set rules – a key aspect of the ART. This represents progress in the “purely digital agents” side of collaborative multi-agent AI, highlighting advanced capabilities like communication and learning of trust, which underpin plausibility for broader applications.
8. **Autonomous satellite swarm experiment – NASA Starling mission, Small Sat Conference (tech report), 08/2024.** *Results:* NASA's Starling mission launched four small satellites in July 2023 to test autonomous swarm cooperation in orbit. The swarm successfully established a **mobile ad-hoc network** between satellites and exchanged data peer-to-peer (using the B.A.T.M.A.N. mesh protocol)[13]. It also ran a distributed decision-making experiment: each satellite made observations (ionospheric measurements) and the group reached **consensus on an optimal joint data-collection strategy**, then adjusted their observation plans *autonomously* based on that consensus[14]. Additionally, the swarm performed coordinated maneuvers (formation flying) with minimal ground control, demonstrating the ability to maintain formation as a group. *Why relevant:* This is a cutting-edge demonstration of multi-agent AI in a challenging domain (space) where continuous connectivity and central control are impractical. The satellites collaborated by sharing sensor data and computing consensus decisions – exactly the kind of “negotiate roles and adapt collectively” behavior described in the ART. The success of Starling's experiments shows that even with only 4 agents, the architecture and algorithms scale to complete tasks cooperatively and robustly (networking, distributed sensing, and coordinated actuation in this case). It paves the way for larger “swarms” of spacecraft and validates the robustness of multi-agent networks under real-world conditions (latency, link disruptions, etc.).
9. **Fleet of farm robots in commercial use – SwarmFarm Robotics (Australia), Advance Queensland report (gov't innovation case study), 02/2025.** *Data:* SwarmFarm, an agricultural robotics company, has **deployed 135+ autonomous robots** on farms across Australia, collectively covering over 6 million acres of operations[15]. Their approach uses **smaller, smarter machines working together** rather than one big machine – e.g. multiple lightweight rover units collaboratively weed or spray crops. This improves efficiency and reduces environmental impact (up to 80% less chemical usage) by targeting only where needed. The robots operate with shared digital maps of the field and coordinate to ensure complete coverage without gaps or overlap. *Why relevant:* This provides real-world evidence that coordinated multi-robot systems are transitioning into **actual products and scaling deployments**. SwarmFarm's large number of units in the field (and millions of acres serviced) indicates that the multi-agent concept is not just a lab demo – it is delivering value to end-users (farmers) today. The fact that a *single operator can oversee multiple farm robots* via a central interface addresses the human-swarm interaction component. This example

underscores the commercial viability and growing adoption of multi-agent AI in industry, as well as the economic drivers (labor savings, reduced chemicals) making it attractive.

10. **Heterogeneous robot team at robotics challenge – Lee et al., arXiv preprint (KAIST Team OCEAN), 10/2024.** *What was done:* Demonstrated an **integrated aerial-ground robotic team** in the 2023 MBZIRC Maritime Grand Challenge. A drone autonomously deployed a legged hexapod robot onto a target vessel (and retrieved it) in a GPS-denied maritime environment[16]. The UAV and hexapod coordinated their actions: the drone provided long-range mobility and vision, while the ground robot handled precise tasks on the moving ship's deck. They used sensor fusion (optical flow, LiDAR, etc.) for localization instead of GPS, and a winch mechanism for the drone to lower and raise the hexapod. The system was **successfully validated in field tests** during the competition, where the KAIST team placed 2nd overall[17][18]. *Why relevant:* This showcases a complex, *ad hoc* multi-agent team with heterogeneous members – exactly the kind of dynamic teaming the ART describes. The UAV and UGV (hexapod) had to communicate and coordinate in real time under challenging conditions (moving platforms, no external positioning). The fact this was done in a competitive setting and worked reliably enough to earn a top prize speaks to the rapid progress in multi-agent autonomy. It also expands the application space (maritime security and rescue, in this case), showing the versatility of the approach. The example highlights how agents with different capabilities can form a team to overcome each other's limitations (flying robot + walking robot), a key advantage of multi-agent systems.
11. **Large Language Models to coordinate robots – Liang et al., arXiv preprint (research, NYU Abu Dhabi), 02/2025.** *Insight:* Proposes and tests a novel multi-robot collaboration framework that integrates **Large Language Models (LLMs)** into the decision loop. The authors note that recent work uses LLMs to improve multi-agent coordination – e.g. by breaking down complex tasks for different robots, assigning roles, and enabling coalition formation through dialogue[19]. Building on this, they introduce a “retrospective actor-critic” approach: one LLM-based module generates plans for the robots (the Actor) and another LLM-based module critiques the outcome and provides feedback to refine the next iteration (the Critic). In simulated trials, this method significantly improved the team's task performance and adaptability in dynamic scenarios[20]. *Why relevant:* This represents a cutting-edge development in the algorithms enabling collaborative AI. By leveraging LLMs (which are adept at communication and reasoning), researchers are tackling the complexity of coordination and flexible planning for multi-robot teams. The improved performance in simulations suggests that more **sophisticated, learning-driven coordination mechanisms** are becoming available – moving beyond rigid pre-programmed protocols. This makes multi-agent AI more plausible and scalable, as agents can communicate in natural-like language and adjust strategies on the fly. It also directly addresses one challenge in the ART description: mixing data-driven models (here LLMs and RL) with rules to allow dynamic teamwork.
12. **Swarm intelligence for multi-robot systems – Nguyen, AppliedMath (MDPI) (Review), 10/2024.** *Summary:* A comprehensive review of swarm intelligence algorithms as applied to multi-robot systems. It concludes that decentralized swarms (inspired by ants, bees, etc.) offer **robust, scalable, and flexible solutions** compared to traditional centralized robotics[21]. Swarm-based multi-robot systems have shown effectiveness in domains like search & rescue, environmental monitoring, agriculture, space exploration and warehouse logistics. Notably, swarms can **adapt to new challenges and continue functioning even if individual robots fail**, since there is no single point of failure[21]. The paper also discusses challenges such as real-time decision-making, communication failures, and unpredictable emergent behaviors, suggesting areas for future research (e.g. better real-time control and safety assurances in critical applications). *Why relevant:* This source provides authoritative context that **validates**

**the core value proposition** of collaborative multi-agent AI. It synthesizes evidence from many studies to affirm that multi-agent systems *do* improve efficiency and resilience, aligning with the ART's claims about reduced human bottlenecks and improved situational awareness through collective sensing. At the same time, it acknowledges the open challenges (communication and safety issues when scaling up), which helps gauge maturity – many theoretical benefits are confirmed, but ensuring reliability and control at massive scales (and in life-critical tasks) remains an active area of work.

### 13. Maturity score (1–7) and reasoning

**Score: 6 (Out of 7).** The overall maturity of *Collaborative Multi-Agent AI* is **high**, with early products and deployments already in use, though not yet fully ubiquitous.

**A. Justification (Evidence-to-rubric mapping):** Several pieces of evidence show that we have moved past basic theory and lab prototypes into the realm of **real-world prototypes, fast-paced development, and initial scaling of products**, which corresponds to rubric levels 4–6. Specifically, we see multiple **proof-of-concept demonstrations** in complex environments (DARPA SubT drones, NASA's Starling satellites, KAIST's maritime robots) – satisfying level 4 by showing functionality in real scenarios and solving key technical hurdles like decentralized control and limited communication[2][14]. Moreover, **well-capitalized actors are heavily invested and racing to deploy this technology** (level 5): for example, defense agencies and companies are testing drone swarms (UAE's Edge, US DARPA, etc.)[7], and big tech firms are tackling multi-agent learning (Meta's CICERO achieved a milestone in cooperative AI[11]). We have clear signs of **early commercial rollout (level 6)** in civilian sectors: the SwarmFarm case shows actual products (autonomous multi-robot fleets) delivered to paying customers with *hundreds of units deployed* and growing adoption[15]. Likewise, Amazon and other warehouse operators have tens of thousands of robots coordinating in their facilities (though not cited above, it's a known industry fact), indicating that multi-agent coordination is already underpinning large-scale operations. These facts rule out lower maturity levels decisively – this is far beyond theory (Lvl 1) or single lab demos (Lvl 2–3). The presence of **multiple competitors and expanding use-cases** (agriculture, logistics, defense, etc.) also shows we are at the cusp of wider scaling. Many projects are now internally or venture-funded for commercialization rather than just research grants, meaning the field is entering an implementation and growth phase.

**B. Why not a full 7:** We stop short of level 7 because the technology, while proven in various domains, is **not yet a seamless, ubiquitous commodity across all industries**. There are indeed competing products and rising demand in certain areas (e.g. multiple agri-robot startups, numerous drone swarm initiatives, various brands of warehouse robots), but collaborative multi-agent AI as a general capability is still in a maturing stage where integration and standardization are limited. Key challenges like reliable real-time coordination under extreme scales ("millions" of agents), guarantees of safety in unpredictable environments, and unified platforms or standards for multi-agent systems are **still being worked out**[21]. In other words, **the ceiling for this tech is very high and not yet reached** – we haven't seen millions of cheap agents working as one in practice, and human oversight tools for swarms are still evolving. To reach level 7, we'd expect to see *widespread deployment and routine use* of large-scale multi-agent systems across many sectors, with robust fail-safe performance and market ubiquity. That level of penetration will likely come in the next decade as the prototypes scale up. For now, the progress is recent and rapid but



somewhat siloed to specific pioneers and early adopters, keeping the overall maturity at a strong **6**.

**C. Sub-component breakdown:** This ART spans different application segments, which have slightly different maturity:

- *Industrial & commercial robotics swarms*: **Level 6–7**. Warehouse robot fleets and farm swarms are already delivering value at scale (hundreds or thousands of units) with multiple vendors in play, indicating near-product maturity[15]. (These drive the score upward; functionality here is largely the same – coordinating multiple mobile agents for efficiency – and it’s proven viable and cost-effective.)

- *Autonomous swarms in open, dynamic environments (drones, S&R, military)*: **Level 4–5**. Successful field trials and demos exist (autonomous drone teams in trials[2], live-fire tests of drone swarms, etc.), and governments are investing heavily, but routine deployment is just beginning. These systems work in principle, but need more validation for reliability and safety before full deployment (hence slightly lower maturity than factory/farm settings).

- *Multi-agent AI software (negotiation, distributed AI without physical robots)*: **Level 4**. Breakthroughs like CICERO show feasibility[11], but these are early examples in limited domains. The algorithms are advancing quickly (especially with new AI like LLMs[19]), yet widespread integration into business or society (e.g. multi-agent AI managing complex processes) is nascent.

Despite this variation, the *core capability* – agents acting jointly and adaptively – is essentially the same across these sub-fields. We therefore weight the overall score by the most advanced implementations, as they demonstrate the full potential of the technology. Given that **functional multi-agent systems are already on the market and scaling up (farms, warehouses)** and others are fast following, a composite score of **6** reflects that high maturity while acknowledging that some aspects (especially highly generalized coordination and ultra-large swarms) are a step away from the absolute peak of maturity. The next milestones (to reach level 7) would be broader adoption, standardized platforms, and consistent trust in multi-agent AI handling critical tasks at scale – all on the horizon but not yet uniformly achieved.

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## ART 03.020 Quantum-Accelerated AI Systems

### 1. ART extraction

**A. Primary capability:** Quantum-accelerated AI systems combine quantum processors with classical AI hardware to tackle computational bottlenecks in AI tasks that are infeasible for classical computers alone. By offloading the most complex subroutines (e.g. searching large combinatorial spaces, parallel evaluation of many solutions) to quantum co-processors, these hybrid systems aim to achieve faster or more energy-efficient learning and decision-making on extremely large-scale data and models. From a user perspective, the AI applications run as usual (via APIs or software libraries), but behind the scenes an orchestration layer selectively invokes remote quantum hardware for those parts of the workload expected to see a quantum speedup or accuracy gain.

### B. Key sub-components or variants:

- *Quantum processing hardware:* The core enabler is quantum computing hardware (superconducting qubits, trapped ions, photonic processors, quantum annealers, etc.) with sufficient qubit count and fidelity. Both gate-model quantum processors and analog/annealing devices are pursued, often accessed over the cloud due to specialized cryogenic and control requirements. Error correction or mitigation technology is crucial to maintain coherence over the complex operations needed for AI tasks.

- *Hybrid algorithms and software integration:* New algorithms are developed to split AI workflows between classical and quantum parts – e.g. variational algorithms, quantum approximate optimization (QAOA), quantum-enhanced kernel methods, or quantum

Boltzmann samplers. Software frameworks (like TensorFlow Quantum, Qiskit Runtime, PennyLane, etc.) and middleware manage the interaction, scheduling quantum jobs within classical AI code. A “quantum gateway” or runtime environment handles data movement and synchronisation so that quantum acceleration is used seamlessly within existing AI pipelines[1][2].

- *Orchestration and HPC integration*: Because quantum resources are scarce and expensive, integration with high-performance computing (HPC) infrastructure is a key variant. This includes hybrid HPC clusters where GPUs/CPUs and QPUs (quantum processing units) are co-located or networked with scheduling systems (e.g. Slurm, CUDA-Q) to dispatch parts of AI workloads to quantum accelerators[3][4]. Various projects (IBM’s quantum-centric supercomputing, national labs’ quantum-HPC testbeds, cloud services like Amazon Braket) are converging on architectures to treat QPUs as special high-end accelerators within classical supercomputers.

- *Target problem classes*: Not all AI tasks benefit from quantum acceleration. The leading sub-areas are combinatorial optimization (e.g. scheduling, routing, feature selection, neural architecture search) where quantum algorithms (annealing or Grover-like searches) might find better optima faster[5]; large-scale sampling and generative modeling (e.g. Boltzmann machines, quantum-enhanced GANs) where quantum samplers explore complex probability distributions[6]; and certain linear algebra subroutines (like kernel evaluations or solving linear systems for machine learning) where quantum algorithms promise polynomial speedups. These define the initial use cases for hybrid AI platforms.

### **C. Maturity indicators:**

- *Scientific feasibility demonstrations*: Peer-reviewed experiments showing that quantum assistance can improve an AI-relevant task are a key indicator. For example, small-scale prototypes that achieve higher accuracy or speed than classical methods on certain classification or optimization problems[7], or hybrid models (quantum + classical) successfully trained on non-trivial data[6]. Such results bolster plausibility.

- *Prototype integration and field trials*: Evidence of quantum accelerators being integrated into real computing environments or tested on practical use-cases. This includes demonstrations of hybrid quantum-classical HPC clusters running AI workloads[3][4], cloud services offering quantum-enhanced ML functions (e.g. D-Wave’s feature selection plugin for scikit-learn[8][5]), or enterprise trials where quantum options are offered for specific optimization jobs. A working proof-of-concept system that industry users can experiment with marks maturity progress.

- *Competition and investment*: Multiple well-capitalized actors entering this space signal growing maturity. Major quantum hardware firms (IBM, Google, IonQ, D-Wave, etc.), big cloud/AI companies (Amazon, Microsoft) and government consortia (EU’s EuroHPC JU, U.S. DOE labs, etc.) all investing in quantum-AI integration efforts is a strong indicator. For instance, national labs partnering with industry to build quantum-accelerated supercomputing testbeds[9][10], and startups offering quantum machine-learning services, suggest the technology is moving beyond isolated research into a competitive development phase.

- *Performance crossing classical thresholds*: A critical maturity marker will be evidence of *quantum advantage* for useful AI problems – i.e. solving a problem faster or better than the best classical alternative. Early signs might be quantum solvers handling larger problem instances or achieving higher solution quality than classical heuristics in optimization tasks[11]. Reaching this point, even on narrowly-defined tasks, would validate the value



proposition and likely accelerate commercialization.

- *Scaling and reliability milestones*: Since long-term viability depends on scaling up quantum hardware, indicators like demonstrated error-corrected operations (logical qubits with lower error rates)[12][13], increases in qubit counts, and stable cloud uptime of quantum processors are important. Achieving error rates low enough for deep circuits or demonstrating modular quantum systems that can expand (as in IBM’s quantum-centric roadmap) shows the approach is approaching technical readiness for wider deployment.

## 2. Evidence (10–20 recent, reliable sources)

3. **IBM (Jay Gambetta) – “Quantum-centric supercomputing: The next wave of computing” (IBM Quantum Blog, Nov 2022)**: IBM’s 2022 Quantum Summit declared **2023 as an inflection point** toward “quantum-centric supercomputers” – modular architectures that tightly integrate quantum processors with classical HPC through a cloud middleware[14]. IBM’s roadmap describes enabling seamless quantum-classical workflows (using tools like Qiskit Runtime and “Quantum Serverless”) so that quantum accelerators can function like GPU-style co-processors in AI applications[15][16]. This shows a major industry player actively engineering the software/hardware stack for hybrid quantum–AI computing.
4. **Z. Yin et al. – *Nature Photonics* 19, 1020 (June 2025)**: Demonstrated **quantum-enhanced machine learning** on a photonic processor for a real classification task[7]. Using single-photon interference (no entangling gates), their quantum kernel method outperformed state-of-the-art classical kernel techniques (Gaussian and neural tangent kernels) on a binary classification benchmark[7]. This peer-reviewed experiment provides concrete evidence that current quantum devices, in at least certain domains, can achieve higher accuracy than classical methods, highlighting the plausibility of performance gains in AI tasks.
5. **A. Gircha et al. – *Scientific Reports* 13:8250 (May 2023)**: Presented a **hybrid quantum–classical generative model** for drug discovery, training a discrete variational autoencoder where a quantum Restricted Boltzmann Machine (RBM) served as the latent layer[6]. The RBM was small enough to run on a D-Wave quantum annealer, which was used to sample latent variables while a classical neural network handled the rest. They successfully trained this model on a chemical dataset (ChEMBL) and generated novel molecular structures[6]. This illustrates a practical prototype using an existing quantum annealer to enhance an AI model, and demonstrates feasibility on presently available quantum hardware (NISQ annealers) for real-world data.
6. **M. Slys et al. – “Hybrid Classical-Quantum Supercomputing” (Preprint, Aug 2025)**: Researchers from Poznan Supercomputing Center (Poland), NVIDIA, and ORCA Computing built the **world’s first multi-user hybrid quantum-HPC cluster**[3]. In this setup, photonic quantum processors (by ORCA) are installed alongside GPUs in a conventional data center, with standard HPC scheduling (Slurm) and NVIDIA’s CUDA-Q software coordinating the quantum/classical workload[3][4]. They demonstrated variational quantum algorithms for machine learning and optimization running on this cluster, showing that *multiple users can share quantum accelerators just like HPC resources*. This is strong evidence of system-level maturity: quantum accelerators can be practically integrated into modern computing centers without exotic infrastructure changes, paving the way for real-world trials.
7. **Oak Ridge National Lab – “ORNL, NVIDIA, HPE advance Quantum Computing, AI, and HPC” (Lab news, Nov 2025)**: DOE’s Oak Ridge Lab announced a partnership with NVIDIA and HPE to develop a **testbed integrating quantum processors with the Frontier exascale supercomputer**[17][9]. They are using NVIDIA’s “NVQLink” and CUDA-Q to link quantum hardware with GPUs/CPUs, aiming to explore quantum acceleration for scientific AI

workloads[9]. The platform, arriving in 2026, will support error-correcting control and hybrid algorithms in one environment. This high-profile investment – effectively building a quantum-augmented supercomputer – underscores that multiple major players see hybrid quantum–AI computing as within reach.

8. **Forschungszentrum Jülich – Integration of 100-qubit quantum system (Germany, 2025):** The Jülich Supercomputing Centre (JSC) expanded its infrastructure (JUNIQ) by adding “**JADE,**” a **100-qubit Pasqal quantum computer, integrated with its new exascale system (JUPITER)**[18]. Inaugurated in 2025, this setup allows researchers to experiment with hybrid HPC-quantum applications for optimization and materials science[18][19]. JSC’s directors emphasize that quantum computing at Jülich is “*not a separate track*” but complements classical HPC, with quantum resources situated alongside supercomputers for a continuum of computing paradigms[19]. This evidences a major European effort to operationalize quantum accelerators in AI and simulation workflows and reflects a broader trend (EuroHPC JU program) of installing quantum nodes at supercomputing centers across Europe.
9. **D-Wave Systems – Press Release: Feature Selection Hybrid Solver (Mar 2023):** D-Wave (a commercial quantum computing company) released a **hybrid quantum feature selection plugin** for machine learning, highlighting concrete enterprise-focused tooling[8][5]. The plugin integrates with the popular scikit-learn ML library, letting developers use D-Wave’s quantum-classical solver to automatically pick influential features in datasets[5]. By abstracting the complex optimization behind a familiar interface, this product shows a push toward real-world AI workflow integration. Its launch – and reports that customers find quantum hybrid solutions beneficial for speeding up model training[20] – signals that quantum acceleration is moving into practical AI software (at least in niche optimization tasks) with commercial support.
10. **A. Shehata et al. – Future Generation Computer Systems 174, 107980 (Jan 2026):** This paper from ORNL outlines a **comprehensive software stack for HPC-Quantum convergence**[1], addressing many technical challenges of hybrid workloads. It proposes hardware-agnostic interfaces for resource management, a quantum platform manager API to plug in different QPUs, and unified scheduling to handle interwoven quantum and classical tasks[1][21]. They implemented test algorithms (e.g. a variational quantum linear solver) to show the framework managing complex workflows and maximizing resource use[2]. The work, funded by the US DOE, serves as a blueprint for future quantum-accelerated HPC systems. Its existence indicates that the community is not just theorizing but actively building the *middleware and tools* needed to deploy quantum accelerators at scale in AI and scientific computing environments.
11. **M. Sciorilli et al. – Nature Communications 16:476 (Jan 2025):** Achieved a breakthrough in **qubit-efficient quantum optimization**. They introduced a variational algorithm that solved a MaxCut graph problem with  $m = 2000$  variables using only 17 trapped-ion qubits[22][11]. In experiments, the quantum solver reached a graph cut solution quality above the known classical hardness threshold (approximation ratio  $>0.941$ ) for that problem size[11]. This result is noteworthy because it suggests a route to tackle industrial-scale combinatorial problems on today’s small quantum devices by clever encoding and hybrid processing. It provides evidence that even before full fault-tolerance, carefully designed quantum accelerators could offer an **optimization advantage** on relevant AI problems (like network design, scheduling, etc.), underscoring the plausibility of value creation in the near term.
12. **Google Quantum AI – Nature 614, 676 (Feb 2023):** Demonstrated the **scaling of quantum error correction**, a crucial stepping-stone for quantum-assisted AI. Google’s team showed that on a 72-qubit superconducting chip, a larger distance-5 surface code (49 physical qubits per logical qubit) achieved a lower error rate per cycle than a smaller distance-3 code (17

qubits)[12]. This marked *the first experimental proof* that adding qubits and complexity can actually suppress errors (the logical error rate ~2.9% vs 3.0%)[12][13]. Reaching this “break-even” and beyond is essential for scaling quantum processors to the sizes needed for AI applications. This achievement, with logical qubits now outperforming uncorrected ones, indicates rapid progress in hardware maturity – it builds confidence that fault-tolerant quantum operations (needed for long or complex AI computations) are on the horizon.

### 13. Maturity score (1–7) and reasoning

**Overall Maturity Score: 5** (out of 7) – *Active R&D with multiple competing prototypes; clear progress post-proof-of-concept, but not yet broadly deployed or proven superior to classical systems in practice.*

**A. Justification of score:** Quantum-accelerated AI systems have moved beyond theory (levels 1–2) and isolated lab demos (level 3) into an intense prototype development phase. We have **credible proof-of-concepts**: e.g. a photonic quantum ML classifier beating classical kernels[7] and hybrid quantum models generating drug-like molecules[6], which **rules out the lower levels** by demonstrating core functionality. Moreover, full prototypes are being assembled in real computing environments – such as the multi-user quantum-HPC cluster in Poznan[3] and quantum-enhanced supercomputing initiatives at IBM and ORNL – indicating that the technology is approaching the level 4 threshold (functional PoC with viability for production). The reason we assign **level 5** is the breadth of well-funded actors now in the race: **major companies, national labs, and startups are investing heavily and even collaborating to build next-stage systems**[17][9]. There are multiple efforts to integrate quantum accelerators into standard workflows (IBM’s Quantum Network with 200+ members, Amazon/Azure quantum cloud services, European HPC centers hosting quantum hardware), which is characteristic of level 5 where competition and development of production prototypes heat up.

Crucially, what **keeps the score at 5 and not 6** is that we have yet to see *routine delivery of this technology to end-users with scaling-up in production*. While D-Wave does offer a commercial quantum service (and even a feature-selection tool[8][5]), and IBM gives cloud access to prototype quantum processors, these are still specialized or pilot services – not widely adopted products solving mainstream AI problems. No clear quantum advantage has been demonstrated on a real-world scale problem that outperforms classical HPC (the **next milestone** needed to justify level 6). Error rates and qubit counts, though improving (with milestones like Google’s error-corrected qubit[12][13]), remain limiting factors that prevent general deployment. In summary, the field has advanced past proof-of-concept into an innovation race (score 5), but **to reach level 6**, we would expect to see **early market offerings being delivered at scale** – for example, turnkey quantum-accelerated AI services with growing enterprise adoption, falling costs, and multiple vendors’ systems in practical use. Those conditions are not yet met.

**B. Sub-component analysis:** The composite score of 5 is an aggregate view, as this ART spans several elements at different maturity:

- *Quantum hardware*: Present quantum processors (superconducting qubits, ion traps, etc.) are roughly at **level 3–4** – laboratory prototypes showing key functionality (entanglement, basic algorithms) and even some narrow advantage, but still needing improvements in error correction and scale. For instance, a 17-qubit system solving a 2000-variable optimization is impressive[11], yet quantum hardware must grow orders of magnitude to tackle general AI

tasks. Recent error-corrected qubit demonstrations (Google, 2023) indicate hardware is advancing steadily toward the threshold of practical reliability[12][13].

- *Hybrid algorithms and software*: Integration frameworks and algorithms are nearer **level 4–5**. We see robust prototypes of middleware (e.g. ORNL’s software stack for quantum-HPC integration[1][2]) and established APIs (Qiskit, Cirq, PennyLane) that allow developers to embed quantum routines into AI code. Many variational and hybrid algorithms have been tested on real devices, showing feasibility in principle. The **viability for production** is being proven by efforts like D-Wave’s hybrid cloud solvers and IBM’s runtime, which focus on user-friendly incorporation of quantum in standard workflows – a sign of approaching commercial readiness.

- *Use-case performance*: For the intended value (accelerating AI), the evidence is still emerging. In niche cases (certain optimizations or kernel methods) we have seen **quantum-enhanced performance (level 4)**, but broadly speaking classical AI is not yet outclassed. The **benefit is divided across sub-areas** – e.g. quantum annealing might help discrete optimizations, while gate-model circuits explore deep learning enhancements. Since all variants aim at the same ultimate functionality (faster or better AI outcomes), we lean toward the higher end of their maturity spectrum in scoring.

Considering these aspects together, we averaged the maturity signals and also noted the **concerted push by multiple stakeholders (hallmark of level 5)**. Thus, **score 5 represents the overall bundle**. The score reflects that the concept is **beyond proof-of-concept and firmly in development/optimization**, with prototypes in integration testbeds and early adopter usage, but still awaiting the breakthrough that would trigger broad deployment and competition in end-user markets (which would correspond to level 6).

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## ART 03.021 AI-Driven Autonomous Scientific Discovery

### 127. **ART extraction**

128. *Primary capability:* AI-driven systems that autonomously conduct much of the scientific discovery process – from generating hypotheses and designing experiments to executing those experiments and interpreting results, all with minimal human intervention. These “AI scientists” act as continuously learning research engines, able to propose research questions and workflows and refine their approach based on data, while remaining transparent and steerable by human experts.

### 129. *Key sub-components/variants:*

- **Large-scale AI models + scientific knowledge bases:** Combining powerful machine learning (e.g. large language models) with structured domain knowledge to reason about hypotheses and experimental design[1][2].
- **Automated experimentation platforms:** High-throughput robotic labs (chemistry, materials, biology, etc.) that can be programmatically controlled to run experiments or simulations, with real-time data collection[3][4].
- **Closed-loop decision systems:** AI agents that iteratively plan experiments, analyze outcomes, then propose the next experiments (active learning), enabling autonomous optimization or discovery without exhaustive human scripting[5][6].



- **Natural language and high-level interfaces:** Interactive front-ends (LLMs, dashboards) allowing humans to set goals or constraints in plain language, which the AI translates into experimental actions[1][7].
- **Safety and verification layers:** Mechanisms to validate experiment proposals and ensure safe, valid operations (e.g. filtering out nonsensical or dangerous actions before execution)[8].

130. **Maturity indicators (evidence of plausibility & progress):** Key signs would include **lab prototypes** demonstrating autonomous research loops (e.g. AI-driven systems discovering new materials, chemicals, or scientific insights)[9][10]. **Proof-of-concept (PoC)** milestones might be an AI-driven lab outperforming or accelerating human-led research (e.g. finding better solutions faster or at lower cost[11]). We'd expect **field trials or real-world deployments**, such as closed-loop AI labs in active use at research institutions or companies[12][13]. **Commercial or scaling signals** could include industry partnerships (lab automation companies integrating AI[14][15]), **well-funded initiatives** (government or corporate programs investing in AI-discovery platforms[16][17]), and early **products or services** (e.g. cloud-based "AI lab" services, or AI-optimized reagents entering the market[13][18]).

131. **Evidence (10–20 recent, reliable sources)**

**1. Autonomous Materials Synthesis Lab – Szymanski et al., Nature (Nov 2023):** Peer-reviewed article. Demonstrates a robotic "self-driving" lab (A-Lab) that planned and executed 57 solid-state inorganic syntheses with minimal human input, successfully producing 36 target compounds in 17 days of continuous operation[5][19]. The AI used ab initio databases and text-mined literature to generate experimental recipes, which were carried out by robots, achieving a high success rate and showcasing closed-loop discovery in materials science (significantly accelerating experimental throughput)[9]. This validates the *feasibility* of autonomous discovery in chemistry and materials.

**2. GPT-4 "Coscientist" for Autonomous Chemistry – Boiko et al., Nature (Dec 2023):** Peer-reviewed article. Reports an AI agent ("Coscientist") driven by GPT-4 that autonomously **designs, plans, and performs complex chemistry experiments** end-to-end[2]. It integrated tools like internet/library search, code execution, and control of cloud laboratory instruments. In six diverse experimental tasks (e.g. optimizing a palladium-catalyzed reaction), the system not only devised and ran experiments but matched human scientists in decision quality[20]. This illustrates plausible autonomy: LLM-based agents can coordinate real lab hardware via natural language and achieve tangible research outcomes[21][12].

**3. AI-Driven Battery Electrolyte Discovery – Noh et al., Nature Communications (Mar 2024):** Peer-reviewed article. Describes a high-throughput robotics platform combined with an active-learning AI to discover improved redox flow battery electrolytes[22]. Starting from >2000 possible solvent mixtures, the AI-guided loop tested <10% of them yet found formulations dissolving **3× more** active material (over 6.2 M concentration) than prior state-of-the-art[23]. This efficient search – narrowing the "haystack" to the best candidates[24][25] – highlights how autonomous experimentation can **vastly accelerate discovery** (540+ solvents characterized in months[26]) and achieve performance beyond what human trial-and-error would likely obtain[27][28].

**4. GPT-5 Autonomous Bioexperiment Loop – Ginkgo Bioworks & OpenAI (preprint, Jan 2026):** Preprint (press release, industry R&D). Ginkgo Bioworks (biotech company) and OpenAI built a closed-loop AI "**robot scientist**" for biochemistry that ran **36,000 experiments over 6 months** with minimal human input[29][30]. The system, powered by a

next-gen GPT-5 model, iteratively designed and executed experiments to optimize a cell-free protein synthesis process, **reducing cost per protein by ~40%** vs. previous best[29][31]. Notably, the AI autonomously proposed new reagent combinations (some later confirmed independently in literature)[32], and the improved reaction mix it developed is now being *sold commercially* as a reagent[13][18]. This is a strong proof-of-concept that AI-driven discovery can yield **practical, marketable innovations**, signaling maturity beyond academia.

**5. AI Agent for Quantum Lab Experiments – Cao et al., *Patterns (Cell Press)* (Oct 2025):** *Peer-reviewed article*. Introduces a “**k-agents**” framework using LLM-based agents to automate *entire* experimental procedures in a quantum computing lab[33]. The AI agents encapsulated lab knowledge and split complex protocols into sub-tasks, enabling **multi-hour autonomous operation** of a superconducting quantum processor[34]. In tests, the system **achieved expert-level performance** – autonomously calibrating qubits and producing entangled quantum states as well as human scientists[35][36]. This demonstrates the *generality* of autonomous discovery: even in cutting-edge physics experiments, AI agents can run experiments and interpret outcomes on par with trained researchers, underscoring the approach’s broad feasibility.

**6. “AI Scientist” for ML Research – Lu et al., *arXiv preprint (Aug 2024):*** *Technical preprint (Oxford/UBC collaboration)*. Describes an *open-ended* AI research system (“The AI Scientist”) that automates the full scientific cycle in the domain of machine learning research[37][38]. Starting from a prompt, the system generates novel hypotheses/algorithms, writes code, runs experiments (training models), and writes up findings as a publishable paper – even performing an automated peer review of its own drafts[39][40]. In a first demonstration, it independently produced new ideas in areas like transformers and diffusion models, each idea developed into a paper at an estimated cost of only ~\$15 in compute[41]. While domain-limited (software experiments), this showcases a plausible future variant: *AI autonomously conducting theoretical or computational research*, indicating how far the automation could go when provided a suitable sandbox.

**7. Enhancing Novel Discovery (not just Optimization) – Bulanadi et al., *ACS Nanoscience Au* (Oct 2025):** *Peer-reviewed article*. Focuses on pushing autonomous scientific agents beyond just optimizing known targets, toward **finding truly new phenomena**. Proposes an “INS<sup>2</sup>ANE” strategy combining a novelty score and strategic exploration to have AI-driven experiments seek out unusual results[42][43]. Implemented on an autonomous microscope system at Oak Ridge NL, this approach led to significantly **greater diversity of discoveries** compared to standard optimization, revealing previously unobserved behaviors in materials imaging[44][45]. This indicates a maturation of the field: researchers are now tackling how AI scientists can surprise us with *unexpected insights*, not just reproduce human-guided goals, which is key to fulfilling the full promise of autonomous discovery.

**8. National “Self-Driving Labs” Roadmap – DOE Workshop Report (Nov 2024):** *National lab consortium report*. Summarizes a U.S. Department of Energy workshop on scaling **self-driving laboratories** across domains[46][47]. It highlights critical needs like standardized data management, AI decision-making frameworks, and integration of robotic instruments at national user facilities[48][47]. The report emphasizes that autonomy will require fusing machine learning with human domain knowledge and careful safety/ethics review, and calls for building a “**Labs of the Future**” **consortium**[49][50]. This shows that major research

stakeholders are actively planning the **infrastructure and policies** for AI-driven discovery, a sign of preparation for broader deployment.

**9. Thermo Fisher & NVIDIA Partner on AI Lab Tools – *Thermo Fisher press release (Jan 2026): Vendor technical announcement.*** Thermo Fisher Scientific (a top lab equipment maker) announced a strategic collaboration with NVIDIA to embed AI capabilities into lab instruments and software at scale[51][52]. The goal is “lab-in-the-loop” experimentation where AI agents assist in experiment design, real-time data analysis, and instrument control during runs[53][54]. For example, their new Attune CytPix flow cytometer uses on-board AI to analyze cell images and guide experiments in real time[55][56]. This industry move shows that **commercial lab platforms are adopting AI autonomy features**, indicating a push toward products that can automate research workflows and *deliver them to end users*.

**10. U.S. DOE “Genesis” Mission for AI-Accelerated Science – *White House Executive Order (Nov 2025): Authoritative government roadmap.*** The Genesis Mission is a national initiative to create an integrated platform linking supercomputers, AI models, and robotic labs to **enable autonomous scientific discovery at scale**[17][57]. It explicitly calls for developing AI agents that can explore hypothesis spaces, automate experiments, and iterate in closed-loop fashion across scientific disciplines[58][59]. This high-level commitment (likened to a Manhattan Project for AI-driven science[60]) reflects both the plausibility and strategic importance seen in this technology: multiple federal labs and major institutions are now funded to realize **AI-run experiments** and shorten discovery cycles, aiming to keep national R&D at the cutting edge[16].

#### 132. **Maturity score (1–7) and reasoning**

**A) Score – 5 (out of 7).**

**B) Reasoning –** The evidence indicates that *AI-driven autonomous discovery* is **well beyond the early theoretical or single-lab prototype stage**, and is now entering an intense development and scaling phase. **Level 3 (lab prototype)** is clearly surpassed: we have multiple working prototypes across domains (chemistry, materials, biology, even quantum physics) showing that key technical hurdles can be solved – e.g. an autonomous materials lab ran 57 syntheses continuously[5], and an AI planned multi-step chemistry experiments with human-level skill[2]. These successes also meet **Level 4 (Proof-of-Concept)** criteria: the autonomous systems demonstrated *clear benefits over traditional approaches*, such as discovering a cheaper process than any human had (40% cost reduction in protein production)[31], or finding battery solvents that far exceeded prior solubility limits[61]. This shows that AI labs can not only function, but *outperform classical R&D baselines*, satisfying the “exceeds previous solutions in benefit” condition for level 4.

We assign **Level 5** because multiple well-funded actors are now pushing toward **production-ready platforms**. Evidence of this “race” includes the partnership of a major lab vendor and an AI chipmaker to build **autonomous lab products** (Thermo Fisher + NVIDIA, 2026)[54], the involvement of big tech (OpenAI, Google DeepMind) with biotech and national labs in this domain[62][63], and the launch of large-scale programs like DOE’s Genesis Mission to unify resources for AI-driven science[17][59]. There is a clear *commercial and strategic momentum*: companies are beginning to **deliver early offerings** (e.g. cloud labs with AI copilot functionality[12], AI-optimized reagents on sale[13], smart instruments like Attune CytPix shipping to labs[55]), and significant investments are flowing (national labs



consortium, new startups, etc.). All this suggests the field is moving fast *post-PoC*, aiming to deploy robust systems in real research environments – exactly the essence of level 5.

Lower maturity levels are ruled out by the breadth and recent pace of progress. Unlike level 2, we now have repeated experimental validation, not just isolated lab tests. And unlike level 3–4, development is not confined to one-off demos; **concurrent efforts** are tackling scaling, usability (natural language interfaces[64]), and integration into existing R&D infrastructure[65][66]. The concept is no longer speculative: it’s actively being engineered into products and national R&D strategies.

We do *not* yet score it a 6, because fully mature **products aren’t widely delivered at scale**. There is not yet a turnkey “AI Scientist” in routine use across industry – current deployments are mostly pilots or specialized use-cases. To reach level 6, we’d expect to see many labs routinely buying or subscribing to autonomous discovery systems, with costs dropping and production volumes rising. That level of market penetration and competition (analogous to, say, widespread use of DNA sequencers or cloud computing in labs) is still forthcoming. Key evidence missing for level 6–7 is broad customer adoption and multiple competing products with significant revenue. We see *early signs* (e.g. Thermo’s initiative, Emerald Cloud Lab’s expansion[67]), but the *ecosystem* of competing, mature products is just beginning to form. In short, **autonomous scientific discovery is in the advanced development/prototyping phase (Score 5)**: proven viable with strong advantages, backed by multiple major players, and now on the cusp of initial real-world rollout – but not yet a ubiquitous commodity in the research marketplace.

**C) Sub-component breakdown:** This ART blends several technologies, each at slightly different maturity, but converging toward an integrated capability:

- *Robotic lab automation hardware*: Fairly mature (many labs already use automated equipment; some cloud lab services exist). **Maturity ~6**, as robots and instruments are delivered and used routinely – however, these operate mostly under human programming rather than full AI autonomy[68][66].
- *AI planning and reasoning software*: Rapidly evolving. LLM-based experiment planners only emerged in the last 1–2 years[2]. They have achieved **proof-of-concept (4)** by executing real experiments, even matching human expert decisions[69][34]. But reliability, safety, and generality are still being improved, and this software isn’t yet a shrink-wrapped product.
- *Integrated autonomous research systems*: The full stack (AI + lab hardware + data systems) is currently at **PoC to pilot stage (4–5)**. Some integrated prototypes have met important benchmarks (e.g. discovering new materials/drugs faster or cheaper) and even delivered an early commercial outcome (new reagent)[18]. Multiple actors are now building on these prototypes (indicating a move into level 5). Overall functionality is similar across variants (all aim to automate the research loop), so the most advanced instances push the composite maturity upward. We therefore weigh the **maximum** demonstrated capability – level 5 – as representative of the bundle’s state. The robustness of the hardware and the clear PoCs achieved justify at least level 4, and the multi-actor push justifies elevating to 5.

In summary, **we score this ART as a 5**, reflecting a technology on the brink of practical deployment. The concept is validated and highly promising (no fundamental science barriers remain – it works), and the race is on to polish and scale it. However, the step to level 6 will require these autonomous discovery systems to transition from pilot projects to widely

adopted research tools, a step likely to unfold in the coming few years. The evidence to date rules out any lower rating, but also underscores the gap to full commercial ubiquity.

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## Group 4 – Human-Machine Interaction & Augmentation

### ART 04.022 Immersive Augmented & Virtual Reality

#### 133. ART extraction

134. *Primary capability:* Integrating **digital content seamlessly with the physical world** via head-worn displays that render immersive augmented, virtual, or mixed reality (XR). This enables virtual objects and information to appear **co-present and spatially anchored** in a user's real environment, or to fully simulate immersive virtual environments.

#### 135. Key sub-components/variants:

- **Augmented Reality (AR) glasses:** Lightweight, transparent smart glasses for everyday use, overlaying graphics onto real-world view. Emphasis on **compact optics** (waveguides, holographic combiners) for wide field-of-view see-through displays, and on all-day comfort (weight, thermal)[1][2].

- **Virtual/Mixed Reality (VR/MR) headsets:** Enclosed or passthrough-view headsets (e.g. VR headsets with high-resolution displays and MR color cameras) for **full immersion**. Prioritize wide FoV, spatial audio, and precise inside-out tracking of environment and user (head, hands, eyes)[3][4]. Often tetherless but heavier, with shorter battery life[5]. Room-scale installations (CAVEs, simulators) offer shared immersion at larger scale.
  - **Spatial mapping & sensors:** Onboard **cameras, depth sensors (LiDAR)** and IMUs to continuously scan surroundings, reconstruct surfaces, and track user position and motions in 3D[3]. **Eye-tracking** cameras and **hand-tracking** (via vision or controllers) enable natural input and foveated rendering[3][4]. Optional body or face tracking can be added for avatars.
  - **User interaction & feedback:** Multimodal inputs – **voice commands, gaze targeting, gesture recognition**, and handheld controllers – provide intuitive control[4]. **Spatial audio** (3D sound) is standard, and **haptic feedback** (e.g. vibrations in controllers, gloves or suits) is sometimes integrated to enhance realism.
  - **Software & content:** Common **XR software platforms (e.g. OpenXR, ARCore/ARKit)** allow developers to extend existing 2D apps into 3D space or build new immersive experiences[6][7]. The system anchors virtual content to real-world **coordinates or surfaces** (persistent AR anchors[8][9]), enabling multi-user shared experiences. **On-device or cloud AI** may personalize the experience by learning user preferences, context, and intent (e.g. adaptive interfaces or intelligent assistants that provide just-in-time guidance)[10][11].
136. **Maturity indicators:** Evidence would include **functioning prototypes and commercial products** (e.g. AR headsets like HoloLens 2, Magic Leap 2; VR headsets like Meta Quest, Sony VR, Apple Vision Pro), with **field trials or deployments** (enterprise or military use, developer kits)[12][13]. Key indicators are **increasing unit shipments**[14], multiple large **companies investing and competing** (Apple, Microsoft, Meta, Google, Sony, etc.), **standards and ecosystems** (OpenXR adoption, content libraries)[6][15], and demonstrated **performance milestones**: e.g. achieving wide FOV, high resolution displays[1][16], accurate tracking, and improvements in battery life or form factor. Also evidence of **value in practice** – studies or trials showing XR reduces task errors, training time, or other bottlenecks – would support plausibility[17][18].
137. **Evidence (10–20 recent, reliable sources)**
138. **Holographic Waveguide AR Display Prototype – Jang et al., Nature Communications (2024):** Researchers demonstrate a **compact near-eye display** combining waveguide combiners with true 3D holographic projection. The prototype achieved a >10° diagonal field-of-view with a software-steerable large eyebox, addressing challenges of **vergence–accommodation conflict and image quality** in AR glasses[19][20]. *This peer-reviewed experiment shows progress toward high-resolution, comfortable AR eyewear, using novel optics to overcome focus depth and compactness limitations.*
139. **Meta-Analysis on AR/MR Training Efficacy – Liu et al. (Macao Polytech/U. Macao), BMC Med. Educ. (Accepted 2025):** Analyzes 29 studies of AR/MR in medical education. **Hands-on skill training improved significantly** with AR/MR: on average ~12.3-point higher skill scores, ~8% lower failure rates, and faster task performance than traditional methods[21]. No major gains in textbook knowledge, but **user acceptance was higher** (e.g. higher perceived usefulness and enjoyment)[22][23]. *Demonstrates that AR/MR can tangibly enhance complex*

*procedural training, supporting the technology's value in reducing errors and cognitive load for real-world tasks.*

140.     **Augmented Reality Assembly Guidance – Osman et al., Int. J. Informatics Visualization (2020, study continued into 2022):** In a controlled trial for PC assembly, an **AR headset overlay** led to **significantly fewer errors and faster assembly times** compared to paper instructions[17]. Users with AR completed tasks with improved accuracy and speed, confirming that **just-in-time 3D guidance** can alleviate misinterpretation and reduce task completion time vs. traditional manuals[24][17]. *This illustrates XR's potential to offload cognitive effort in complex layout understanding and procedural work.*
141.     **US Army IVAS Field Trials (HoloLens-based) – Army Times (Dec 2023):** The Army has procured **10,000+ AR combat headsets** (Integrated Visual Augmentation System) based on Microsoft HoloLens tech for testing and training[12]. Early versions (IVAS 1.0/1.1) were delivered in 2022–23, and an improved 1.2 prototype (20 units) began troop trials in 2023 with ~280 more sets planned by 2025 for broader fielding[12][13]. These see-through headsets integrate **night vision, thermal imaging, and tactical data**: soldiers can view weapon-sight video feeds in their HUD, see digital waypoints/enemy markers overlaid on terrain, and even control micro-drones with live AR map updates[25][26]. *This indicates a well-funded, at-scale prototype deployment addressing situational awareness bottlenecks; it also reveals current challenges (field of view, soldier comfort) being iteratively solved in a high-stakes environment.*
142.     **Global AR/VR Headset Shipments – IDC Worldwide Quarterly Tracker (IDC press release, Mar 2023):** Reports that **2022 saw ~8.8–9.7 million AR/VR headsets shipped** (slight dip in growth), and **2023 shipments were forecast ~10.1 million** (14% YoY growth)[14]. Consumer VR remains the dominant segment (gaming and entertainment driving volume), but IDC notes **increasing investment in consumer AR glasses** by brands like Xiaomi, Oppo, TCL, etc., alongside major VR device launches from Sony (PSVR2), Meta, Apple, and Pico[27][28]. *This underscores that multiple well-capitalized industry players across the US, Asia, and Europe are delivering XR hardware to a growing market (tens of millions of units annually), reflecting improving technology and expanding interest.*
143.     **Google “Android XR” Platform Launch – S. Izadi (Google VP), Google Blog (Dec 2024):** Google announced **Android XR**, a new OS for AR/VR devices made with Samsung & Qualcomm, signaling a unified ecosystem for upcoming headsets and glasses[6]. The developer preview supports standard XR frameworks (**ARCore, OpenXR, Unity**) so existing mobile apps and data can **seamlessly extend into 3D space** (e.g. YouTube, Maps, Chrome running as floating AR windows)[7]. It integrates Google’s **“Gemini” AI assistant** that can see and understand the user’s environment and context – users can interact conversationally about what’s in view or get guided through tasks in AR[10]. Google also emphasized plans for **all-day AR glasses** that are as lightweight as normal eyewear, tightly integrating with smartphones and cloud services[29][11]. *This highlights significant software infrastructure maturity: tech giants are actively prepping for mass XR adoption by enabling cross-device app compatibility, AI-driven context awareness, and a pipeline of devices from multiple manufacturers.*
144.     **Apple Vision Pro Technical Documentation – Apple (June 2023):** Apple’s “spatial computer” (Vision Pro) showcases the state-of-the-art: it features dual **micro-OLED displays with 23 million pixels total** (approaching retinal resolution) for an immersive MR visual experience[30]. The headset is studded with **12 cameras and 5 sensors**, including **two color pass-through cameras, six IR tracking cameras, four eye-tracking cameras, a LiDAR depth scanner**, plus IR projectors for precise hand and eye tracking[3]. It supports **natural hands-free input** (tracked hands, eye-gaze dwelling, and voice commands) as primary interaction[4].



**Spatial audio** is delivered via integrated speakers and beamforming mics[31]. A dedicated R1 chip processes sensor data in 12 ms for responsive mixed reality. *Notably, the Vision Pro's battery life is ~2.5 hours on a wearable pack[5], illustrating the power/thermal constraints of this compact form-factor, despite Apple's advanced silicon.* Overall, this **commercial product** exemplifies the high-end of XR capabilities (ultra-high resolution, precise environment capture, intuitive UI), while highlighting ongoing limits in **wearability (~800 g headset) and endurance[32][5]**.

145. **Magic Leap 2 AR Headset – Product Spec (Magic Leap, v1.2, 2022):** The Magic Leap 2 (enterprise-focused AR glasses) introduced **proprietary optics that doubled the field-of-view** (~70° diagonal, up from ~50°) while maintaining a see-through display[2]. It also added **Dynamic Dimming™** – an electrochromic layer that can electronically dim the lenses up to 99.7%, improving contrast of AR imagery even in bright environments[33][2]. To achieve all-day wearability, ML2 offloads processing and power to a hip-mounted “Compute Pack,” making the **headset ~50% smaller and 20% lighter** than the prior model[34]. It features one of the highest compute specs in AR (custom AMD SoC) with **2–3× performance boost**, and includes **advanced sensors** (eye tracking, hand tracking, spatial mapping cameras) plus **iris-scanning biometrics** for secure logins[35][36]. The device runs an open **Android-based OS** to ease custom app development and IT integration[37]. *This represents a refined production prototype of AR glasses: significantly improved visual and ergonomic performance over earlier generations, albeit at high cost (~\$3,000) and still tethered. It underscores progress in optical engineering and the emphasis on enterprise use (with data privacy controls for on-premises/cloud and multi-user management)[38].*
146. **Persistent Multi-User AR Content – Google ARCore Cloud Anchors (Dev Documentation, updated Nov 2025):** Google's Cloud Anchor API allows AR applications to **host virtual anchors in the cloud that persist over time and across devices[8]**. For example, a user can pin a virtual object or note to a real-world location (like a machine in a factory or a spot on a remote site) and other users, even on different platforms (Android or iOS), can later see that same AR content precisely overlaid in the same place[8][9]. **Shared AR experiences** are enabled by exchanging a Cloud Anchor ID, letting multiple people collaborate in real time (e.g. two users see and manipulate the same virtual object on a table from their own devices)[39][40]. *This cloud-backend capability demonstrates that the ecosystem has evolved to support persistent, networked spatial content, which is crucial for real-world deployment of AR in maintenance, remote assistance, and collaborative design – addressing the bottleneck of content calibration and multi-user consistency.*
147. **Next-Gen AR Display Tech – TriLite CTO J. Reitterer interview, Markt & Technik/TriLite News (Dec 2023):** Industry experts acknowledge that **optical display quality remains a key constraint** for consumer AR. For instance, **microLED micro-displays**, once expected to enable compact AR glasses, are “*still too expensive, not bright enough, and don't provide sufficient resolution*” at scale – even Apple's flagship device opted for microOLED instead[1]. In response, companies are pursuing alternatives like **Laser Beam Scanning (LBS)** projectors, which use MEMS mirrors and laser diodes. LBS engines can be extremely small and lightweight while delivering very bright images; importantly, “*LBS is the only available tech that maintains size/weight while increasing field-of-view and resolution*”[16]. TriLite and partners (TDK, ams Osram, Dispelix, etc.) in 2023 demonstrated a postage-stamp-sized LBS projector (Trixel 3) that won awards for enabling true eyeglasses-like AR form factors. *This evidence highlights active R&D in overcoming optical and manufacturing bottlenecks: a push toward mass-producible, wide-FOV displays for AR that could finally achieve the cost, brightness, and slim form factor needed for broad consumer adoption[41][1].*
148. **Maturity score (1–7) and reasoning**

## Proposed Maturity Score: 6 (Advanced prototypes and initial products, nearing scale-up)

**A) Justification for score:** The immersive AR/VR technology bundle has moved well beyond lab demos – it now features **commercial products in the hands of users** and **multiple competing major players**, which rules out Levels 1–4. VR headsets especially are a maturing market: millions of units ship yearly and are iteratively improving[14][27], satisfying Level 6 criteria (“products delivered to customers in increasing amounts; application areas expanding”). High-end MR devices like the Apple Vision Pro are launching as polished products (albeit expensive), demonstrating full functionality (rich visuals, intuitive interaction) that clearly **exceed prior solutions** like flat screens in immersion and capability[3][4]. The evidence also shows **fast-paced progress and heavy investment**: e.g. Google’s and Meta’s platforms, Apple’s device, and others all advancing in parallel[6][27]. This competitive ecosystem with well-funded actors pushing toward scalable production (Apple’s supply chain, Qualcomm reference designs, etc.) is characteristic of Level 6.

Level 5 (post-Proof-of-Concept prototypes) is too low given that **multiple products are already deployed** outside the lab. For instance, **enterprise and defense AR systems are in field trials and limited deployment** (thousands of IVAS headsets contracted by the US Army)[12][13], and companies like Magic Leap are on their second-generation AR device being sold to industry[2][34]. Such traction indicates we are past one-off prototypes – the technology works well enough to attract early customers and iterative refinement, which aligns with Level 6.

We do not yet assign Level 7 because **mass-market adoption and sustainable commercial traction are still emerging**. While there are competing products on the market (Meta vs. Apple vs. Pico in VR, etc.), the overall XR sector has not yet proven “*rising demand*” from a wide consumer base or achieved economies of scale to sharply lower prices (in fact, AR glasses remain expensive). *What’s still missing for Level 7:* We need to see **broader consumer uptake of AR devices** (beyond enterprise and enthusiasts) – for example, truly wearable AR glasses at affordable prices – and multiple firms profitably scaling up production for a **wide clientele**. Current evidence shows technical viability and early-market penetration, but not yet the *ubiquity* or cost reduction that Level 7 implies. Moreover, some critical bottlenecks (display brightness, battery life, content breadth) remain to be fully solved before XR is a mainstream, in-demand commodity. Thus, the field as a whole is best characterized as **on the cusp of scale (Level 6)**, rather than fully scaled.

**B) Sub-component breakdown:** It’s useful to note that within this bundle, **VR/MR headsets** are slightly more mature than **AR glasses**. Consumer VR (e.g. standalone headsets like Oculus/Meta Quest) has a several-million-user install base and a content ecosystem, roughly fitting a Level 6–7 (products delivered at scale with active competition)[27][28]. In contrast, true AR smart glasses (transparent, all-day devices) are at roughly Level 4–5: functional prototypes exist (e.g. HoloLens, Magic Leap, pre-release Apple glasses) and giants are heavily investing, but widespread deployment and cost reduction are still pending[2][11]. The **overall XR score of 6** is an approximate average of these states. We weight the score toward 6 because VR/MR’s success demonstrates the core technology’s feasibility and market value (pulling the average up), and AR glasses – while a step behind – are benefiting from the same advances in sensors, processors, and software. The **common functionality across variants (blending digital and physical worlds for human use)** means progress in one domain accelerates the others. Therefore, as a bundle, immersive AR/VR earns a solid Level 6: key



hurdles are actively being solved, early products are out, and the path to wider adoption in the next few years is credible – but the *final leap* to ubiquitous, everyday use (Level 7) will require further improvement in form factor, cost, and public demand as evidenced by future large-scale rollouts.

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## ART 04.023 Brain-Computer Interfaces (BCI)

### 149. ART extraction

**A. Primary capability** – Direct, high-bandwidth communication between the human brain and digital systems, enabling users to send commands or information by *thought* and receive feedback without relying on conventional peripheral devices. This would bypass the speed and precision limitations of speech, typing, or touch by interfacing closer to neural activity. In essence, the ART promises a **brain-computer interface (BCI)** that can *read* neural signals (to decode intentions, imagined movements, attention, etc.) and *write* information back (via sensory feedback or direct neural stimulation), creating a seamless interactive loop.

### **B. Key sub-components / variants –**

- **Non-invasive BCIs (wearables):** External headsets or caps (e.g. EEG or optical imaging) that detect brain signals through the scalp, requiring no surgery. These prioritize safety and convenience but must overcome signal noise and limited bandwidth due to skull attenuation.
- **Minimally invasive BCIs:** Implanted electrode arrays that sit on the brain surface or within blood vessels (e.g. ECoG grids beneath the dura, or stent-electrode devices) without penetrating brain tissue deeply. These promise higher signal quality than wearables while reducing surgical risk relative to fully penetrating implants.
- **Fully implantable BCIs (intracortical):** High-density microelectrode arrays inserted into brain tissue, or advanced neural probes, capable of directly recording from and stimulating neurons. These offer the richest, high-bandwidth signals (and bidirectional capability) at the cost of invasive surgery and biocompatibility challenges.
- **Neural decoding & feedback systems:** Software and algorithms (often AI/ML-based) that interpret complex neural activity patterns in real time and translate them into control signals or device commands. These systems learn and adapt to each user's brain signals. Coupled with this are output modalities – from conventional visual/audio cues to **neurostimulation feedback** (stimulating the brain to convey sensory information or cues directly).
- **Packaging & connectivity:** The hardware is envisioned in wearable form factors (headsets) or fully implanted units with **wireless power and data** links. This includes on-board signal amplification/processing and secure wireless communication to external devices or cloud resources. Key engineering components are power management (to minimize heat), miniaturized electronics, and robust encapsulation to protect both the electronics and the brain over long durations.

### **C. Maturity indicators** – Evidence of progress for this ART would include:

- **Successful prototypes in humans (clinical trials):** e.g. paralyzed or locked-in patients

using BCI implants to control computers, communicate (typing or speech), or operate assistive devices in real-world settings. Repeated demonstrations of reliable, real-time control or sensation over months would show viability beyond isolated lab experiments.

- **High-channel, high-bandwidth devices demonstrated:** Hardware breakthroughs such as **large electrode-count implants with wireless data transfer** and long-term stability, or non-invasive systems achieving unprecedented resolution. Metrics like number of channels (order of 1000+), data rates (Mbps), and longevity of recordings/stimulation would indicate the bottlenecks of signal quality and scalability are being solved.

- **Movement toward commercialization:** Regulatory designations or approvals (e.g. FDA Breakthrough Device status, human trial approvals), **well-funded companies and consortia** building production prototypes, and **early product deployments**. For instance, multiple competing startups securing large investments and engaging in human trials, or partnerships with tech/medical device firms, suggest the field is transitioning from academic research to commercial development.

- **Ecosystem readiness:** Evidence of practical use-cases being tested (BCI-controlled consumer electronics, VR/AR integration, neuroprosthetic limbs with feedback, etc.), and the establishment of standards or safety protocols for neural data handling. Increasing participation of users outside the lab (at-home BCI use, externally monitored) and improving cost/power profiles would also mark a maturing technology.

#### 150. Evidence (10–20 recent, reliable sources)

151. **Wireless 65k-electrode BCI chip – Jung et al. (Columbia/Stanford/UPenn) – *Nature Electronics* (peer-reviewed) – Dec 2025.** **Link:** A fully implantable *subdural* BCI with a 50 µm-thick flexible chip (256×256 electrodes) was demonstrated[1][2]. It integrates 65,536 electrodes with 1,024 simultaneous recording channels and 16,384 stimulation channels, all on one CMOS chip, and communicates wirelessly at 100 Mbps (~100× higher throughput than prior wireless BCIs)[2][3]. This high-bandwidth implant, termed “BISC,” showed *chronic, reliable recordings* in pig cortex for 2 weeks and is designed to “slide” under the skull with minimal invasiveness[4][5]. **Significance:** Demonstrates a leap in scaling (orders-of-magnitude more channels) and system integration (on-chip processing + wireless power/data), tackling key bottlenecks of signal bandwidth and implant size for BCIs. It shows that high-density, *minimally invasive* BCIs are technically feasible and approaching clinical translation (studies in human patients were underway)[6][7].

152. **Endovascular BCI human trial – Mitchell et al. (University of Melbourne & Synchron) – *JAMA Neurology* (peer-reviewed) – Mar 2023.** **Link:** Reported the first *in-human* trial of a **minimally invasive** brain implant delivered via blood vessels (the “Stentrode” device) in four patients with ALS[8][9]. Over 12 months, the implanted endovascular electrodes remained stable with **no serious adverse events, no vessel blockage, and no migration**[8]. Neural signals (bandwidth ~233 Hz) were recorded reliably, and at least five distinct imagined movement commands could be decoded from each patient’s motor cortex activity[10][11]. All four users successfully used the BCI to control a personal computer for tasks like texting and emailing by thought alone[10][12]. **Significance:** Validates the safety and practicality of a **minimally invasive BCI** (inserted through the jugular vein, avoiding open brain surgery) over long-term use. It achieved real-world functionality – patients controlled digital devices hands-free – indicating a viable path to wider clinical deployment[13]. This also shows progress on a key maturity factor: multi-month home use is possible with an implant that greatly lowers surgical risk, supporting the plausibility of scaling BCI access to more patients.

153. **Brain-to-text/speech neuroprosthesis – Brandman, Stavisky et al. (BrainGate Consortium)** – *Nature / NEJM (peer-reviewed)* – Aug 2023 & Aug 2024. **Link:** A series of breakthroughs enabled **paralyzed patients to fluently communicate via BCI**. In one study, two intracortical implants (Utah arrays) recorded motor cortex signals from an ALS patient to decode intended speech at up to **62 words-per-minute** with ~25% error rate (Nature 08/2023). Subsequently, an improved BCI system translated neural signals into text *and* audible speech with **up to 97% accuracy**, as reported in NEJM[14][15]. The device (implanted in the speech motor cortex) allowed the user to converse by just attempting to speak – brain signals were decoded into phonemes and spoken aloud by a computer in real time[16][17]. Over 32 weeks, the system was used for 250+ hours of self-paced conversation, maintaining ~97% word accuracy with a large 125,000-word vocabulary after training[17][18]. *Significance:* These results shatter previous communication-speed records for BCIs, approaching natural speech rates and reliability. They demonstrate that *high-bandwidth* neural decoding paired with modern AI models can restore communication to nearly normal levels[19]. The sustained use and high accuracy achieved underscore the maturation of both the hardware (multi-array implants) and algorithms (deep learning decoding of neural activity), providing strong evidence that BCIs can meet real-world performance requirements for people with paralysis.
154. **Real-time speech BCI with low latency – Anumanchipalli & Chang teams (UC Berkeley/UCSF)** – *Nature Neuroscience (peer-reviewed)* – Mar 2025. **Link:** Researchers developed an **AI-driven BCI that streams neural activity to audible speech in near real time**[20][21]. Using a high-density electrode array on the cortical surface of a volunteer (an implanted ECoG grid) and novel streaming algorithms, they **eliminated the usual lag** in BCI speech prosthetics[21]. The system decoded the user's attempted speech and synthesized it into a voice output *almost instantaneously*, enabling a natural rhythm of conversation. Crucially, the approach generalized across different interface types: it was shown to work with intracortical microelectrode signals and even non-invasive electromyographic (EMG) sensors on the face[22][23]. *Significance:* Tackles a major usability challenge – latency – bringing BCI communication closer to normal human conversation speed[21]. It also suggests future BCIs could be modality-agnostic, using whatever signals available (invasive or non-invasive) with advanced AI decoding. This progress in software/algorithms complements the hardware advances, indicating the BCI field is addressing both sides of the “bandwidth” equation (neural signal capture *and* interpretation in real-time).
155. **Brain-spine motor bypass in human – Lausanne/EPFL (M. Courtine & G. Bloch)** – *Nature (peer-reviewed)* – May 2023. **Link:** A team in Switzerland demonstrated a **wireless brain-computer spinal interface** that enabled a chronically paralyzed man to regain natural walking ability[24]. An implant in the motor cortex captured the intention to move and transmitted it in real-time to a stimulator in the spinal cord below the injury, effectively forming a “digital bridge” over the lesion[24]. With this setup, the patient could stand, walk, and even climb stairs *controlled by his thoughts*, in outdoor and home settings[25][26]. Notably, after several months of use, the patient's neurological function improved to the point that some voluntary movement was possible even with the BCI turned off (suggesting activity-dependent plasticity). *Significance:* This is a milestone for *closed-loop BCIs* with both recording and stimulation: it validated that high-bandwidth neural signals can be used to restore complex motor functions in real life[25]. The work combines many aspects – implantable hardware, decoding algorithms, and neurostimulation – and shows the BCI can achieve **clinically meaningful outcomes (walking)**, underscoring the technology's transformative potential if matured. It also illustrates progress on safety/durability, as the system functioned reliably in daily activities, outside lab control.

156. **Non-invasive high-resolution BCI (DARPA “N<sup>3</sup>” program) – Grover et al. (CMU) –** *Journal of Neural Engineering / Univ. report* – Jul 2023. **Link:** Under a DARPA-funded project, researchers achieved **unprecedented spatial and temporal resolution in a fully non-invasive neural interface**[27][28]. By using novel electrode “patches” and tailored current injection patterns, they effectively made the skull “transparent” to electrical currents, focusing stimuli and recordings at specific brain regions with far greater precision than standard EEG or TMS[29][27]. In *animal studies* (rodents and monkeys), the team’s high-density wearable patches could steer currents to target motor cortex areas finely enough to distinguish adjacent hand/arm regions[30]. They built a platform to both **record and stimulate** brain activity through the intact scalp at high resolution, and as of 2023 they had progressed to initial *human testing (Phase 3)* with this technology[31][28]. **Significance:** Demonstrates that non-invasive BCIs need not be low-bandwidth forever – through advanced physics and engineering (flexible electronics, optimized waveforms), the team showed **it’s possible to dramatically improve signal focus without surgery**[27][32]. This addresses a key variant of the ART: if refined, such wearable BCIs could offer a safer, wide-access alternative for brain–computer communication. The fact that human trials are underway indicates a tangible path toward practical non-invasive BCIs with much higher performance than today’s EEG headsets.
157. **Paradromics “Connexus” high-data-rate implant – Paradromics Inc. –** *Company technical press release* – May 2023. **Link:** Paradromics announced an implant platform (Connexus Direct Data Interface) featuring **modular intracortical electrode units** and achieved an FDA Breakthrough Device Designation[33]. The system uses multiple small implants (“cortical modules”), each with **~1,600 channels**, linked to a subcutaneous hub for power and wireless communication[34]. By networking up to 4 modules, the device can record from 6,000+ neurons simultaneously – enabling *high data-rate streaming of brain signals*. The first target application is an assistive communication prosthesis to translate brain activity into text or speech in real time for patients with paralysis[35][36]. With a \$33 M Series A raise, Paradromics is preparing first-in-human trials for this system[37][33]. **Significance:** This illustrates the industry push toward **scalable, high-channel-count BCIs** and shows confidence from regulators (Breakthrough status) and investors in the technology. The Paradromics design emphasizes a path to manufacturing (leveraging multiple smaller implants rather than one huge array) and *high-bandwidth wireless data relay*[34][38]. It highlights that well-funded startups are now engineering devices not just for lab experiments but for *clinical translation*, with hardware and business roadmaps aimed at commercial deployment.
158. **Precision Neuroscience “Layer 7” cortical interface – Rapoport et al. (Precision) –** *Nature Biomed. Engineering (peer-reviewed) / industry news* – Oct 2025. **Link:** Precision Neuroscience (a Neurotech startup) published design and trial results for a **thin, flexible ECoG implant** that can be inserted through a *sub-millimeter slit* in the skull[39]. The device is a postage-stamp sized film, *only one-fifth the thickness of a human hair*, holding 1,024 electrodes; multiple modules can be combined (they’ve used up to four to cover 8 cm<sup>2</sup> of cortex)[39][40]. In a pilot with **5 human patients** (during brain tumor surgeries), the device recorded high-resolution neural data and even detected when a patient was trying to speak with ~80% accuracy after only 4 minutes of calibration[41][42]. The implant can also **deliver stimulation** without penetrating the brain, and in animal tests it recorded distinct signals from electrodes just 300 μm apart, indicating very fine spatial resolution[41][43]. The Layer 7 system received FDA clearance in 2023 for temporary intraoperative use (e.g. mapping brain activity during surgery)[44]. **Significance:** Validates a *minimally invasive* approach: high-density neural interfaces can be introduced with **no craniotomy and no penetrative probes**, significantly lowering risk[45]. Yet it still achieves “brain safety and performance” comparable to traditional electrodes[45]. The study also underscores momentum toward clinical adoption – FDA clearance and human data – and suggests such thin-film BCIs could be made *removable or*



*upgradable* (“modular and reversible” design), aligning with long-term maintenance needs at scale[39][46].

159. **Multimodal BCI integration & industry progress – (Summary of 2025 developments) –** *Fierce Biotech (trade news)* – Nov 2025. **Link:** By late 2025, the BCI sector saw **rapid commercialization efforts with multiple players**. Synchron, for example, raised \$200 M in a Series D to *expand operations and pursue FDA approval* of its **wireless Stentrode BCI**, which had by then been implanted in 10 patients across the US and Australia[47]. In 2023–25, a patient with a Synchron implant was able to **control an iPad and even an Apple Vision Pro headset by thought alone**, using the BCI to navigate apps, type messages, and interact with smart home devices (lights, Alexa) entirely hands-free[48]. Meanwhile, competitor Neuralink secured \$280 M (Jul 2023) and \$500 M (Sep 2024) in funding and began its first human trials, and other startups like Precision and Paradromics (USA) as well as *Science Corp.* (whose **retinal implant BCI restored partial vision** in AMD patients) made headline progress[49][50]. Companies are hiring aggressively and building out manufacturing/research facilities to develop **production-grade BCI devices**, and several devices have FDA Breakthrough status. *Significance:* Clear evidence of *multiple well-capitalized actors entering the final prototyping and trial phase* simultaneously[51][52]. There is a competitive race to bring BCIs to market, with fast-paced advances not just in labs but in *engineering, testing, and regulatory engagement*. The example of an ALS patient using a BCI with everyday consumer tech shows these interfaces are on the cusp of practical use outside research settings[48]. Collectively, these developments indicate that the field has moved beyond isolated experiments into a nascent **industry**, a key sign of growing maturity.

160. **Maturity score (1–7) and reasoning**

**Overall Maturity Score: 5** (out of 7) – **Advancing toward viable products:** Multiple converging BCI approaches have progressed through proofs-of-concept into active **clinical trials and pre-commercial prototypes**, backed by significant funding and institutional support. This corresponds to rubric level 5, where well-capitalized actors are racing to develop production-ready systems post-PoC and investing in scaling up the technology.

**Justification (Evidence-to-rubric mapping):**

- **Exceeds Levels 2–3 (theory & lab prototype):** BCIs are far past basic feasibility demonstrations. The core scientific principle – that neural signals can be recorded/decoded for device control – was established decades ago, and in recent years we’ve seen **robust prototypes working in human patients** for extended periods. For instance, the *12-month human trial of the Stentrode BCI* showed stable, safe operation and enabled everyday digital communication by thought[8][11], which is well beyond a lab demo. Similarly, intracortical BCIs have achieved unprecedented communication speeds (60–90 WPM) and accuracy ~97% in paralyzed users[15][19], indicating that fundamental technical hurdles (signal capture, decoding algorithms) have been solved to a degree that meets real user needs. These achievements rule out maturity levels 1–3 decisively.

- **Meets Level 4 (functional PoC):** The evidence shows **multiple functional PoCs hitting performance and viability targets**. Key breakthroughs – like the wireless 1024-channel BCI chip (BISC) that marries high bandwidth with minimal invasiveness[2][3], or the brain-spine interface restoring natural walking[24] – demonstrate that BCIs can deliver unique capabilities *beyond* what prior solutions offer. Many systems now operate untethered and user-friendly (wireless, wearable or fully implantable), a sign they are designed with eventual production in mind. Moreover, early **regulatory milestones** (e.g. FDA Breakthrough designations for multiple BCI devices[33][49]) and initial *at-home* uses (patients using BCIs

with tablets, VR headsets, etc. in daily life[48]) show that these prototypes are viewed as viable for deployment, not just isolated experiments. This solidly fulfills Level 4 criteria.

- **Approaching Level 5 (competitive development):** We assign **Level 5** because there is now a *competitive ecosystem of companies and research groups* driving the technology toward market. Over the last 2–3 years, at least a half-dozen well-funded startups (Neuralink, Synchron, Paradromics, Precision, Blackrock Neurotech, Science Corp., etc.) – often backed by major investors or government programs – have built BCI prototypes and are entering or conducting **clinical trials**[51][52]. They are explicitly working on manufacturable, implantable devices with the intent to commercialize in the near term (e.g. Synchron’s Series D to “accelerate commercialization” of its BCI, aiming for an FDA clearance and product launch)[51][53]. The **fast-paced progress** is evidenced by successive records and breakthroughs: higher channel counts and wireless throughput (scaling to thousands of electrodes and 100 Mbps links)[2][3], increasing numbers of human users, and integration with consumer technologies. Importantly, **no fundamental science roadblocks remain** – the focus has shifted to engineering reliability, safety, and user experience, which is characteristic of this stage. In summary, the groundwork for BCI’s core feasibility is done and the race is on to refine and deploy it, matching the description of level 5.

**Why not Level 6 yet?** BCIs have not fully reached widespread product delivery or scaling in the open market. *Level 6* would require that products are being delivered to many customers with expanding production and rapidly dropping costs. As of early 2026, BCI devices are still generally in the **clinical trial and early adopter phase** – e.g. dozens of human implants worldwide, not thousands; primarily in research or medical contexts rather than a general consumer market. We do see the first signs of future scaling (e.g. companies building manufacturing lines, multi-million-dollar investments for scaling, and some **limited commercial sales of simpler BCIs** like EEG headsets). However, the high-bandwidth, implantable systems described in the ART are *just entering* pivotal trials and have not yet seen mass deployment or revenue-generating sales. No competing products are broadly on the market for end-users yet (aside from niche research and medical use). Achieving level 6 will likely require regulatory approvals and initial commercialization – for example, an FDA-approved BCI for paralysis available to hospitals/clients, with units being produced and sold – which is anticipated within a few years but not reality at present.

**Sub-component nuances:** This ART spans a spectrum from non-invasive to fully invasive BCIs, which are at slightly different maturity stages. **Non-invasive BCIs** (e.g. EEG wearables) are *technologically simpler* and some are **already commercial** (for wellness, gaming, etc.), but currently they offer limited bandwidth and have not proven the transformative value described (they largely remain niche gadgets). **Implantable BCIs** (both minimally invasive and penetrating types) are where the highest performance lies and where recent progress is fastest – these are in clinical trials with strong results but not yet sold products. If we were to score separately: non-invasive BCI tech might be around *Level 6 in terms of product availability* (since EEG devices are sold), but perhaps *Level 3–4 in terms of achieving the high-bandwidth promise*. Invasive BCIs are about *Level 4–5* (successful prototypes and entering production trials). On balance, because the **ultimate value proposition** of the ART (high-bandwidth, reliable brain–computer links) is being driven primarily by the invasive and minimally invasive implementations, the overall maturity is taken as **Level 5** – reflecting the leading edge where multiple groups are actively transitioning those high-performance BCIs from lab to market. This single score represents an **aggregate view** of the full BCI technology



bundle: core functionality has been demonstrated with clear benefits, and the field is now in the competitive development phase on the cusp of initial commercialization, but has yet to achieve wide deployment or a mature market ecosystem.

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## ART 04.024 Advanced Prosthetics & Exoskeletons

### 1. ART extraction

- **Primary capability:** Wearable robotic prostheses and exoskeletons that *restore or enhance human mobility and strength* by tightly integrating with the user's body and neural control signals. These systems aim to act as natural extensions of the body, allowing amputees to move prosthetic limbs intuitively and able-bodied users to amplify strength or endurance in daily tasks.
- **Key sub-components/variants:**
  - **Neuro-integrated prosthetic limbs:** Robotic arms or legs that interface with muscles or nerves (via EMG sensors, nerve implants, etc.) for intuitive control and that provide **haptic feedback** (touch/pressure sensations) back to the user.
  - **Powered exoskeleton suits:** Rigid full-body or limb frameworks worn externally (over clothes or integrated into garments) to **support and amplify movement** (e.g. enabling paralyzed users to walk, or workers to lift heavy loads with reduced effort). Includes **soft exosuits** using textiles and lightweight actuators for assistive support.
  - **Advanced actuators & sensors:** Lightweight, high-torque **electric actuators** (with low noise and high backdrivability) and dense sensor arrays (motion sensors, force/pressure sensors, etc.) embedded in the device to closely monitor user movement and intent.
  - **Adaptive control and AI:** **Adaptive software control systems** (often with machine learning or model-based control) that interpret user intent (from muscle signals, body posture, or even brain signals) and adjust assistance in real time. These systems use **pre-trained models with ongoing user-specific calibration** to improve over time, adjusting for posture changes, fatigue, or specific tasks.
  - **Interface methods:** Both **non-invasive interfaces** (surface EMG electrodes, smart wearable controllers, voice or smartphone commands) and **invasive interfaces** (surgically implanted electrodes in muscles or nerves, osseointegrated bone anchors with wired feedthroughs) are being explored to improve signal reliability and bidirectional communication with the nervous system.
  - **Haptic feedback mechanisms:** Various techniques (vibratory motors, pressure pads on skin, nerve stimulation implants) to **return sensory feedback** (touch, proprioception) to the user, closing the loop for more natural control of prosthetic or exoskeletal limbs.
- **Maturity indicators (evidence to look for):**
  - *Human trials and field deployments:* Successful **clinical trials or real-world tests** of prosthetic/exoskeleton systems (e.g. amputees performing tasks with neurally controlled

bionic limbs; paralyzed patients walking with exoskeletons; workers using exosuits on job sites) demonstrating safety and functional improvements.

- *Proof-of-concept breakthroughs*: Published experiments showing resolution of key challenges – e.g. a prosthetic hand with multi-finger touch feedback enabling complex manipulations, or an exoskeleton auto-adjusting assistance based on user fatigue.
- *Regulatory approvals and standards*: **Regulatory clearances (FDA, CE, etc.)** for devices, inclusion in clinical guidelines or insurance policies, and development of safety/performance standards – indicating the tech is moving from lab to market.
- *Commercial products and adoption*: Evidence of **products in production and sale** – for instance, units shipped or revenue from exoskeleton companies, hospitals or rehab centers adopting exoskeleton programs, military or industry purchasing these devices.
- *Ecosystem and competition*: Presence of **multiple companies and research teams across regions** investing in the technology – e.g. well-funded startups and major biomedical firms launching products, government or defense contracts for exosuits, and international research consortia/roadmaps – signaling competitive drive and progress toward scalable manufacturing and cost reduction.
- *Performance metrics near practical thresholds*: Achievements in battery life, device weight, lifting capacity, response latency, etc., that approach the requirements for everyday use (for example, an exoskeleton that runs an 8-hour work shift or a prosthetic hand performing tasks as quickly as a natural hand). Evidence that costs are coming down or will with scaling (e.g. described cost range comparable to cars/machinery) would also indicate maturation toward wider deployment.

## 2. Evidence (10–20 recent, reliable sources)

- **Multichannel haptic feedback unlocks prosthetic hand dexterity** – Moaed A. Abd et al., *Scientific Reports* (peer-reviewed) – Feb 2022.  
*Researchers demonstrated a soft robotic armband that provides multi-channel haptic feedback to upper-limb amputees using a dexterous prosthetic hand. With distinct tactile feedback for each finger, subjects could simultaneously grasp and carry two objects without visual cues, completing tasks faster and without dropping or crushing the items[1][2]. This shows that rich sensory feedback can dramatically improve prosthetic hand control, tackling a major challenge (the one-grip-at-a-time limitation) and making the prosthesis feel more like a natural extension.*
- **Restoration of natural somatic sensations to amputees (neurostimulation study)** – Soghoyan et al., *Frontiers in Neuroscience* (peer-reviewed) – accepted Oct 2024 (open-access via NIH PMC).  
*Reports a trial with two transhumeral amputees who received implanted electrodes in peripheral nerves and spinal cord. By electrically stimulating these interfaces, the users felt tactile and proprioceptive sensations in their missing hand, which enabled them to discriminate object sizes and softness using a bionic hand[3]. Over practice, the sensations became more natural and helped reduce phantom limb pain[4][5]. This demonstrates a feasible bidirectional neural interface in humans – a key proof-of-concept for prosthetics that “feel” and respond like biological limbs.*
- **Emerging value of osseointegration for intuitive prosthetic control (systematic review)** – Alessandri-Bonetti, Peretti, Aszmann et al., *PRS Global Open* (peer-reviewed) – 2024.  
*A review of transhumeral (above-elbow) amputees using bone-anchored prostheses. It finds that osseointegrated prosthetic implants (which rigidly fix the prosthesis to the skeleton and can house electrode connections) led to significantly improved range of motion and daily*

function compared to traditional socket-mounted prosthetics. Notably, “one study demonstrated [that] an osseointegrated implant [can serve] as a bidirectional gateway for signal transmission, enabling intuitive control of a bionic hand.”[6]. In essence, the prosthesis can directly tap into the user’s nerves/muscles through the bone implant, allowing more natural mind-controlled movement and sensation. This highlights a path to reliable, long-term integration of prosthetic limbs with the body’s neuromuscular system.

- Somatosensory restoration and neural control strategies in lower-limb prostheses** – D.M. Mariscal, B. Driscoll, H. Huang, L.E. Fisher et al., *npj Biomedical Innovations* (review) – Dec 2025.

A comprehensive review of technologies for bidirectional lower-limb prosthetics. It notes that while most prosthetic legs are still passive or autonomously-controlled, powered limbs have emerged (e.g. Össur’s Power Knee, Ottobock’s Empower ankle) and some are commercially available across different countries[7]. These powered knees/ankles improve walking but lack direct user neural input, so the review discusses recent efforts to bridge that gap with neural interfaces. For example, systems to stimulate nerves for feeling from a prosthetic foot and to capture signals from residual muscles for more responsive control are in development[8]. The review underscores that multiple teams are now integrating invasive and non-invasive interfaces to create truly “smart” prosthetic legs, reflecting rapid progress built on the successes of upper-limb bionics.
- Leveraging LSTM, tactile sensors, and haptic feedback to augment prosthetic control** – Sudhir S. Zhuwawu & Haitham El-Hussieny, *Scientific Reports* (peer-reviewed) – Aug 2025.

Demonstrates an AI-driven approach to more intuitive prosthetic hand use. The team equipped a prosthetic hand with soft fingertip tactile sensors and used a trained LSTM neural network to classify the type of grasp the hand was performing. They provided the user with a unique vibrotactile feedback pattern for each grasp type. In real-world tests, the system could predict the grasp within <1 s with ~87–89% accuracy and cue the user via haptics[9]. This allowed users to know the hand’s grip state without looking, improving decision-making and control[10][11]. Such adaptive, intelligent control – combining sensor data, machine learning, and user feedback – shows the plausibility of prosthetics that partly “understand” their own state and assist the user in operating them more naturally.
- Molina Healthcare Clinical Policy: Powered Exoskeleton for Ambulation** – Molina Healthcare (insurer technical policy) – updated Oct 2025.

Summarizes the regulatory and clinical status of lower-body exoskeletons in the U.S. healthcare system. It notes that multiple robotic exoskeletons have FDA 510(k) clearance (product code PHL) for rehabilitation use, including the ReWalk, Ekso GT, Indego, and ExoAtlet-II devices[12]. Initially approved for spinal cord injury paraplegia, indications have expanded – e.g. “In June 2022, the EksoNR became the first exoskeleton approved for patients with multiple sclerosis,” and in “March 2023, the ReWalk Personal Exoskeleton received FDA approval for use on stairs and curbs.”[13][14]. Furthermore, two devices (ReWalk and Indego) are approved for personal/home use[15]. This is strong evidence of maturation: the technology has moved into real clinical deployment, with regulatory bodies acknowledging improved safety/function (even tackling challenges like stair-climbing) and insurers evaluating coverage.
- Ekso Bionics Reports Record Annual Revenue of \$18.3 Million** – Ekso Bionics (press release, via Globe Newswire) – Mar 4, 2024.

Ekso Bionics, a leading exoskeleton manufacturer, announced that in 2023 it sold 151 exoskeleton units (EksoHealth devices for rehabilitation), a record high, driving a 42% year-over-year revenue increase to \$18.3 M[16]. The company attributes the growth to “strong demand” and notes expanding use “across the continuum of care from hospital to home”[17].

*This commercial evidence shows that powered exosuits are not just experimental – they are shipping in growing numbers to real customers. With a NASDAQ-listed company and rising sales, it indicates competition and investment in scaling up production, and suggests that costs may gradually decrease with volume. (For context, a single unit can be priced on the order of a new car, so economies of scale are crucial.)*

- **Hands-free Atalante exoskeleton in post-stroke gait and balance rehabilitation: a safety study** – A. Delva et al., *Journal of NeuroEngineering & Rehabilitation* (peer-reviewed) – 2025. Evaluated the French-made Atalante X exoskeleton (a self-balancing, hands-free lower-body exosuit by Wandercraft) in a multi-center trial with 40 stroke patients. After 5 training sessions, no serious device-related adverse events occurred; 82.6% of participants completed a usability test and 90% reported satisfaction with the exoskeleton[18]. Significant improvements in gait speed, distance, and balance scores were observed post-training ( $p < 0.05$ )[19]. The authors conclude the device is safe, feasible, and well-tolerated for post-stroke rehab, warranting larger trials[20]. This is a concrete demonstration of an advanced exoskeleton being used on actual patients: it validates not only the engineering (battery-powered dynamic walking with no need for crutches) but also user acceptance. Such field trials are a critical maturity milestone on the path to routine clinical adoption.
- **German Bionic Apogee Exosuit Debut at CES 2023** – German Bionic / MassRobotics news blog – Jan 2023. Describes the launch of the German Bionic Apogee, a 5th-generation industrial exoskeleton. The Apogee is an AI-supported, network-connected wearable that provides up to 30 kg of lower-back lifting assistance per lift and active walking support to reduce fatigue and injury[21][22]. It is dust- and water-resistant and designed for everyday workplace use. The suit won the CES 2023 “Best of Innovation (Wearable Technologies)” award and garnered media attention from Wired, AP, Reuters, etc., highlighting it as a “cool” and practical innovation. This indicates that powered exosuits are moving toward mainstream recognition in industry. The Apogee’s specs (significant lift assist, ergonomic design) and accolades show that vendors are addressing real-world requirements (comfort, durability, data connectivity) needed for scaling in industrial and logistics environments.
- **ReWalk 7.0 Personal Exoskeleton & FDA clearances** – Lifeward/ReWalk Robotics (press info via CMS and company IR) – 2023–2024. ReWalk Robotics, a pioneer in rehabilitation exoskeletons, has incrementally improved its personal exosuit and navigated regulatory hurdles. In 2023, the FDA cleared an update allowing the ReWalk Personal 6.0 exoskeleton to be used on stairs and curbs[23], a first for a personal wearable robot. By 2024, U.S. Medicare assigned a billing code (K1007) for exoskeletons and is evaluating reimbursement, and ReWalk announced a new model (ReWalk 7.0) with cloud connectivity and adjustable speeds[24]. These developments show both technical progress (expanding device capability from level surfaces to stairs) and growing institutional acceptance.\* Inclusion in the healthcare reimbursement system is especially telling: it implies the technology is considered efficacious enough to justify cost coverage, which will drive broader adoption once final payment policies are in place.

*(Additional context: Outside the healthcare domain, exoskeletons have seen interest from militaries (e.g. U.S. Marines and Air Force testing Sarcos’s Guardian XO for heavy lifting[25][26]) and automotive manufacturers (Hyundai, Toyota, GM, etc. developing wearable assist devices for factory workers). Major prosthetics companies (Ottobock, Össur) have also acquired exoskeleton startups and are investing in “bionic” limb tech. Such cross-sector activity supports the notion that advanced prosthetics & exosuits are moving toward a commercial scaling phase.)\**



### 3. Maturity score (1–7) and reasoning

**Final Score: 6** (Early Commercialization/Scaling Phase)

**A) Why not lower:** The evidence shows this ART is **well beyond lab demonstrations (Levels 2–3)**. We have multiple **functional prototypes and PoCs solved (Level 4)** – for instance, neural interfaces enabling amputees to feel and control prosthetic limbs in trials[3], and exoskeletons that allow paraplegics to walk and even climb stairs[14]. Crucially, we also see **post-PoC product development and delivery (Levels 5–6)**: at least five competing companies (ReWalk, Ekso Bionics, Indego/Parker, ExoAtlet, Wandercraft, etc.) have brought medical exoskeletons to market with regulatory approval[12], and new entrants like German Bionic and Sarcos are pushing industrial exosuits. Sales figures – e.g. 151 rehab exos sold in one year[16] – and expanding use cases (SCI to stroke to MS patients[13]) show **growing customer adoption and investment**, which rules out Level 4 or 5 (where technology would still be in prototype or pilot-deployment stage). In essence, the core capabilities of this ART (powered wearable mobility devices) have been **proven viable and are already helping users outside the lab**, a hallmark of Level 6 maturity.

**B) Why not higher:** The technology hasn't yet reached wide, exponential adoption or full maturity in all aspects, which prevents a Level 7 rating. Many deployments today are still in controlled or niche environments (hospitals, rehab centers, pilot industrial sites) rather than ubiquitous use. **Customer demand, while rising, remains limited by high costs and ergonomic constraints**, and companies like Ekso Bionics are still in the process of achieving profitability (sales are growing but in the low hundreds of units, and external funding is still important[17][27]). Moreover, some of the most “radical” features – for example, surgically integrated prosthetics with seamless brain-level control and realistic sensation – are *just entering early clinical trials*, not yet commercialized. The evidence shows important breakthroughs (like an implanted interface letting an amputee intuitively control a robotic arm[6]), but these remain case studies or limited series at present. To justify Level 7, we would expect **mass-market competition and self-sustaining growth** – e.g. thousands of units annually, major reductions in price, and these devices becoming common in everyday workplaces or standard care for disabilities. That scenario is still unfolding. In summary, the **overall domain is in a Level 6 stage**: real products exist and are improving quickly, new players continue to enter, and early adopters are seeing value – but the technology is not yet a widely adopted commodity across its potential applications, and some sub-technologies need a bit more maturation to reach the next stage.

**C) Sub-component breakdown:** This ART spans somewhat distinct fronts – high-integration neuroprosthetics versus wearable exoskeletons – which are at **different maturity levels** today:

- **Medical & rehabilitative exoskeletons: Level 6.** Multiple FDA-cleared products are on the market and being delivered to hospitals and personal users[12][16]. Companies in the US, EU, and Asia are improving these devices' capabilities (e.g. use on stairs, hands-free balancing) and scaling up production. There is active competition and even progress toward insurance reimbursement, indicating a transition from experimental to standard-of-care (e.g. stroke rehab trials showing safety and benefits[18][20]). This segment sees internal R&D investment by firms and some economies of scale emerging, consistent with early Level 6 characteristics.

- **Industrial/military exosuits: Level 5 (~5 to 6).** This overlaps with the above but focuses on augmenting able-bodied workers. We see well-capitalized efforts (Sarcos, Hyundai, German Bionic, etc.) deploying prototypes and first-gen products (some units in field trials with logistics companies and military tests) – for example, an exosuit lifting 30 kg repeatedly won innovation awards[21]. However, widespread adoption in workplaces is just beginning, and many such projects are still seeking the optimal balance of cost, power, and usability. There are signs of rapid progress (venture funding, partnerships like Sarcos with airlines and the U.S. Air Force), but until these suits become common equipment for factories or construction, this sub-field sits at high Level 5 or entering Level 6.
- **Advanced prosthetic limbs (with neural control & feedback): Level 3–4.** Here the fundamental science is proven and **lab prototypes** have shown that implanted sensors/stimulators can restore naturalistic control and sensation[3]. There is **clear academic and clinical interest** (with breakthroughs published in top journals and pilot patients gaining functions previously impossible). However, these solutions are largely in research or early clinical feasibility stages – not yet widely productized. Only a handful of patients worldwide have received fully implanted, brain- or nerve-integrated prosthetic systems to date. Thus, this sub-component is around Level 3 (experimental demonstrations) pushing into Level 4 (initial proof-of-concept in real use conditions). It will need further engineering for reliability, plus regulatory and manufacturing advances, to catch up with the exoskeleton realm.
- **State-of-practice prosthetics (myoelectric bionic limbs without invasive interface): Level 6.** It's worth noting that current high-end prosthetic arms and legs – such as multi-articulated hands (Ottobock Bebionic, Touch Bionics i-Limb) or microprocessor knees and ankles – are **established products**. They leverage simpler control methods (surface EMG signals, pre-programmed patterns) and have seen moderate adoption for decades. Their presence indicates that the *baseline technology (robotic limb hardware)* is mature. The ART description, however, is about **radically enhancing these with closer integration and feedback**, which is why we emphasize the Level 3–4 status of those novel features rather than the legacy devices themselves.

Considering these sub-scores, the overall **integrated score is chosen as 6**. We weighted the exoskeleton progress more heavily in the average because exoskeletons are a major part of the ART's value proposition (reducing physical burdens for many people) and are closer to commercialization at scale. In essence, wearable exosystems are already entering the market (dragging the average upward), while neural prosthetics are a step behind but on a fast track. The **bundle's functionality – augmenting human mobility – is being realized in practical products (exoskeletons) now**, even as the full vision (especially for neural prosthetics) will unfold over the next decade. This justifies a **Level 6**: the field as a whole has clearly moved into early market deployment, with momentum toward wider growth, though not yet a ubiquitous technology.

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## ART 04.025 Haptic and Multi-Sensory Feedback Systems

### 161. ART extraction

162. **Primary capability – “rich touch” feedback:** Enable users to precisely *feel* and control artificial limbs, tools, or virtual objects through advanced haptic feedback. This entails recreating a wide range of tactile sensations (pressure, texture, temperature, motion, limb/tool position) in real-time, far beyond today’s simple buzz or force cues. The goal is fluid, fine-grained manual control with sensory realism, closing the loop between user actions and feedback.
163. **Key sub-components/variants:**
- **High-density sensors & actuators:** Arrays of miniaturized pressure sensors and haptic actuators (vibrational motors, microfluidic or electroactive elements, etc.) to achieve high spatial resolution and varied stimuli. For example, flexible “electronic skins” with densely packed sensing and feedback pixels[1][2].
  - **Multi-modal feedback mechanisms:** Multiple stimulation modes combined – e.g. **force/pressure** actuators for weight or resistance, **vibrotactile** actuators for texture/fine touch, **thermal** elements for hot/cold, and even **electrical/nerve stimulation** for direct neural feedback[3]. Wearable devices may integrate force + vibration + temperature in one system to enrich the sensation palette.
  - **Wearable and integrative form factors:** Haptic interfaces embedded in soft, skin-like materials (gloves, clothing, patches) or **woven into textiles**, as well as **prosthetic interfaces** implanted or attached to the body (e.g. nerve-connected prosthetic hands). Variants range from haptic VR gloves and full-body suits to feedback-equipped exoskeletons and neuroprosthetic implants.
  - **Signal processing & adaptive control:** Real-time controllers and AI algorithms that modulate actuator signals based on sensor inputs and user context. This provides *closed-loop feedback* with low latency (within milliseconds), adapts intensity to user preference, filters noise, and can learn from usage patterns to improve the feedback relevance over time.
164. **Maturity indicators (evidence of progress):**
- *Laboratory prototypes demonstrating multi-sensory feedback:* e.g. research devices that combine multiple haptic modalities (force + vibration + temperature) and show improved user performance or realism in tasks.
  - *User trials and proofs of concept:* Testing with humans (including amputees or operators) that show the technology restores sensations (touch, proprioception) and improves control or reduces errors[4][5].
  - *Integration into functional systems:* Working demos of feedback-enabled prosthetic limbs or VR/AR gloves operating in real-world scenarios (rehabilitation tasks, virtual training, tele-surgery, etc.), indicating practical viability (comfort, safety, robustness).
  - *Early commercial prototypes or products:* High-end haptic gloves, suits, or prostheses entering limited markets (e.g. enterprise or medical devices) – with published specifications on feedback resolution, response time, durability, and initial cost – signaling a transition from research to scalable engineering[6][7].
  - *Multiple active R&D programs:* Significant funding, startups, or industry initiatives (in at least two regions) focused on advanced haptics – suggesting

competition to refine prototypes for production (improving weight, power consumption, materials, and cost towards broader deployment).

165. **Evidence (10–20 recent, reliable sources)** (*All sources are from the last 4 years*)
166. **Multi-modal wearable haptics – review (2022):** *Ya Huang et al., Materials Today Physics, Jan 2022*. A peer-reviewed review that highlights the need to combine different haptic feedback modalities (force, thermal, electrical/nerve stimulation) in wearable interfaces. It notes that single-mode haptic devices each have shortcomings, and that integrating multi-mode feedback can significantly improve realism and overcome current challenges for VR/AR and robotics[3][8]. This underscores the plausibility of the ART’s core idea that richer, multi-sensory feedback is both necessary and being actively pursued.
167. **Tactile sensor advances for rich feedback (2025):** *Hothefa S. Jassim et al., Biosensors and Bioelectronics: X (peer-reviewed review), Oct 2025*. This article surveys recent progress in tactile sensing technologies for human–robot interaction. It documents new **mechanoreceptor-mimicking sensors** (piezoresistive, capacitive, piezoelectric) with enhanced sensitivity and flexibility, and addresses how challenges in scalability, durability, and cost are being tackled[9]. These advances in high-density, robust tactile sensors support the feasibility of dense sensor arrays needed for fine-grained haptic systems. Integration of such sensors with AI (for self-learning feedback tuning) is also discussed[10], aligning with the ART’s vision of adaptive, smart feedback loops.
168. **Flexible haptic actuators for wearables (2025):** *Wei Wang et al., Nano Research (Review), Aug 2025*. A comprehensive review of **flexible, lightweight haptic actuators** that can be comfortably worn. It explains that traditional haptic devices were often bulky and rigid, limiting long-term use, whereas new designs using soft materials, textiles, and compliant structures can deliver forces and vibrations while conforming to the body[11]. The article surveys material and actuation innovations (electroactive polymers, microfluidics, flexible electromagnetic actuators, etc.) and shows how these enable wearable haptics in VR, teleoperation, and healthcare. This suggests that practical constraints of weight and comfort are being addressed by current research, increasing the plausibility of all-day wearable feedback systems.
169. **Wireless e-skin with touch sensing & feedback (2022):** *Dengfeng Li et al., Science Advances 8(51): eade2450, Dec 2022*. Researchers at CityU Hong Kong demonstrated a **soft electronic skin patch** (7×10 cm, ~4 mm thick) with a 4×4 array of “actuator pixels” that double as pressure sensors[12]. The wireless patch (Bluetooth-enabled) can both detect a user’s touch and reproduce it on a remote user’s patch in real-time, effectively enabling two-way touch communication (“touch IoT”)[13][12]. Pressing on one patch generates corresponding pressure/vibration on the other. This prototype proves the concept of a self-contained, multi-user haptic network and demonstrates millisecond-range closed-loop feedback in a wearable format, directly supporting the ART’s feasibility (rich touch feedback, networking, robustness for remote interaction).
170. **Multi-directional skin actuator (Science 2025):** *Kyoung-Ho Ha, Jaeyoung Yoo, Shupeng Li, John A. Rogers, Yonggang Huang et al., Science, Mar 2025*. A peer-reviewed breakthrough reporting a **“full freedom-of-motion” haptic actuator** about the size of a coin that can apply forces to the skin in any direction – not just normal vibration, but also stretching, shear (sliding), and twisting forces[14]. The device is compact, battery-powered, and wireless (Bluetooth), and multiple actuators can be arrayed on the body. It can combine different motion stimuli and operate with finely programmable intensity and timing, creating unprecedentedly realistic touch sensations[14][15]. This achievement demonstrates scientific feasibility: it shows that hardware can generate a rich palette of tactile cues at high fidelity.

Published in a top journal, it provides strong evidence that ultra-refined haptic feedback (with multi-axis, multi-modal output) is no longer just theoretical but has been experimentally realized in the lab.

171. **Nerve-interface prosthetic sensation (2023):** *Paul Čvančara et al., npj Flexible Electronics 7:51, Nov 2023.* This open-access study reports on *implanted* thin-film electrode arrays (polyimide-based intrafascicular electrodes) that provided sensory feedback to three human amputees using prosthetic hands. The implants in the arm nerves remained stable and functional for up to 6 months, with **no signs of corrosion or degradation** and **consistent, precise elicitation of sensations** over the entire period[16][17]. Users could reliably feel touch/pressure via nerve stimulation when using their bionic hand. This evidence shows both plausibility (closed-loop neural feedback in prosthetics works in practice) and improving maturity – addressing safety/longevity for permanent implantation, which is crucial for real-world prosthetic adoption. It confirms that connecting haptic systems directly to nerves (one of the more radical aspects of the ART) is actively being tested with promising results.
  
172. **“HaptiYarn” textile haptics (2024):** *Pasindu Lugoda et al., IEEE Transactions on Haptics 17(4):964-969, Oct–Dec 2024.* Demonstrates a novel approach to make haptic systems lightweight and unobtrusive by weaving actuators into clothing. The team developed **HaptiYarn – an actuator yarn** that can be knit into garments[18]. Each yarn, controlled by micro-scale pneumatic pulses, can expand radially (~28 mm displacement) to squeeze the body at precise spots. Integrated graphite nanoparticles in the elastomer yarn improved durability (withstood >7,500 cycles without performance loss)[19]. They created a prototype VR vest with 8 such yarn actuators, enabling the wearer to “feel” immersive feedback (like virtual hugs or impacts) across the torso[20]. This is evidence of practical engineering progress: haptic feedback delivered via ordinary textiles, maintaining comfort and breathability. It addresses the ART’s concern for wearability and shows a path to high-density actuator integration using advanced materials and fabrication (supporting the idea that specialized manufacturing – here, multi-layer yarns – can produce robust yet flexible haptic devices).
  
173. **High-resolution tactile sensor array (2025):** *Chengran Cao et al., (MDPI open-access), accepted Aug 2025.* Reports a **256×256 tactile sensor array** with microscale structured sensors achieving **spatial resolution of 0.5 mm** – finer than a human fingertip’s ~1 mm discrimination threshold[1][2]. The sensors use 10 μm pyramidal microstructures and a CNT-based resistive layer, yielding ultra-high sensitivity (~8.1 kPa<sup>-1</sup> in the low-pressure regime) and detection of very light touches (down to 90 Pa)[1]. The array, coupled with a thin-film transistor readout, successfully captured and reconstructed subtle textures such as Braille dots and 500 μm surface patterns[21][2]. It also demonstrated good response speed (~125 ms) and stability over 1000+ cycles. This is a key enabling tech for the ART: such high-density, high-sensitivity sensor arrays could allow artificial limbs or haptic devices to *sense* texture and pressure with human-like (or better) fidelity, which can then be fed back to the user. The manufacturing approach (molded microstructures + solution processing) is noted as scalable[22], suggesting a path toward cost-effective production – partially addressing the ART’s manufacturing and cost bottlenecks.
  
174. **Multi-modal prosthetic feedback trial (2023):** *Emre Sariyildiz et al., Sensors 23(20):8492, Oct 2023.* This experimental study evaluated a **hybrid haptic+proprioceptive feedback system** on a prosthetic hand. The setup combined a **mechanotactile pressure feedback** (applying proportional force on the user’s arm corresponding to the prosthetic’s grip force) and **vibrotactile feedback** to signal discrete hand aperture (grip positions)[23]. In tests with 32 able-bodied participants (using a prosthetic simulator): (i) With tactile feedback, users could better judge how much force the bionic hand was applying (though some

underestimation occurred at higher forces). (ii) With proprioceptive (vibration) cues, participants **identified four different hand positions (open, wide, narrow, closed) with 100% accuracy** without visual cues[24]. (iii) Using both feedback modes, subjects could recognize objects of different shape and stiffness with **90.5% overall accuracy**[24]. Notably, these results were consistent across different feedback locations on the arm and muscle states. This study is evidence that multi-sensory feedback improves functional outcomes: it shows plausibility that an artificial hand with such feedback can restore complex perception (object differentiation by touch) and confirms maturity beyond theory – a closed-loop *proof-of-concept* in humans, using relatively simple, non-invasive hardware (force pads and vibrators on the skin).

175. **Thermal feedback in prosthetics (2024):** *Jonathan Muheim et al., Med (Cell Press) 5(2):118-125, Feb 2024.* Reports the first successful integration of **temperature feedback** in a prosthetic hand. Researchers exploited “phantom thermal sensation” – by heating/cooling specific spots on an amputee’s residual arm, they induced the feeling of warmth or coolness *in the missing (prosthetic) hand*. They built a standalone thermal feedback module into a commercially available bionic hand and conducted a long-term single-case trial[25][26]. The amputee could distinguish hot, cold, and ambient objects, different material properties (metal vs plastic), and even tell an artificial hand from a human hand via warmth, with **accuracy comparable to his intact hand**[26]. In a standardized test (400+ days span, 15 sessions), he consistently sorted objects by temperature correctly in real time. No adverse effects were reported, and the phantom thermal sensations remained stable over 13 months[27][28]. This is a notable milestone for multi-sensory haptics: it adds the thermal modality to the feedback mix and demonstrates viability in a real-world scenario (integrated with a prosthetic used in daily life). It indicates increasing maturity – not only are such systems being prototyped, but they are now tested with end-users under extended timelines, an important step toward clinical adoption.
176. **Haptic feedback reduces robotic surgery error (2025):** *Hironobu Takano et al., Journal of Robotic Surgery 19(1):662, Oct 2025.* This study investigated the impact of adding haptic force feedback to a surgical tele-robot (in a cadaveric experimental setup). Six surgeons performed robotic tissue manipulation tasks with either no feedback, moderate feedback, or full force feedback. The key finding was that **grip forces significantly decreased as haptic feedback was added**[5] – surgeons squeezed more gently when they could feel resistance, which is critical for preventing tissue damage. Task completion time and motion efficiency didn’t change much, but from a safety perspective this is big: haptic feedback “suggested enhanced surgical safety” by curbing excessive force[5]. This evidence speaks to the value proposition of the ART – in domains like telesurgery (or any remote/robotic operation), richer feedback reduces errors and improves control. It also shows that such feedback systems have moved into realistic testing (surgery scenarios), indicating a growing maturity in specialized applications (medical robotics).
177. **Enterprise-grade haptic gloves shipping (2023):** *HaptX (industry product announcement), as reported by UploadVR – Ian Hamilton, Oct 2022.* HaptX, a well-funded haptics startup, moved from prototypes to a production model with its **“Gloves G1” haptic gloves**. These gloves use hundreds of microfluidic air actuators that displace the user’s skin to simulate touch and force feedback. The G1 system includes a 17-pound backpack air compressor and was offered for enterprise pre-order at ~\$5,500 per pair (with ~\$500/mo subscription)[6][7]. Shipping was planned for Q3 2023 to industrial and research customers. While still expensive and not consumer-focused, this marks one of the first commercially available, full-featured haptic wearable products. The high density of actuators and the presence of a few such companies (HaptX, and others working on gloves or suits) show that



the technology is transitioning from lab to market. It validates the ART's assumption that initial costs would be comparable to high-end equipment and that early adoption is in specialized markets. The existence of a production-ready glove with multi-point feedback confirms a level of technical maturity (meeting safety, integration, and reliability requirements for sale) and underscores that multiple actors are in competition to solve remaining issues (reducing size/weight – e.g. Meta's Reality Labs prototype gloves – and lowering cost).

178. **Maturity score (1–7) and reasoning**

**Overall Maturity Score: 4 (Proof-of-Concept demonstrated, nearing prototype stage).**

**Justification:** The evidence above rules out the lower maturity levels – this is far beyond theoretical (Level 1) or initial lab observation (Level 2). We now have **multiple working prototypes and demonstrations (Level 3+)** solving key technical hurdles: e.g. a multi-modal haptic patch and glove arrays[13][14], a prosthetic hand with multi-sensory feedback tested over months[26], and sub-millimeter sensor/actuator resolutions[1]. Crucially, there are **integrated proof-of-concept systems (Level 4)** that meet core functionality requirements: the Science 2025 actuator and CityU e-skin show feedback with sufficient richness and speed for practical use, and the prosthetic trials demonstrate feedback improving real task performance (object recognition, safer grip)[4][5]. These successes clearly exceed what previous “vibration-only” solutions could do, supporting a Level 4 PoC status for the overall technology.

Some aspects are even approaching Level 5: for example, HaptX's shipping product and competing efforts indicate that **well-capitalized actors are now developing production-grade prototypes** (in VR/AR haptics, at least)[6]. However, this ART is a *bundle of technologies* across different domains, and their maturity is uneven. **Sub-component breakdown:**

- **VR/AR wearable haptics: Level 5.** Advanced prototypes like HaptX G1 gloves (USA) and other haptic suits are in late-stage development with significant investment, targeting niche deployments. Big players (e.g. Meta Reality Labs, startups in Japan/Korea) are actively competing to refine these devices. The presence of a market-ready glove system[6] and rapid progress in actuator materials[11] and form-factors suggest that production prototypes exist and initial customers are receiving units – aligning with Level 5 criteria.
- **Prosthetic sensory feedback (medical/assistive): Level 3–4.** While the scientific feasibility is proven (restoring touch and even temperature in amputees[26]), the technology remains in clinical trial or lab prototype phase. No mass-produced sensory prosthesis is on the market yet; efforts are largely research-driven (e.g. EU and DARPA programs, academic spinoffs). Given that single-patient studies have shown success (a strong Level 3 demo) and small-scale trials are expanding, this sub-field is on the cusp of Level 4 (functional PoC with viability) but not yet at widespread commercial prototyping.
- **Industrial/robotic haptics (teleoperation, exoskeletons, training): Level 4.** Research prototypes have been integrated into real scenarios like robotic surgery simulators[5] and industrial training rigs, demonstrating clear benefits. Some startup products (force-feedback robot controllers, haptic training simulators) exist in pilot deployments. The technology meets functional needs and is plausibly cost-justified in

high-end applications, but it's not broadly adopted or produced at scale (no large commercial rollout yet, keeping it short of Level 5).

Given these variations, we average the maturity to **approximately a 4**. In essence, **the core capabilities of “haptic and multi-sensory feedback systems” are already demonstrated in working prototypes (Level 4)**. The **jump to Level 5** (early commercial and competitive phase) is underway in some areas (wearables for VR), but **not uniformly achieved across all applications**. To fully reach the next level, we would need to see more **converged progress**: multiple companies shipping robust products in this category, lower-cost manufacturing scaling up, and broader user adoption beyond pilot users. Evidence of this – such as competing haptic prosthetics entering the market, or lighter haptic suits moving from demo to product – is still emerging. Once the technology sees wider production financing and a growing customer base (e.g. consistent orders for haptic wearables, established supply chains for components), the score would advance. For now, the ART sits at **Level 4**: proven feasible with strong prototypes and initial real-world trials, and on the brink of broader commercialization pending further integration and cost reduction.

[1] [2] [21] [22] High-Density Tactile Sensor Array for Sub-Millimeter Texture Recognition - PMC

<https://pmc.ncbi.nlm.nih.gov/articles/PMC12390072/>

[3] [8] Recent advances in multi-mode haptic feedback technologies towards wearable interfaces - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S2542529321002637>

[4] [23] [24] Experimental Evaluation of a Hybrid Sensory Feedback System for Haptic and Kinaesthetic Perception in Hand Prostheses

<https://www.mdpi.com/1424-8220/23/20/8492>

[5] Effectiveness of haptic feedback during local and remote robotic surgery: single-blind cadaveric study - PubMed

<https://pubmed.ncbi.nlm.nih.gov/41045436/>

[6] [7] New Haptic G1 Gloves From HaptX Ship Late 2023, \$5,500 Per Pair

<https://www.uploadvr.com/haptx-gloves-g1-price-shipping/>

[9] [10] Recent advances in tactile sensing technologies for human-robot interaction: Current trends and future perspectives - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S2590137025000962>

[11] Main applications of flexible haptic feedback actuators. (a) System of... | Download Scientific Diagram

[https://www.researchgate.net/figure/Main-applications-of-flexible-haptic-feedback-actuators-a-System-of-VR-rendering\\_fig7\\_391985254](https://www.researchgate.net/figure/Main-applications-of-flexible-haptic-feedback-actuators-a-System-of-VR-rendering_fig7_391985254)



[12] [13] Wireless, soft e-skin for interactive touch communication in the virtual world | ScienceDaily

<https://www.sciencedaily.com/releases/2023/02/230223132833.htm>

[14] [15] Feeling the future: New wearable tech simulates realistic touch - Northwestern Now

<https://news.northwestern.edu/stories/2025/03/feeling-the-future-new-wearable-device-mimics-the-complexity-of-human-touch>

[16] [17] Bringing sensation to prosthetic hands—chronic assessment of implanted thin-film electrodes in humans | npj Flexible Electronics

[https://www.nature.com/articles/s41528-023-00284-x?error=cookies\\_not\\_supported&code=992eed0f-eae1-4bc3-9d35-e44aabd0c05c](https://www.nature.com/articles/s41528-023-00284-x?error=cookies_not_supported&code=992eed0f-eae1-4bc3-9d35-e44aabd0c05c)

[18] [19] [20] HaptiYarn: Development of an Actuator Yarn That Can Transform Everyday Textiles Into Haptic Devices - PubMed

<https://pubmed.ncbi.nlm.nih.gov/38437069/>

[25] [26] [27] [28] A sensory-motor hand prosthesis with integrated thermal feedback - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S266663402300404X>

## ART 04.026 AI Understanding of Human Intent & Context

179. **ART extraction**

180. *Primary capability:* AI systems that infer a user’s underlying intent and situational context from rich, multi-modal behavioral cues, moving beyond literal commands to understand “what people mean.” These systems aim for more natural, human-like interactions by interpreting tone, gestures, facial expressions, gaze, posture, proximity, etc., in addition to spoken or typed commands.

181. *Key sub-components/variants:*

- **Multi-modal sensor inputs & fusion:** Aggregating data from microphones (speech/prosody), cameras (facial expressions, body language, gaze), wearables (physiological signals, motion), ambient IoT sensors, etc., and fusing them in real time to form a coherent context model.
- **Specialized inference modules:** e.g. gaze tracking and eye-contact detection, posture and gesture recognition, micro-expression and emotion detection (affective computing), and social signal processing (identifying engagement level, roles, turn-taking cues).
- **Situational context modeling:** Continuously maintaining a model of “who is present and doing what,” inferring likely goals, attention focus, and social dynamics (e.g. speaker vs. listener roles, group vs. individual context) from observed cues.
- **Adaptive response generation:** AI adjusts its interaction modality and timing based on context – choosing whether to respond via speech, visual display,

haptic feedback, or silently adjusting a setting – and tailoring its tone and behavior to user preferences, accessibility needs, and cultural/social norms (e.g. remaining silent in meetings, using formal vs. casual language, etc.).

- **Edge and cloud deployment:** Depending on latency, energy, and privacy needs, such context-understanding AI might run on-device using AI accelerators (comparable to high-end phone/AR hardware) for instant response, or offload to cloud services (with enterprise-level pricing) for more intensive analysis – or a hybrid of both.
- **Privacy and human override:** Built-in data privacy protections (on-device processing, data anonymization, etc.) and user controls are critical, given the sensitive nature of continuous monitoring. Users must be able to review, tweak, or override the AI's inferences and actions to ensure trust and alignment with human intentions.

182. *Maturity indicators/evidence:*

- **Research prototypes and demos:** Lab-proven systems combining multiple modalities (vision, audio, etc.) to interpret user intent in real time (e.g. an AR assistant that uses eye-gaze + pointing to resolve ambiguous commands). Evidence would include peer-reviewed studies demonstrating such prototypes in realistic tasks or user studies.
- **Benchmarks and accuracy gains:** Creation of multi-modal intent recognition benchmarks, and recent papers showing that these AI models outperform unimodal baselines (e.g. higher intent classification accuracy when combining speech and facial cues), indicating the scientific feasibility of inferring context/intent<sup>[1][2]</sup>.
- **Pilot deployments & partial features:** Early integration of context-aware features in commercial products. For example, laptops and smart displays now include human-presence sensors and gaze detection to auto-dim or wake screens, or voice assistants adding vision-based speaker recognition or “conversation mode” to handle multi-user environments. Such instances signal that industry is testing the waters with context-sensing capabilities.
- **Multiple actors & investment:** Large tech companies (Amazon, Google, Apple, Microsoft, etc.) and interdisciplinary research labs globally are actively pursuing “ambient” or context-aware AI for assistants, AR/VR, vehicles, and smart environments. Evidence of well-funded programs (e.g. DARPA's “Artificial Social Intelligence for Teams”) and corporate roadmaps/press releases about context-intelligent features demonstrates competition to develop robust production-grade systems.
- **Standards and ethics considerations:** The emergence of guidelines or debates around emotion AI and context inference (e.g. privacy standards, calls for regulation of affect recognition) also indicates that the technology is maturing enough to draw societal scrutiny – a sign that real deployments are on the horizon, albeit gated by ethical concerns.

183. **Evidence (10–20 recent, reliable sources)**

184. **A Survey on Multi-modal Intent Recognition: Recent Advances and New Frontiers –**  
*Zhihong Zhu et al. (Tencent Jarvis Lab & CUHK) – Peer-reviewed conference survey (Findings of*

EMNLP 2025) – **Nov 2025**. [2][3] A comprehensive survey of 60+ studies (2019–2024) on **multi-modal intent recognition (MIR)**, where AI combines text, audio (prosody), and visual cues (gestures, expressions) to infer user intent. It highlights that integrating diverse modalities enables a more *holistic interpretation of human intent* than text or speech alone, with rapid recent progress and even unified benchmarks/leaderboards now in place[2][3] – evidence that the research community has coalesced around this challenge and demonstrated substantial accuracy gains over unimodal systems.

185. **Deep Learning Approaches for Multimodal Intent Recognition: A Survey** – H. Zhang et al. – **Preprint (arXiv 2507.22934)**, supported by China National R&D Program – **July 2025**. [1][4] This article finds that fusing inputs from audio, text, vision (even gaze and physiological signals) has *significantly improved the accuracy of intent recognition in real-world scenarios*[1]. Advanced deep learning techniques (transformers for cross-modal fusion, etc.) let models leverage complementary information from each modality, yielding more robust understanding of user goals[1]. It also outlines remaining challenges – e.g. handling asynchronous or conflicting signals and modality mismatches – underscoring that **sensor fusion and context inference** are technically feasible but need further refinement for reliability[4].
186. **GazePointAR: A Context-Aware Multimodal Voice Assistant for Pronoun Disambiguation in Wearable AR** – Jaewook Lee et al. (Univ. of Washington & Univ. of Illinois) – **Peer-reviewed (CHI 2024)** – **May 2024**. [5][6] Demonstrates a fully functional **prototype voice assistant on AR glasses** that uses *eye-gaze + pointing gestures + conversation context* to interpret ambiguous user commands. For example, the user can look at an object and ask “What is **this**?” – the system replaces “this” by recognizing the gazed-at item, then answers appropriately[5]. In lab trials with 12 users, participants found these context-aware interactions more natural and human-like than today’s assistants[6]. This is a proof-of-concept that AI can infer intent (“what’s over there?”) from spatial context and nonverbal cues in real time, solving problems (pronoun resolution) that current commercial VAs cannot handle[7].
187. **Context-based Emotion Recognition: A Survey** – Rizwan Abbas et al. (Zhejiang Univ. & Westlake Univ.) – **Peer-reviewed journal (Neurocomputing)** – **Feb 2025**. [8][9] Reviews the fast-growing field of **affective computing with context**, showing that emotion recognition accuracy is greatly enhanced by incorporating context like body language, tone of voice, and situational cues rather than relying on facial expression alone. Deep learning advances in the last few years have enabled real-time emotion detection systems (e.g. detecting driver fatigue or retail customer sentiment on the fly)[9]. The survey stresses that emotions are culturally and socially influenced, so context-aware models are crucial for reliability[10]. This supports the ART’s feasibility in recognizing *emotional tone and engagement level* as part of understanding intent, while noting the need to adapt to individual and cultural variation.
188. **“Ambient intelligence” will accelerate advances in general AI** – Rohit Prasad (Head Scientist, Amazon Alexa) – **Industry research blog (Amazon Science)** – **Jan 2023**. [11][12] Amazon’s Alexa team articulates a vision of **ambient AI** assistants that proactively understand users by combining **multisensory inputs** and **affect recognition**. They highlight two critical capabilities: (1) *processing multiple sensor streams* (mics, cameras, even ultrasound) and fusing them to infer the user’s goals, and (2) *interaction skills* including conversational fluidity and recognizing/responding to human emotions[11]. The blog notes that Alexa is evolving to become *more natural, personalized, and proactive* – e.g. anticipating needs via awareness of the shared environment and acting on the user’s behalf when appropriate[12]. This indicates major industry investment toward AI that continuously models context and intent in line with the ART description.

189. **STMicroelectronics Human Presence Detection for Laptops** – *STMicroelectronics (press release)* – **Vendor technical announcement** – **June 2025**. [13][14] European chipmaker STMicro introduced an advanced **Human Presence Detection (HPD)** module for PCs, combining a time-of-flight ranging sensor with on-device AI algorithms. This module, already designed into >260 laptop models, lets computers “sense” if a user is present or approaching, enabling *hands-free logins (Windows Hello)*, auto-lock when you walk away, and ~20% daily power savings by intelligently managing sleep states[13][14]. The solution improves privacy (e.g. alerting if someone is shoulder-surfing) and demonstrates **ambient context awareness** in commercial hardware. The broad adoption of these sensors shows that real-time multimodal sensing (in this case, detecting a human via depth sensor + AI) is *already deployed at scale*, a stepping stone toward more complex intent-aware interfaces.
190. **Eye-Tracking and Gaze Estimation for AR/VR: A Review** – *Liwan Lin et al. (Xiamen University)* – **Peer-reviewed journal (Electronics)** – **Aug 2025**. [15] Surveys recent AR/VR headsets’ eye-tracking capabilities and notes they can provide *real-time insights into user attention and intent*, enabling systems to dynamically adapt content or interface based on where you’re looking[15]. For example, the Apple Vision Pro and Meta Quest Pro use eye-gaze as a primary input modality. This reflects a tangible component of the ART: devices that **infer user intent (what the user is focusing on)** from gaze and adjust their behavior accordingly. Such **gaze-based intent inference** is now reliable enough for consumer use, lending plausibility to AI that monitors subtler cues like eye contact and attention in broader contexts.
191. **Toward Socially-Aware LLMs: Multimodal Approaches to Human Behavior Understanding** – *Ahn et al. (Univ. of Michigan, Microsoft Research, et al.)* – **Preprint (arXiv 2510.23947)** – **Oct 2025**. [16][17] Reviews 176 studies on AI systems that combine large language models with visual/audio perception to analyze human social behavior. It finds AI is being applied to **interpret complex social contexts** – e.g. models that assess student engagement from classroom videos, or that infer teamwork dynamics (roles, strategies) from multi-person interactions[16]. The authors define core capabilities for “socially intelligent” AI aligned with this ART: the ability to interpret multi-modal social cues, reason about multi-party dynamics, and infer individuals’ mental states and intentions[17]. The existence of this large body of work and its interdisciplinary nature (AI, HCI, education, etc.) shows a concerted effort to endow machines with **human-level social context understanding**, supporting both the plausibility and the recognized value of such technology.
192. **Qualcomm on On-Device AI for Contextual Experiences** – *Qualcomm Technologies* – **Industry whitepaper** – **2024**. [18][19] Qualcomm outlines its roadmap for **context-aware AI agents running on consumer devices**. It envisions personal AI that can “predict user needs and proactively execute tasks” by continuously learning a user’s preferences and context locally (via a personal knowledge graph)[18]. Crucially, they note this will make *AI the primary UI*, with natural language, image, video, and gesture inputs replacing today’s explicit interfaces[19]. The whitepaper points out that efficient on-device AI processing allows such agents to operate *securely and continuously without cloud dependency*, aligning with the ART’s emphasis on real-time inference and privacy. Qualcomm’s investment in multi-modal AI hardware (smartphone SoCs, AR/VR platforms, automotive “digital chassis” for intelligent cockpits) is strong evidence of industry momentum toward **ubiquitous context-aware AI** in the next generation of devices.
193. **DARPA ASIST (Artificial Social Intelligence for Successful Teams)** – *U.S. DARPA Program (I2O)* – **Government research program** – **2019–2023**. [20][21] The DARPA ASIST program was devoted to developing AI agents with **Theory of Mind and situational awareness** to work in teams with humans. Its goal was to demonstrate machine “social skills” like inferring human teammates’ goals and knowledge state, predicting their needs, and taking *context-*

*aware helpful actions* during missions[20]. The program description emphasizes that AI has made little progress in understanding the “most important part of its environment: humans,” and ASIST sought to fill that gap by giving AI the ability to interpret context and maintain shared mental models with people[21][20]. The existence of this multi-year, completed project (with multiple research teams and testbeds) signifies both the **feasibility and strategic importance** of AI that deeply understands human intent and context, at least in constrained team scenarios – a strong precursor toward the broader ART vision.

#### 194. **Maturity score (1–7) and reasoning**

##### **Final Score: 4 (Proof-of-Concept demonstrated)**

**A. Justification of score:** The evidence places “AI understanding of human intent & context” at a **transitional stage between lab prototypes and early practical implementations**, corresponding to **Level 4**. Multiple **proof-of-concept systems** have been *scientifically demonstrated* that fulfill key functionality of the ART: for example, the CHI 2024 demo of a gaze+gesture-driven assistant shows that machines *can* interpret non-verbal context to disambiguate user intent in real time[5]. Likewise, multimodal AI models now reliably outperform purely text- or audio-based systems, proving the core principle (fusing diverse human signals) and solving previously blocking problems of intent recognition accuracy[1]. These successes go beyond a Level 3 “lab prototype” because they tackle real-world complexity (e.g. handling pronouns in unconstrained speech, or detecting emotion across different settings) and demonstrate **viability for practical use** (the AR assistant was tested with naive users, and industry benchmarks show significant gains)[6][1]. We also see **commercial readiness signals**: parts of this technology are already **integrated into products** (e.g. laptops with presence-sensing AI, smart speakers using vision for multi-speaker context[22]), indicating that some components meet production requirements in robustness and cost. The involvement of big tech companies and well-funded projects (Amazon’s ambient Alexa vision, Qualcomm’s on-device AI, DARPA ASIST, etc.) means progress is rapid and focused on scaling up – a hallmark of the PoC-to-product transition (Level 4–5).

**B. Why not a higher score?** The **holistic, generalized version** of this ART (an AI that fluidly understands any user’s intent, in any context, and adapts like a human assistant) is *not yet a finished product* or an industry standard – it remains an active R&D frontier. We do **not** have Level 5 evidence of multiple companies selling directly competing “intent-aware AI” products or a fully finished production prototype. Instead, we see *fragmented partial implementations*: one product might detect faces and gaze, another detects tone, but they are not unified into a single system that consistently handles the full spectrum of human context. Key challenges identified in research – such as **cultural/generalizability issues, multimodal data conflicts, and privacy/ethics constraints**[4][10] – are still being worked through before wide deployment. Moreover, public **backlash over emotion recognition** (e.g. Zoom’s now-paused plan for video call “emotion AI”) shows that social acceptance and policy frameworks lag behind, which currently slows commercialization. Thus, the technology as a whole hasn’t reached Level 5’s “finishing phase of a production prototype” or Level 6’s “broad market adoption” – no virtual assistant yet offers the full intent-and-context awareness envisioned (we see *prototypes* and *roadmaps* instead of consumer-ready, fully trusted solutions).

**C. Sub-component breakdown:** This ART comprises several interdependent tech strands with **uneven maturity**:



- **Multi-modal sensing & fusion:** *Maturity ~5.* Sensors (cameras, mics, depth, wearables) and edge AI chips are already in devices worldwide, and frameworks for sensor fusion exist. For instance, human-presence detection and gaze tracking are shipping in laptops and AR/VR headsets[13][15], and cloud APIs for sentiment or vision analysis are offered by multiple vendors. There is active competition here (sensor/AI hardware from Apple, Qualcomm, STMicro, etc.), suggesting an approaching **production scale** for the sensing layer. However, fusion at scale (combining *all* modalities robustly) still faces integration challenges (synchronization, power management).
- **Intent inference algorithms:** *Maturity ~3–4.* Academia and corporate labs have prototyped the **context interpretation algorithms** – e.g. fusion models that beat baselines[1], or assistants like GazePointAR[5] – demonstrating the concept works. Yet, these are early-stage implementations (often task-specific or in controlled studies). They meet functionality requirements (they clearly exceed what previous single-modal systems could do, fulfilling the rubric for Level 4), but **reliability, bias and edge cases** remain concerns. We haven’t seen a *general* intent-understanding AI handle the messiness of everyday life outside of pilot tests. Further training on larger datasets and solving open research problems are needed to reach consistent real-world performance (transition to Level 5/6).
- **Adaptive response & HCI integration:** *Maturity ~4.* There are proofs that adaptive, context-aware responses improve user experience (users in studies found it more natural[6]). Modern HCI research and some voice assistants have started implementing adaptive behaviors (e.g. Alexa’s “Conversation Mode” uses vision to decide if it’s being addressed[22]). Still, the *full* repertoire of modality switching and social-norm adherence (as described in ART) is experimental. No off-the-shelf assistant yet, for example, silently switches your phone to vibrate because it “knows” you’re in a meeting – but the building blocks (calendar context, audio scene analysis for meeting sounds, etc.) are emerging.
- **Privacy, personalization, override mechanisms:** *Maturity ~3.* Technically, solutions like federated learning, on-device processing, and user dashboards for data are known, but **trust and policy frameworks** are lagging. The need for these safeguards is recognized (research frequently cites them, and standards bodies are beginning discussions), but their implementation will likely come as the tech nears productization. Right now this aspect is more a requirement than a delivered feature set, keeping the overall maturity moderated.

Considering these sub-components together, the **overall ART** functionality – an AI that seamlessly understands intent and context – is roughly an **average of the above**, which lands around **Level 4**. Some pieces (sensors, hardware) are ahead, indicating the platform is ready, and there is **clear recent progress** pushing the tech beyond proof-of-concept (justifying higher than Level 3). However, the **ultimate integration and refinement** needed for a polished, widely-deployed product is still in progress. Therefore, Level 4 is appropriate: the concept has been proven viable in prototypes and even partial real-world deployments, but further development and convergence of sub-technologies are required to reach full commercial realization.

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## ART 04.027 Brain-to-Brain Interfaces

### 195. ART extraction

**A) Primary capability** – Enabling direct exchange of brain activity patterns between individuals as a new communication channel. This would vastly increase communication bandwidth and reduce ambiguity by transmitting perceptions, intentions, or mental states directly, rather than through speech or text. It promises novel forms of coordination, letting people “share mindsets” for enhanced collaboration or situational awareness.

### **B) Key sub-components/variants –**

- **Brain activity sensing:** Non-invasive or minimally invasive neural sensors (e.g. EEG, MEG, fNIRS, or high-density implants) to record the sender’s brain signals associated with specific thoughts, intentions, or sensory experiences.

- **Decoding algorithms:** Adaptive machine learning models trained per user to translate raw neural signals into a *shareable digital representation* of the sender’s intended message or



state (while filtering noise or irrelevant activity).

- **Communication link:** A secure digital interface (wired or wireless) to transmit the encoded neural information between brains. This could be a direct device-to-device link or a network if multiple brains (“BrainNet”).

- **Brain stimulation/output:** Targeted neural stimulation or feedback at the receiver’s side to *write* information into the brain. This might use transcranial magnetic stimulation (TMS), focused ultrasound (tFUS), transcranial electrical stimulation (tES), optogenetics (in animals or with genetic mods), or implanted microstimulators to induce structured perceptions, cues, or biases rather than fully formed thoughts.

- **Multi-brain configurations:** Interfaces can be unidirectional (one sender, one receiver) or bidirectional (two-way exchange), and may scale to networks (multiple senders and receivers). Early systems are mostly one-to-one; future “brain networks” could allow **many-to-many** information sharing[1][2].

- **User controls & consent:** Interface software to manage channels and permissions – users choose *what type* and *how much* information to share, maintaining privacy and safety. This includes calibration routines for each user and safety interlocks to prevent unintended influence.

**C) Maturity indicators** – We would look for evidence of **laboratory proofs-of-concept** where information is successfully sent from one brain to another (e.g. solving tasks via brain-to-brain link), and demonstrations moving beyond trivial signals (more than a simple binary “yes/no”). Key indicators include: **bidirectional prototypes** (two people exchanging information simultaneously), **multi-person experiments** (networks of 3+ brains)[3][4], and **improved bandwidth** (transmitting more complex stimuli or faster signals). Progress toward practical use would be signaled by integrated BBI “**headset**” **systems** rather than ad-hoc lab setups – for example, non-invasive BBI rigs achieving real-time operation. Other signs include **field trials or clinical tests** (e.g. using BBI to aid a disabled patient with a therapist’s help), and **multiple independent groups or companies** heavily investing in BBI-related technology (a competitive R&D environment). Evidence of **safety and ethics frameworks** being discussed (military or healthcare contexts) also suggests the concept is taken seriously enough to prepare for deployment. Finally, early **commercial prototypes or large funding rounds** for BBI-specific startups (or BCI companies explicitly aiming at brain-to-brain communication) would indicate maturity toward viable products.

196. **Evidence (10–20 recent, reliable sources)**

***Brain-to-brain direct coupling demonstrated (human experiment, 2025): Matani et al., Brain Research, Jan 2026 – Peer-reviewed paper.\**** Publication date: **01/2026**.

Findings: **Discovered a form of “volume current coupling” that electrically links two human brains’ signals directly. Two people were connected via transcranial electrodes that allowed leakage currents from one brain to influence the other. When isolated subjects were linked this way, one person’s brain activity induced measurable bias in the other’s behavior[5][6].** **Significance:** It shows a direct brain-to-brain channel affecting cognition without any computer decoding\*\*, suggesting new physical mechanisms for BBI. This lab demo confirms the plausibility of brain-to-brain information transfer using purely electrical coupling, and that such coupling can alter behavior (albeit in a limited way), underscoring the scientific feasibility of BBIs.

**Systematic review of BBI research (15 studies) – field is nascent: Nam et al., Frontiers in Neurorobotics, May 2021 – Peer-reviewed systematic review.\*** Publication date: 05/2021. Findings: Reviewed all BBI experiments up to 2020 (15 studies total). Most were unidirectional and used a BCI (EEG) on a sender plus a CBI (usually TMS) on a receiver[11]. A common approach was evoking *phosphenes* (flashes in vision) via TMS based on another person's EEG, enabling binary signals (yes/no)[1][7]. Notably, 86% of studies were one-sender/one-receiver; only ~13% tried more complex setups[7]. No standard method for stimulation has emerged – groups variously tried TMS, tDCS, ultrasound, optogenetics, etc. Bidirectional BBI in humans has been very rare (only one early study in 2015 used a partial two-way loop)[1][8]. **Significance:** This shows BBIs had passed the initial proof-of-concept stage by 2020 but remained extremely limited in capability (mostly transmitting one-bit signals or simple triggers). It establishes a baseline: the concept works in principle (ruling out Level 1), but by 2020 BBIs were still laboratory curiosities requiring significant setup and calibration, with no multi-channel high-bandwidth communication yet\*\*. It also highlights key hurdles like inconsistent neurostimulation methods and need for more than 1:1 links – challenges that subsequent research is now tackling.

**Multi-person BBI “BrainNet” and collaborative problem solving: (Jiang et al., 2019) Nature Scientific Reports – Peer-reviewed experimental paper.\*** Publication: 11/2019. Findings: Demonstrated *BrainNet*, the first multi-person, non-invasive BBI for group collaboration[9]. Three people (two “Senders” with EEG caps and one “Receiver” with EEG+TMS) jointly played a Tetris-like game by exchanging binary signals via brain-to-brain links[9][10]. Senders saw the game and decided whether to rotate a piece, encoding “Yes/No” by focusing or not focusing on a flashing light (EEG steady-state response). The Receiver, blind to the game, received the senders' decisions through TMS-induced phosphenes and integrated this input to make moves[11]. Over repeated trials, the group achieved task performance above random chance. **Significance:** Although slightly older (2019), this milestone experiment showed feasibility of a network BBI (2→1) and that brains can collaborate on a task using a direct neural link. It proved scaling beyond one-to-one is possible and that a BBI can do more than send a single bit in isolation – here a team used it to solve a visuo-motor task. BrainNet's success provided a template for future BBI systems, moving the field closer to Level 3 maturity (lab prototype with key functionality) by showing multiple users exchanging meaningful information\*\*[9][10]. It also flagged the high computational demands of real-time decoding and the intensive user training needed, which current research is working to streamline.

**DARPA “MOANA” project – towards non-invasive, high-speed BBI headsets: Robinson (Rice Univ.) et al., DARPA N3 Program – U.S. Defense research project (press release)\*.** Date: 01/2021 (follow-up funding awarded). Details: The MOANA project (“Magnetic, Optical and Acoustic Neural Access”) received \$8M from DARPA to build a dual-function wireless headset for brain-to-brain communication[12][13]. The goal is a minimally invasive, bidirectional BBI: it uses infrared light for reading brain activity and magnetic fields (with injected magnetic nanoparticles) for writing into the brain, targeting <50 ms latency links[14][15]. In initial tests, the team showed they could optically detect neural signals through a skull and precisely stimulate neurons in vitro via magnetothermal effects[15]. Phase 1 solved key physics challenges (photon collection through skull, magnetic nanoparticle heating control). Now in Phase 2, 16 partner labs are integrating

these into a rodent BBI prototype, with a goal of human testing in ~2023[16][14].

**Significance:** MOANA represents a well-funded, multi-disciplinary push to overcome the main technical blockers: it's developing high-bandwidth non-surgical I/O (optical diffuse tomography and magnetogenetics) and modular wearable designs[17][18]. Notably, DARPA set specs to rival implant performance (read/write 16+ channels in 16 mm<sup>3</sup> of brain at <50 ms[19][20]). By Phase 3 they aim to demonstrate a closed-loop *human* BBI link[21]. This indicates the technology is transitioning from isolated academic demos to coordinated prototype development\*\*, a hallmark of Level 3 maturity. The involvement of DARPA and teams at Battelle, Carnegie Mellon, Johns Hopkins APL, PARC, Teledyne, etc. (in parallel N3 projects)[22] underscores that multiple well-resourced actors see promise in high-performance brain interfaces, accelerating progress toward practical BBIs.

**EU “BrainBIT” project – all-optical BBI for rehab (ERC grant): Pavone et al. (Univ. of Florence), BrainBIT project report (CORDIS) – Authoritative research project report.\*** Project period: 12/2016 – 05/2022. Results: **Developed advanced** two-photon optogenetics technology to read and write neural activity across brains with high resolution[23][24]. In zebrafish larvae, they achieved whole-brain functional imaging while simultaneously stimulating specific neurons, allowing them to capture an animal's neural pattern for a behavior and *induce that pattern in another animal*[25][26]. They demonstrated transferring a neural signature associated with efficient motor recovery from one mouse to another: mice with better post-stroke rehabilitation were used as “donors” of neural activity templates, which were optogenetically replayed in other mice to improve their recovery[25][27]. The project overcame challenges in separating optical read vs write signals by shifting to two-photon excitation (different wavelengths)[28], and built a “pump-and-probe” framework for cross-brain stimulation. **Significance:** This is a successful in-vivo BBI demonstration in mammals for a therapeutic outcome (*enhancing stroke rehab in mice*) using no electrodes – purely light-based. Achieving whole-brain neural transfer with spatiotemporal precision was a major technical hurdle, and BrainBIT's innovations (e.g. two-photon excitation, fast volumetric imaging) show plausibility for high-fidelity BBIs[24][29]. While still preclinical, it points to BBIs addressing real-world bottlenecks (rehabilitation efficacy) and illustrates international progress (EU investment) alongside US efforts. It also highlights that later-generation BBIs may initially appear as “specialized installations” (since current two-photon setups are bulky and costly), with a roadmap to miniaturization.

**First bidirectional human BBI in the works (NSF project): NIU Press Release (C.S. Nam), Feb 2025 – University news (NSF grant announcement).\*** Date: 02/2025. Details: Reports a new \$600k NSF-funded project led by Prof. Chang Soo Nam (NIU) and Dr. Xiaoning Jiang (NC State) specifically to develop a two-way brain-to-brain interface in humans[30][31]. The team will combine noninvasive *brain-reading* (EEG, MEG or fNIRS) with *brain stimulation* (in particular focused ultrasound, tFUS) to allow two participants to send and receive information *simultaneously*[32][33]. They note that since 2013, basic one-way BBI has been shown in labs, but no fully bidirectional BBI exists yet[34][35]. The goal is to pioneer the first true two-way BBI system, where each person's intentions can be encoded and delivered to the other in real time. Envisioned applications include doctor-patient communication for locked-in patients, enhanced stroke rehabilitation, and rapid idea sharing between healthy users[36][31]. **Significance:** This grant indicates that mainstream research funding agencies are now backing BBI development. The emphasis on

**tfUS is notable: ultrasound offers deep, focused stimulation with no implants, aligning with the ART's noninvasive aspiration.** If successful, this project would mark a jump to Level 4 (proof-of-concept): *a functional prototype meeting basic requirements for real-time, two-way operation in humans.* The fact that achieving bidirectionality is a stated milestone suggests current BBIs have been constrained (mostly one-way), and hitting this target would resolve a “previously-blocking” limitation. This effort, alongside others, shows clear recent momentum to move BBIs from isolated one-direction demos to robust interactive systems.

**High-density wireless brain implant boosts I/O bandwidth: Shepard & Tolias et al., Nature Electronics (press via Columbia Engineering), Dec 2025 – Peer-reviewed research (neural engineering).\*** Publication date: 12/2025. Breakthrough: **Unveiled an ultrathin, paper-like brain implant (“BISC”) with 65,536 electrodes and 16,384 micro-stimulators on a single CMOS chip[37], enabling high-bandwidth wireless read/write to the cortex[38][39].** Inserted under the skull (minimally invasive ECoG), it streams brain signals at up to 100 Mbps (over WiFi-like UWB) and supports real-time AI decoding of complex movements, speech and visual intent[40][41]. Initial clinical tests showed the device can be implanted through a small skull opening and remain stable, recording rich neural data[42]. Its integrated design (all components on one 3×3 mm chip) drastically reduces size and power requirements versus traditional BCIs[37][43]. **Significance:** While not a BBI itself, this represents state-of-the-art in brain interface hardware, attacking the “fidelity of sensing and stimulation” bottleneck cited in the ART description. BBI feasibility depends on such high-resolution, real-time interfaces. BISC's success suggests that transmitting *vast amounts of neural information* is becoming technically viable[41][44]. For BBIs, one could imagine two BISC implants (one in each person) linking via a wireless network to exchange thousands of channels of neural data – a scenario far beyond today's few-bit EEG/TMS links. In terms of maturity, this **demonstrates that** critical sub-systems (BCI and CBI)\*\* are nearing commercial-grade performance (the device even received NIH funding for epilepsy therapy[45]). Thus, one major barrier to practical BBIs – the lack of a high-bandwidth “neural modem” – is being addressed, paving the way for future BBI prototypes that meet the latency and throughput demands for real use.

**Dual-brain stimulation enhances cooperation via neural synchrony: Zheng & Lu, Neurolmage, Aug 2025 – Peer-reviewed experimental paper.\*** Finding: **Applied** simultaneous transcranial direct current stimulation (tDCS) to two people **during a Prisoner's Dilemma game, aiming to synchronize a specific brain region (right temporoparietal junction) involved in social cognition[46][47].** The study with 81 pairs showed that **active dual-brain stimulation** significantly increased inter-personal brainwave synchrony (measured by hyperscanned EEG/fNIRS) compared to sham or one-sided stimulation[48][47]. Crucially, pairs with enhanced neural synchrony adopted more cooperative strategies and earned higher mutual rewards in the game[49][47]. The effect was causal: turning the synced stimulation on and off led to corresponding changes in brain synchrony and cooperation levels[47][50]. **Significance:** This **demonstrates a rudimentary BBI use-case:** modulating two brains together to improve shared outcomes. Instead of transmitting an explicit message, the interface biased both participants toward a “team mindset” (via induced brain synchrony), which is one envisioned mode of BBI (sharing biases/attention rather than fully formed thoughts). The result validates that altering brain states in concert can meaningfully change behavior in

**a social task – essentially** augmenting human teamwork via neurotechnology. *It speaks to plausibility (brains can be externally aligned for better coordination) and hints at near-term applications like training or therapy: e.g. boosting therapist-patient rapport or keeping pilots in sync. As an experimental milestone, it goes beyond one-way information transfer and into shared cognitive state management, which is a key value proposition of BBIs in the ART description (adapting workflows around collective attention/fatigue).*

**Big industry investment in noninvasive BBI tech (ultrasound-based): Mullin, Wired, Jan 2026 – Tech journalism (factual report).**\* Context: **Reports on Merge Labs, a startup co-founded by OpenAI’s CEO Sam Altman, emerging from stealth with \$252M in funding to build brain-computer interfaces that use ultrasound for both reading and writing brain activity[51][52]. Merge’s approach foresees no surgical implants – instead, using gene-delivered molecules and focused ultrasound to noninvasively interface with neurons[53][54].** OpenAI’s involvement suggests the goal of integrating AI with high-bandwidth brain input/output, aligning with Altman’s “merge” concept of human-AI hybrid cognition[55]. The article notes that while companies like Neuralink (implanted BCIs) have raised >\$1B, Merge aims for a wearable, mass-accessible neural interface, and that other startups (e.g. Synchron, Paradromics) are also heavily funded in this space[52][56]. **Significance:** This is strong evidence of a *rapidly maturing ecosystem* around brain interfaces, which BBIs will directly benefit from. The fact that a quarter-billion dollars is being poured into noninvasive read/write modalities shows that key enablers for BBIs (like safe high-throughput neural links) are attracting major investment and talent\*. *Although Merge is initially focused on brain-to-computer links, the technologies (ultrasound neuromodulation, “neural foundation models” for decoding brain signals[57]) are exactly what a future BBI needs. This competitive landscape – OpenAI, Neuralink, academic spinoffs – indicates a Level 3–4 environment for BCI, which in turn propels BBI readiness. In short, multiple well-capitalized actors are racing to perfect noninvasive neural I/O, bringing BBIs much closer to reality. (Notably, Merge’s vision statement explicitly mentions ultimately achieving “broadly accessible” brain interfaces that blur humans and AI[55], essentially the long-term BBI ambition).*

### 1. Maturity score (1–7) and reasoning

#### Proposed Score: 3 (Laboratory prototype demonstrated)

**A) Justification – Brain-to-brain interfaces** have decisively moved past theoretical speculation (Level 1) and initial feasibility tests (Level 2) into the realm of working lab prototypes, but they have **not yet achieved a proof-of-concept that meets practical deployment criteria**. The evidence shows multiple **independent demonstrations of core functionality** – for example, transmitting information from one human brain to another to solve tasks[9][11], or linking animals to share motor or sensory states[25][27]. These experiments prove the fundamental *operating principle*: that neural signals can be captured, encoded, sent, and meaningfully decoded into another brain (ruling out Levels 1 and 2). Additionally, key previously-blocking problems have seen progress, such as:

- **Multi-node communication:** Going from one-to-one to multi-person networks (e.g. BrainNet’s 3-person BBI[9][10]) solved a conceptual hurdle and showed BBIs can scale beyond a single channel.
- **Improved I/O resolution:** Projects like MOANA and BISC have achieved orders-of-magnitude better neural reading and writing capability (milliseconds latency,  $\sim 10^4$ – $10^5$



channels)[18][37], addressing the fidelity bottleneck that once limited BBIs to sending a yes/no signal.

- **Noninvasive bidirectionality (in progress):** Efforts funded by DARPA and NSF are explicitly targeting two-way communication without surgery[33][21] – a milestone not yet reached but clearly in sight, which would remove one of the last “show-stoppers” for a convincing PoC.

With these advances, we have **laboratory prototypes that achieve necessary functionality**: for instance, the dual-brain tDCS study (2025) demonstrated that a BBI can actively enhance cooperation between people by syncing their neural activity[49][47] – directly showing a benefit unattainable by conventional means (you cannot induce that effect with normal communication). That addresses the ART’s “value-creation” claim on a small scale. Similarly, the rodent optical BBI (2020) achieved rapid info transfer for precise locomotor control[58][59], proving BBIs can surpass reflex-speed communication. These are **qualitatively new capabilities**, indicative of Level 3.

However, **evidence for Level 4 is not yet present**. A Level 4 PoC means a functional prototype that meets *real-world commercialization requirements* in reliability, integration, and clear advantage. What’s missing is demonstrated *robustness and scaling*: current BBI setups require heavy calibration, controlled lab settings, and often bulky equipment (e.g. MRI or optical rigs, tethers to PCs). There is **no BBI system yet that one could deploy in a practical scenario** (say, two operators in the field silently coordinating by BBI). Security, privacy, and regulatory aspects remain unproven at prototype level as well. In short, **no BBI has met the bar of being “viable for production” or clearly superior to existing solutions**. For example, the information rates achieved so far are still far below what simple speech or text can convey – a BrainNet game or yes/no question via BBI is orders of magnitude slower than speaking in person. Thus, while rapid progress is evident, BBIs remain in the experimental stage, not the product stage. The recent surge in funding and multi-group R&D (DARPA, EU, startups) suggests we are on the cusp of more integrated demonstrations (transitioning toward Level 4), but those results are just emerging (e.g. the first bidirectional human BBI is *planned*[35], not completed; initial human tests for MOANA are proposed[16], not yet reported). The **strongest evidence** (like multi-person BBI and high-density neural interfaces) *rules out* Level 2 definitively – we’re beyond isolated curiosity tests. Yet the **lack of any deployed prototypes or competitive commercial products** rules out Levels 5–7, and the absence of a polished, end-to-end working system at human “real-life” scale means Level 4 is not fully met.

**B) Evidence mapping to rubric** – Level 3 is characterized by a lab prototype showing necessary functionality with a key problem solved, even if cost/durability issues remain. We have:

- **Necessary functionality achieved:** We have seen **successful brain-to-brain information transfer** (binary signals in humans[9], visual pattern sharing in animals[58], and even induced cooperative behavior[49]). This indicates BBIs *can* do what was previously only hypothetical (direct neural communication).
- **Previously blocking problem solved:** Early on, it was unclear if noninvasive BBI was even possible. Now, between BrainNet and MOANA’s work, they’ve solved issues like *synchronous EEG-TMS control* and *through-skull optical signaling*[60][15]. Another

blocker – extremely low bandwidth – is being overcome by new hardware (e.g. BISC’s 100 Mbps link[41]). These achievements were essential steps toward viability.

- **Production issues remain:** Indeed, current systems are far from portable or affordable. For example, BrainBIT’s 2-photon microscope is not something you’d find outside a lab, and even the upcoming MOANA headset will initially be complex and costly (comparable to an advanced medical device). There is no evidence of cost reduction or mass manufacturability yet – pointing to Level 3 (prototype) rather than 4 (product-ready PoC).

**C) Sub-component maturity (bundle analysis)** – The ART combines multiple technologies (neural sensing, decoding AI, wireless link, neural stimulation). These pieces have somewhat different maturity levels today:

- *Non-invasive neural sensing (EEG, fNIRS, etc.):* Fairly mature (used clinically and in consumer EEG headsets), but limited in resolution. Cutting-edge sensing like high-density EEG or emerging tech (optical, MEG) is improving. Overall ~Level 4 for basic EEG (commodity devices exist), but only ~Level 3 for the **new high-res optical/ultrasound methods** being developed (shown in lab, not yet general-use).
- *Neural decoding algorithms:* Machine learning for BCIs is an active area – e.g. AI decoding of speech from brain signals just hit practical demos in 2023. For BBIs, personalized decoding is essential. This sub-component is around Level 3–4: proven in lab (AI decoding enables real-time BCI control in labs[61]) but not a finalized product (needs more training data and generalization).
- *Neural stimulation outputs:* TMS/tES are well established in research (Level 4 in sense they are used in clinics for other purposes), but **precise information injection** is nascent. Focused ultrasound (tFUS) and magnetogenetics have shown promise in lab animals[62][63] but are at Level 2–3 experimentally. Invasive stimulators (microelectrodes) are at Level 4 for medical implants (e.g. DBS), but using them for BBI is Level 2 (no dual implant BBI done yet).
- *Secure wireless communication link:* This is relatively mature (wireless EEG packs, Bluetooth etc., Level 5), but ultra-low-latency, high-bandwidth brain links are just reaching prototypes (the BISC UWB link – Level 3). However, standard networking tech can be leveraged, so we can consider this piece not a limiting factor now.

Because these sub-components must work *together* for a BBI, the overall system maturity is constrained by the least mature elements – notably, *neurostim output and integration*. In practice, today’s BBIs function, but with low fidelity and intensive setup, which places the **overall system at Level 3**. We therefore aggregate to **Level 3**, reflecting that **the concept is proven with working prototypes in research settings, but significant development is needed to approach a usable, scalable product**.

**What’s needed to reach Level 4?** We’d expect in the next few years a demonstration of a **full-loop BBI in humans** where two people achieve a complex task *better or faster* via the BBI than by other means, using a relatively self-contained device. For instance, a bidirectional BBI that enables a locked-in patient and a healthy user to communicate basic thoughts (on the order of a few bits per second) reliably would constitute a Level 4 PoC – it would show clear benefit over the status quo (no communication or slow assistive tech) and be on a path to practical deployment. To get there, ongoing work must improve the information rate (so that



meaningful chunks of data – not just binary – can be exchanged) and reliability/latency of the system, as well as ensure safety and consent mechanisms are foolproof. The evidence suggests those advances are underway (with AI decoding, better hardware, and serious funding), but until they coalesce into an integrated demonstration, BBI remains at **Maturity 3**.

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## ART 04.028 Memory Prostheses

### 2. ART extraction

3. **Primary capability:** Implantable “memory prosthesis” devices that interface with the brain’s memory circuits to **restore or enhance memory function**. These implants would sense neural activity during memory formation and **record the neural patterns**, then later **replay or stimulate those patterns** to reinforce recall or replace missing signals, effectively **substituting for damaged memory-encoding processes**.

### 4. Key sub-components/variants:

- *Neural interface hardware:* Miniaturized, implantable electrode arrays placed in memory-related brain regions (e.g. hippocampus) to **record and stimulate neural signals**, designed to match the brain’s circuit layout and dynamics.
- *Sensing & decoding algorithms:* On-board or external **signal processing models (e.g. “memory decoding models”)** that detect when new memories are being formed by analyzing multi-site neural activity patterns, and that predict the appropriate output pattern for memory storage[1][2].
- *Data storage & processing:* Embedded memory and controllers to **store neural activity patterns** (in compressed, anonymized form) and run real-time computations (possibly AI or model-based) to decide when and how to stimulate.
- *Stimulation/replay system:* Electrical stimulators to **inject recorded patterns back into the brain** (e.g. into downstream hippocampal neurons) at opportune moments, subtly reinforcing weak memories or **“replaying” memory codes** to enable recall that would otherwise fail.
- *External interface & personalization:* Secure wireless interfaces for **configuration and updates**, allowing clinicians to adjust parameters and download software. Over time the system would **learn the individual’s unique neural signatures of memory success** and personalize the stimulation patterns. Multiple implants could be networked together and linked to external devices for synchronization and data telemetry.

- *Power and safety constraints:* Low-power operation (microwatt–milliwatt range) with careful thermal management to avoid tissue heating, and **biocompatible packaging** for long-term implantation. The device must be **fully implanted (no transcutaneous leads)** and inductively powered or with rechargeable batteries, similar to a cochlear implant or deep-brain stimulator. Heat dissipation, battery life, and **fault tolerance (to avoid dangerous failures)** are critical design factors.
- *Surgical and cost considerations:* Requires neurosurgical implantation (initially as complex as epilepsy or Parkinson’s implants). Early devices would be expensive (akin to major surgery plus specialized hardware), but with scale could approach costs of common implants (e.g. cochlear or cardiac devices).

5. **Maturity indicators (evidence):**

- *Laboratory demonstrations:* Peer-reviewed studies showing **proof-of-concept in animals or humans**, e.g. recording hippocampal activity and electrically improving memory performance in memory-impaired subjects. Evidence of memory retention improvements or restored recall in controlled tasks would indicate plausibility.
- *Prototype devices:* Development of **implantable multi-channel neural prosthesis prototypes** (wireless, closed-loop systems) tested in vivo. Key metrics include number of channels (e.g. tens of electrodes), ability to record and stimulate simultaneously, stability over time, and safe operation. Large-animal studies or first-in-human trials of such prototypes would mark progress toward practical use.
- *Clinical trials and consortia:* Initiation of **clinical trials** (or advanced pilot studies) in patients with memory loss (e.g. Alzheimer’s, TBI, epilepsy) using a memory prosthesis system. Also, **major funded programs** (e.g. DARPA’s Restoring Active Memory, EU’s ERC projects) or industry efforts (startups, medtech companies) competing in this space show momentum.
- *Efficacy beyond existing methods:* Evidence that this approach can **significantly improve memory recall or storage compared to no intervention or traditional stimulation**. For example, measurable percent improvements in memory tests, or restoring memory function that was lost, would demonstrate it “exceeds previous solutions.”
- *Multi-actor development:* Multiple teams (academic, government, industry) **building similar systems** is a sign of maturity – e.g. more than one company with working prototypes, or devices approaching regulatory approval. Patents on concrete designs, vendor datasheets for memory-prosthesis-capable implants, or roadmaps from authoritative bodies would support this.

6. **Evidence (10–20 recent, reliable sources)**

7. **Hippocampal prosthesis improves memory in human patients – Couture et al., *Frontiers in Comp. Neuroscience* (Feb 2024):** A Wake Forest/USC research team implanted multielectrode arrays in 14 epilepsy patients and delivered content-specific stimulation patterns in the hippocampus during memory tasks. They found this “memory prosthetic” stimulation significantly boosted recognition of images – in subjects with memory impairment receiving bilateral hippocampal stimulation,

performance improved roughly 4-fold more often than it worsened[3][4]. This provides the first peer-reviewed demonstration that tailored electrical codes can enhance human memory encoding, validating the feasibility of a memory prosthesis.

8. **News: First successful neural prosthetic to recall specific memories – Atrium Health Wake Forest (Feb 2024):** Reports on the above study as “the first successful use of a neural prosthetic device to recall specific memories” in humans[5]. Using a patient’s own neural firing patterns, the implant delivered spatio-temporal stimulation in the hippocampus, yielding detectable memory improvements in ~22% of trials overall. Notably, almost 40% of memory-impaired patients with bilateral implants showed significant gains in memory performance[6]. This press release underscores that memory recall was enhanced without adverse effects, marking a breakthrough in memory restoration technology.
9. **Human trial shows 11–54% memory improvement with hippocampal implant – USC Viterbi News (Oct 2024):** In a collaborative clinical trial with 24 epileptic volunteers, researchers tested a prototype hippocampal memory prosthesis. The device used each person’s intracranial electrodes and a computational model to detect and reinforce memory encoding. Results showed volunteers with the prosthesis had 11% to 54% better memory test scores compared to control conditions[7]. This significant boost – observed in real patients recalling images over seconds to days – constitutes a proof-of-concept in humans[8]. The article notes that this was achieved by “piggybacking” on existing epilepsy implants and an external processor, and it paved the way for upcoming fully implantable versions[9].
10. **Closed-loop stimulation targeting memory networks – Ezzyat et al., Cerebral Cortex (Jan 2024):** A multi-center clinical study (47 patients) demonstrated that closed-loop brain stimulation can reliably improve episodic memory when delivered to optimal sites. A machine-learning model monitored brain signals during a word recall task and triggered stimulation in the lateral temporal cortex during predicted “poor encoding” moments. Memory retrieval improved significantly – but only when electrodes were near key white-matter pathways and strongly connected to the brain’s memory network[10][11]. Stimulation at those ideal locations yielded the largest memory gains and reduced low-frequency brain activity associated with memory failure. These findings not only confirm that adaptive stimulation enhances memory, but also show how to optimize electrode targeting for effective memory prosthetics.
11. **60-channel wireless memory prosthesis prototype (in vivo validation) – Rizzuto et al., Brain Stimulation 2025 (press release, Jan 2026):** Nia Therapeutics (USA) announced a fully implantable Smart Neurostimulation System (SNS) that was tested in large animals as a closed-loop memory prosthesis[12]. The wireless implant can record from 60 electrodes across four brain regions – 10× more channels than current clinical devices – reflecting the distributed nature of memory circuits[13]. In chronic sheep studies, the SNS system showed stable long-term performance: it could decode brain states with high accuracy and deliver programmed stimulation that reliably modulated neural activity (e.g. dose-dependent shifts in hippocampal EEG rhythms)[14]. Histology showed no tissue damage. This device builds on human research where adaptive stimulation during poor-encoding periods improved recall ~20%[15], and Nia is now preparing for first-in-human trials in TBI patients by 2026[16]. (Source: Nia Therapeutics press release via Business Wire.)\*

12. **Emerging multi-channel implants (industry & academia) – Fisher et al., review in *Brain* (2024):** A recent review of deep brain neurostimulation technologies notes that millimeter-scale, multi-channel brain implants are nearing clinical translation for memory and other cognitive applications. For example, Nia Therapeutics and CorTec Neuro (Germany) have each run pre-clinical trials on skull-mounted implantable stimulators, while others like Motif Neuro are testing novel dural stimulators[17]. These systems, larger than earlier micro-devices, can house more processing and electrodes on-device. The review highlights that such multi-target closed-loop devices – including Neuralink’s high-channel BCI now in clinical trial – are part of a wave of neurotech aimed at network-level disorders (like memory loss) rather than single focal lesions.
13. **EU consortium advancing memory prosthesis in primates – MEMOPROSTHETICS project report (EU ERC, July 2025):** An EU-funded research program (CNRS, France) is developing a neuroprosthesis for memory circuits in non-human primates[18][19]. They implanted dozens of electrodes in three brain areas (hippocampus, entorhinal cortex, prefrontal cortex) to record and stimulate neural networks involved in memory encoding[20]. So far, the team has identified neural oscillation changes correlated with memory tasks and begun testing whether targeted electrical stimulation can improve memory formation[21][22]. Early results showed that certain high-amplitude stimulations in hippocampus or entorhinal cortex can disrupt memory, guiding the search for safe, pro-memory stimulation parameters[23]. The project is now optimizing stimulation protocols and working to miniaturize the system into a fully implantable device, aiming to pave the way for clinical trials in Alzheimer’s or brain-injury patients[24].
14. **Review: Engineering a hippocampal memory prosthesis – Liu et al., *Curr. Opinion Biomed. Eng.* (Dec 2022):** This review summarizes two decades of progress toward hippocampal prosthetic memory devices, highlighting both neuroscience and hardware advances. It notes that modern neural “interrogation” tools (multi-electrode arrays, optogenetics, etc.) have mapped hippocampal memory codes, and early-stage prosthetics have been tested in animals[25][26]. For example, recent experiments connected live rodent hippocampus slices with a neuromorphic memristor circuit that acted as an artificial synapse – showing that a silicon device could influence hippocampal neurons in vitro[27]. The authors emphasize bio-inspired approaches (neuromorphic hardware mimicking neuronal firing) as a path to restore memory function in Alzheimer’s disease, and cite that hippocampal prosthetic models have already shown success in rodents, monkeys, and human feasibility studies.
15. **Adaptive 40 Hz stimulation chip boosts memory in Alzheimer’s mice – Lv et al., *Nature Commun.* 16:5948 (July 2025):** Chinese researchers developed “NeuroRevive-FlexChip,” a flexible neural implant that combines dopamine sensing with electrical stimulation in the hippocampus[28]. In Alzheimer’s-model mice, this chip applied 40 Hz stimulation to CA1 while monitoring dopamine in real time. The treatment restored more normal dopamine release and reduced pathological hyper-synchrony in hippocampal activity[29]. Treated mice showed modest improvements in spatial memory (Y-maze test) and even a reduction in  $\beta$ -amyloid deposition, compared to controls[30][31]. This innovative closed-loop neuromodulator – which targets a neurochemical aspect (dopamine) alongside electrical activity – underscores the expanding toolkit for memory prosthesis research, though it remains at preclinical stage.
16. **Maturity score (1–7) and reasoning**  
**Score: 4 (Proof-of-Concept demonstrated).**

**Rationale:** The concept of a memory prosthesis has progressed well beyond theory (Levels 1–2) into tangible laboratory and *in vivo* demonstrations. **Multiple teams have built and tested prototype systems that restore memory functions in animals and even human patients**, satisfying the criteria for at least Level 3. In fact, the evidence shows we have reached **Level 4: Proof-of-Concept**. Recent human trials and advanced prototypes indicate that the technology is functional and addressing real-world requirements, though not yet a market product:

- *Level 3 vs 4:* We have **laboratory prototypes proven in humans**, not just isolated lab benchtop tests. For example, the 2024 Frontiers study demonstrated a **working hippocampal prosthesis in human patients, measurably improving their memory performance**[\[3\]](#)[\[4\]](#). This solved a key previously blocking problem – that is, encoding and re-injecting meaningful memory “codes” to boost recall – something only theorized before. Likewise, in monkeys and rodents, closed-loop implants have shown they can influence memory-related signals. These successes rule out Level 2 (“just basic lab verification”) and firmly achieve Level 3. Moreover, the devices have moved from racks of equipment to **miniaturized implantable prototypes**: e.g. Nia’s 60-channel wireless implant and the ERC group’s multi-electrode primate implant, which indicates engineering viability beyond a one-off demo[\[12\]](#)[\[20\]](#). The presence of a **dedicated startup (Nia Therapeutics) building medical-grade hardware** and preparing for clinical trials is a strong indicator we are at PoC stage and pushing toward productization[\[16\]](#).
- *Evidence of Level 4 (PoC):* The emerging prototypes meet many **commercialization requirements in functionality**. Nia’s fully implantable device, for instance, is wireless, closed-loop, and high-channel-count – features necessary for a practical therapy (existing clinical neurostimulators were insufficient at 4–6 channels)[\[13\]](#). It has been validated in chronic animal tests with stable performance and safety[\[14\]](#), suggesting robustness. Similarly, academic teams are already focusing on **miniaturizing and integrating components (sensors, stimulators, on-chip models)** into implantable packages[\[9\]](#). The USC group’s plan for a “fully implantable, polymer-based device” within 1–2 years shows a clear path to a deployable prototype[\[9\]](#). These are all hallmarks of a PoC transitioning out of the lab. Importantly, the approach **clearly exceeds previous solutions** – there is currently no alternative treatment that can restore memory loss from conditions like dementia or brain injury. Early human tests achieved up to ~50% improvement on memory tasks that would otherwise be unassisted[\[32\]](#), a benefit far beyond any classical cognitive training or drugs can provide. This validates the value proposition needed for commercialization.
- *Why not Level 5 or above?* The technology is not yet at a stage of widespread competition or commercial deployment. **No memory prosthesis is on the market**, and while one startup (and perhaps one or two consortium efforts) are in the race, we do not yet see “several well-capitalized market actors” with products (Level 5). We have one notable venture-backed company entering first human trials, but no evidence of multiple companies selling devices or strong customer demand – those would correspond to Levels 6–7. In short, the concept has moved from academia into early clinical translation (PoC/prototype phase), but *not* into full product development cycles or scaling manufacturing. Key gaps remain before the next maturity level: for instance, **regulatory approval and large-scale trials are outstanding**, and long-term reliability/cost issues have not been fully ironed out (the implants have only been tested chronically in a handful of animals or short human trial sessions). We also haven’t seen competition between firms or significant private-sector investment beyond initial startups. Achieving Level 5+ will require demonstrating efficacy in broader patient populations (e.g. successful Phase I/II trials of a memory prosthesis for Alzheimer’s or TBI), securing regulatory approvals, and attracting major industry players or partnerships to finance product launch.



None of these has happened yet – thus the **maturity remains at the proven prototype stage (Score 4)**, with a clear path forward but still substantial development to go.

*Sub-component breakdown:* This ART involves a convergence of sub-technologies – neural interface hardware, decoding algorithms, and closed-loop stimulation therapy – each at slightly different maturity, but overall comparable. The **implant hardware** (high-channel neural stimulators) is quite advanced (arguably entering Level 4 on its own, as devices like the 60-channel SNS exist and are nearing clinical testing)[12]. The **memory decoding algorithms and stimulation paradigms** have been validated in research settings (Level 3–4, given human and primate studies showing they work but with room to improve consistency[33][34]). These components function together, and the overall system’s maturity is essentially the sum of its parts. Since all sub-components aim at the same application (restoring episodic memory) and must be integrated, we treat the bundle as a single technology. **Each piece has cleared the “it works in principle” hurdle, and the combined system has been demonstrated in a clinically relevant scenario – thus the integrated maturity is Level 4.** Continued progress (to Level 5) will likely occur as these prototypes enter formal clinical trials and as more companies/institutions invest in competing implementations, which, according to the evidence, is the anticipated next step within the coming decade.

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## Group 5 – Robotics & Physical Autonomy

### ART 05.029 Self-Driving Vehicles

#### ART extraction

- **Primary capability (claimed)**
- Road vehicles that can drive for extended periods on public roads **without continuous human control**, potentially reaching unsupervised “driverless” operation in some operational design domains (ODDs).
- Software-defined driving (perception → prediction → planning/control, or end-to-end learned stacks) that can be validated, monitored, updated, and scaled across fleets.
- Safety-structured autonomy: redundancy, health monitoring, and safe fallback behavior as systems move from supervised to unsupervised operation.
- **Key sub-components / variants**
- Sensor suites and fusion: camera-centric vs. multimodal (camera + radar + lidar/ranging), and redundancy strategies.
- High-precision localization and mapping: HD-map–dependent geofencing vs. reduced-map / perception-first generalization.
- Onboard compute and software stack: modular pipelines vs. end-to-end learned driving; OTA updates and continuous improvement via fleet data.
- Safety engineering and assurance: scenario-based validation, safety case frameworks, SOTIF-oriented hazard reasoning, in-service monitoring.
- Governance & oversight: crash/incident reporting regimes, type approval / deployment permits, liability frameworks.

- Remote operations: remote assistance for rare exceptions vs. direct teleoperation; human factors, latency, and operational boundaries.
- Robustness constraints: extreme weather/visibility degradation; construction/temporary control; cybersecurity.
- **Maturity indicators that “count” as evidence**
- **Commercial deployment with driverless operation** (even if geofenced/limited ODD) and paying customers.
- Publicly documented **regulatory approvals** (deployment permits; authorization to charge fares; type approval / legal frameworks).
- **Measured in-service safety outcomes** (e.g., claims/crash-rate benchmarks, injury/airbag deployment outcomes) with transparent methodology.
- **Operational-scale data** (tens of millions of miles; sustained reporting pipelines; collision reporting volumes).
- **Standards and assurance toolchains** (SOTIF, scenario-based evaluation, safety-case standards, assumptions standards, OTA engineering standards) that enable certification and scaling.

**Evidence (10–20 recent, reliable sources)**

#### **Standards and engineering frameworks for safety, testing, and OTA updates**

1) **Title:** ISO 21448:2022 — *Road vehicles — Safety of the intended functionality (SOTIF)*

**Organization:** ISO[1]

**Venue/type:** International standard (safety assurance guidance for functional insufficiencies)

**Publication date:** June 2022

**Link (URL):** <https://www.iso.org/standard/77490.html>

**What it reports / why it matters:** Defines a structured framework for addressing hazards that arise from functional insufficiencies (especially relevant to perception/decision systems), which is foundational for plausibility and for regulator-ready assurance cases beyond classic functional safety. [2]

2) **Title:** ISO 34502:2022 — *Road vehicles — Test scenarios for automated driving systems — Scenario based safety evaluation framework*

**Organization:** ISO

**Venue/type:** International standard (scenario-based ADS safety evaluation)

**Publication date:** November 2022

**Link (URL):** <https://www.iso.org/standard/78951.html>

**What it reports / why it matters:** Provides a scenario-based safety evaluation process for ADS (notably for limited access highways), directly supporting scalable validation approaches needed to move from pilots to larger deployments. [3]

3) **Title:** ANSI/UL 4600 (Edition 2) — *Evaluation of Autonomous Products*

**Organizations:** ANSI[4]; UL[5]

**Venue/type:** Safety standard (safety case / evaluation standard for autonomous products)

**Publication date:** March 2022 (Published Date)

**Link (URL):**

[https://www.shopulstandards.com/ProductDetail.aspx?productId=UL4600\\_2\\_S\\_2](https://www.shopulstandards.com/ProductDetail.aspx?productId=UL4600_2_S_2)

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**What it reports / why it matters:** The existence of an updated, formal safety-evaluation standard indicates the field is beyond pure R&D and is aligning around deployability artifacts (safety cases, hazard coverage, assessment expectations). [6]

4) **Title:** IEEE 2846-2022 — *IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems*

**Organization:** IEEE[7]

**Venue/type:** Standard (assumptions/foreseeable scenarios for safety-related ADS models)

**Publication date:** April 2022

**Link (URL):** <https://standards.ieee.org/ieee/2846/10831/>

**What it reports / why it matters:** Codifies a minimum set of assumptions and reasonably foreseeable scenarios that must be considered in safety-related ADS models—an important step toward verifiable, auditable safety arguments at scale. [8]

5) **Title:** ISO 24089:2023 — *Road vehicles — Software update engineering*

**Organization:** ISO

**Venue/type:** International standard (process requirements/recommendations for vehicle software updates)

**Publication date:** February 2023

**Link (URL):** <https://www.iso.org/standard/77796.html>

**What it reports / why it matters:** Establishes software update engineering requirements spanning organizations and systems, supporting the OTA-driven development path described in the ART and linking maturity to controlled, traceable field updates. [9]

#### **Government and regulatory evidence for market-readiness and oversight**

6) **Title:** *Connected & Automated Mobility 2025: Realising the benefits of self-driving vehicles in the UK*

**Organization:** UK Department for Transport[10] (presented to Parliament)

**Venue/type:** Government report/roadmap

**Publication date:** August 2022

**Link (URL):**

<https://assets.publishing.service.gov.uk/media/62ff438c8fa8f504cdec92df/cam-2025-realising-benefits-self-driving-vehicles.pdf>

**What it reports / why it matters:** Summarizes UK policy, timelines, and international regulatory alignment, including references to ALKS regulatory evolution and cybersecurity/software-update regulatory focus—evidence of institutionalization beyond lab prototypes. [11]

7) **Title:** *Automated Vehicles Act 2024 — Explanatory Notes*

**Organization:** United Kingdom[12] (Explanatory Notes prepared by Department for Transport)

**Venue/type:** Government legal framework documentation

**Publication date:** May 2024 (Royal Assent referenced as 20 May 2024)

**Link (URL):**

[https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen\\_20240010\\_en.pdf](https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen_20240010_en.pdf)

**What it reports / why it matters:** Documents a modern legal framework for regulating automated vehicles, supporting maturity via clarified authorization concepts, operational regulation, and incident/marketing restriction mechanisms. [13]

8) **Title:** CPUC approves permits for Cruise and Waymo to charge fares for driverless passenger service in San Francisco

**Organization:** California Public Utilities Commission[14]

**Venue/type:** Government regulatory approval (commercial driverless passenger service authorization)

**Publication date:** August 2023

**Link (URL):** <https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-approves-permits-for-cruise-and-waymo-to-charge-fares-for-passenger-service-in-sf-2023>

**What it reports / why it matters:** Confirms commercial driverless ride service authorization (charge fares, any time of day) for Cruise[15] and Waymo[16] in San Francisco[17]—strong maturity evidence that the technology is operationally deployed under regulator conditions (though still ODD-bounded). [18]

9) **Title:** California DMV approves Mercedes-Benz automated driving system for certain highways and conditions

**Organization:** California Department of Motor Vehicles[19]

**Venue/type:** Government deployment permit / regulatory approval

**Publication date:** June 2023

**Link (URL):** <https://www.dmv.ca.gov/portal/news-and-media/california-dmv-approves-mercedes-benz-automated-driving-system-for-certain-highways-and-conditions/>

**What it reports / why it matters:** Grants a deployment permit allowing Mercedes-Benz[20] to commercially offer a Level 3 system on designated highways with explicit ODD limits (e.g., daylight, ≤40 mph, excludes heavy rain/fog/construction zones), demonstrating regulated commercialization and the persistence of environmental constraints. [21]

10) **Title:** California DMV — Autonomous Vehicle Collision Reports (public reporting portal)

**Organization:** California DMV

**Venue/type:** Government dataset/registry (mandatory collision reporting)

**Publication date:** February 2026 (page states “As of February 20, 2026”)

**Link (URL):** <https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/autonomous-vehicle-collision-reports/>

**What it reports / why it matters:** Indicates collision reporting obligations and the scale of reported real-world operations (“939 Autonomous Vehicle Collision Reports” as of Feb 20, 2026), supporting maturity analysis via sustained, institutionalized incident reporting pipelines. [22]

11) **Title:** Third Amended Standing General Order 2021-01 — Incident reporting for ADS and Level 2 ADAS

**Organization:** National Highway Traffic Safety Administration (NHTSA)[23]

**Venue/type:** Government order / reporting requirement

**Publication date:** April 2025 (dated April 24, 2025; effective June 16, 2025)

**Link (URL):** [https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01\\_2025.pdf](https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01_2025.pdf)

**What it reports / why it matters:** Formalizes and updates mandatory incident/crash reporting requirements for ADS and Level 2 systems, which is a key maturity signal: regulators are actively managing operational risk with data-driven oversight rather than treating AVs as purely experimental. [24]

12) **Title:** Report to Congress (Biannual) — NHTSA research and rulemaking activities on vehicles equipped with ADS

**Organization:** NHTSA (USDOT)

**Venue/type:** Government report (rulemaking + research status update)

**Publication date:** July 2025

**Link (URL):** <https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-07/report-congress-research-rulemaking-automated-driving-systems-july-2025-tag.pdf>

**What it reports / why it matters:** Shows active federal efforts to adapt oversight (e.g., reporting amendments, exemption program changes, rulemaking initiatives) and to develop assessment methodologies—evidence that commercialization is “real enough” to merit continuous regulatory infrastructure. [25]

13) **Title:** Understanding Safety Challenges of Vehicles Equipped with ADS — Analysis of ADS Disengagements

**Organization:** U.S. Department of Transportation (USDOT)[26] (HASS COE)

**Authors:** Mubassira Khan[27] et al.

**Venue/type:** Government technical report

**Publication date:** August 2024

**Link (URL):** [https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS\\_COE\\_Understanding\\_Safety\\_Challenges\\_of\\_Vehicles\\_Equipped\\_with\\_ADS\\_Aug2024.pdf](https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS_COE_Understanding_Safety_Challenges_of_Vehicles_Equipped_with_ADS_Aug2024.pdf)

**What it reports / why it matters:** Analyzes California disengagement reports (2022–2023) and notes reporting inconsistency (e.g., distinct descriptions in only ~4% of reports) and that human drivers initiated disengagements in a large share of cases—evidence that scaling validation and consistent reporting remain maturity bottlenecks. [28]

#### Fielded-system safety outcomes and scaling evidence

14) **Title:** Comparative safety performance of autonomous- and human drivers: a real-world case study of the Waymo Driver

**Authors/organizations:** Luigi Di Lillo[29] et al.; Swiss Re[30] + Waymo (industry/academia affiliations listed)

**Venue/type:** Peer-reviewed paper (Heliyon)

**Publication date:** July 2024

**Link (URL):** <https://pubmed.ncbi.nlm.nih.gov/39114012/>

**What it reports / why it matters:** Proposes and demonstrates a claims-based comparative safety method using large insurance baselines (e.g., hundreds of thousands of claims and large driving exposure) and reports that the Waymo Driver improves safety vs. calibrated human baselines—direct plausibility/maturity evidence from real deployments rather than simulations alone. [31]

15) **Title:** Comparison of Waymo Rider-Only crash rates by crash type to human benchmarks at 56.7 million miles

**Authors/organization:** Kristofer D Kusano[32] et al.

**Venue/type:** Peer-reviewed paper (Traffic Injury Prevention)

**Publication date:** Epub May 2025 (journal issue Oct 2025)

**Link (URL):** <https://pubmed.ncbi.nlm.nih.gov/40378124/>

**What it reports / why it matters:** Uses 56.7 million rider-only miles (through end of Jan 2025) and finds statistically significant crash-rate reductions vs matched human benchmarks

across outcomes (e.g., notable reductions for vehicle-to-vehicle intersection crashes), indicating an at-scale driverless service with measurable safety performance. [33]

### **Operational safety cases, regulation-compliance practice, and edge-condition limits**

16) **Title:** Assuring Regulatory Compliance of Connected and Automated Vehicles during their Operational Lifetime

**Organization:** CITA[34] / IAMTS (whitepaper series)

**Venue/type:** Technical whitepaper / best-practice report (industry standards/testing ecosystem)

**Publication date:** April 2023 (issued 2023-04-21)

**Link (URL):** [https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304\\_V1.1.pdf](https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304_V1.1.pdf)

**What it reports / why it matters:** Discusses how UNECE regulation scope (including ALKS changes) and cybersecurity/software-update management requirements (R155/R156) affect lifecycle compliance, and emphasizes multi-pillar validation (test track, real world, simulation, in-service monitoring)—evidence of maturation toward lifecycle governance. [35]

17) **Title:** UL 4600: What to Include in an Autonomous Vehicle Safety Case

**Author:** Philip Koopman[36]

**Venue/type:** Peer-reviewed technical article (IEEE Computer)

**Publication date:** May 2023

**Link (URL):**

[https://users.ece.cmu.edu/~koopman/pubs/Koopman2023\\_UL4600\\_Safety\\_Case.pdf](https://users.ece.cmu.edu/~koopman/pubs/Koopman2023_UL4600_Safety_Case.pdf)

**What it reports / why it matters:** Explains why road testing alone cannot scale to the assurance levels needed for driverless deployment and frames UL 4600 as a “safety case” umbrella—supporting the ART’s claim that formalized redundancy, hazard coverage, and lifecycle safety monitoring are essential to maturity. [37]

18) **Title:** Performance Verification of Autonomous Driving LiDAR Sensors under Rainfall Conditions in Darkroom

**Authors/organization:** Jaeryun Choe[38] et al. (Korea Conformity Laboratories affiliation shown)

**Venue/type:** Peer-reviewed experimental paper (Sensors)

**Publication date:** December 2023 (Published 19 Dec 2023)

**Link (URL):** <https://www.mdpi.com/1424-8220/24/1/14>

**What it reports / why it matters:** Quantifies LiDAR behavior under controlled rainfall conditions (e.g., 0–40 mm/h; 10–30 m) and supports the ART’s constraint claim that adverse weather/visibility remains a technical limiter—important for plausibility boundaries and ODD definition. [39]

19) **Title:** A Roadmap Towards Remote Assistance: Outcomes from Multidisciplinary Workshop at the 2023 Intelligent Vehicles Symposium

**Repository/organization:** German Aerospace Center (DLR)[40] eLib record

**Authors:** Maytheewat Aramrattana[41] et al.

**Venue/type:** Peer-reviewed conference paper (Springer CCIS / HCI International 2024)

**Publication date:** June 2024 (DLR eLib “Date: 8 June 2024”)

**Link (URL):** <https://elib.dlr.de/204846/>



**What it reports / why it matters:** Identifies remote assistance as an event-driven support layer (high-level guidance rather than continuous driving) and outlines research gaps in human factors, remote station design, and HAV design—evidence that remote assistance remains part of practical deployments, consistent with the ART description. [42]

20) **Title:** Improving road user perception in adverse weather: An augmented HMI for remote assistants of automated vehicles

**Author:** Andreas Schrank[43] et al.

**Venue/type:** Peer-reviewed experimental paper (Transportation Research Part F; open access)

**Publication date:** August 2025

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S1369847825001810>

**What it reports / why it matters:** Demonstrates via controlled experiment (34 participants; fog varied) that augmenting remote-assistance interfaces with sensor-derived information can reduce collisions and improve situation awareness—directly relevant to the ART’s claim that remote assistance may remain necessary for rare edge cases, especially in poor visibility. [44]

21) **Title:** AI Safety Assurance for Automated Vehicles: A Survey on Research, Standardization, Regulation

**Author:** Lars Ullrich[45] et al.

**Venue/type:** Preprint (arXiv) with journal-reference metadata

**Publication date:** April 2025 (arXiv submission date)

**Link (URL):** <https://arxiv.org/abs/2504.18328>

**What it reports / why it matters:** Synthesizes the state of AI safety assurance for automated vehicles across technical research and standards/regulation, highlighting that safety assurance for increasingly learned stacks remains an active, unresolved maturity barrier even as deployments expand. [46]

**Maturity score (1–7) and reasoning**

**Final maturity score: 6 [47]**

**Why level 6 fits, with explicit rubric mapping**

**What evidence rules out levels 1–4 (theory, lab confirmation, lab prototype, PoC only):**

Commercial and regulated deployments exist and are being evaluated with real-world safety and incident data. California’s regulator explicitly approved driverless passenger service with fare-charging authorizations in San Francisco (i.e., not merely a test) [18], and California’s DMV granted a deployment permit enabling consumer-facing Level 3 operation (within defined highway/condition constraints) [21]. Moreover, peer-reviewed studies evaluate deployed driverless operations using claims/crash-rate methodologies at tens of millions of miles scale, which goes well beyond PoC demonstrations. [48]

**What evidence rules out level 5 (post-PoC, still primarily “finishing production prototype”):**

Level 5 would be consistent with multiple actors racing toward production prototypes, but level 6 requires actual delivery to customers. The CPUC authorization is specifically about commercial passenger service with driverless vehicles (service delivery), [18] and the crash-



rate study explicitly analyzes 56.7 million rider-only miles through January 2025, implying sustained, real-world driverless operations rather than a limited pilot. [33]

### **Why the evidence supports level 6 (products delivered; scaling; expanding governance):**

- **Products/services delivered:** Driverless passenger service authorized to charge fares in a major city; regulated Level 3 system permitted for consumer use in defined highway conditions. [49]
- **Growing operational footprint & institutional oversight:** California's collision reporting system shows an extensive body of reported incidents over time (939 collision reports received as of Feb 20, 2026), indicating ongoing operations under a reporting regime rather than isolated demos. [22]
- **Measured performance at scale:** Peer-reviewed work compares deployed driverless operations against human benchmarks using insurance claims and crash-rate typologies across tens of millions of driverless miles. [48]
- **Regulatory scaffolding for scaling:** Federal crash/incident reporting requirements (Third Amended SGO) and NHTSA's ongoing research/rulemaking reports show that scaling is coupled to evolving, formal oversight pathways. [50]

### **What is still missing to justify level 7**

Level 7 requires that **competing products are being delivered and customer demand is rising**, with broad competition and growth financing across a wide clientele. The evidence above supports real deployments, but also shows that: - Operations and commercialization remain **ODD-limited** (explicit restrictions in the Level 3 deployment permit; and continuing attention to scenario-based validation, reporting, and safety case development). [51]

- **Edge-case handling and adverse weather** are still active constraints (LiDAR degradation under rainfall; remote assistance and human factors research for poor visibility), indicating incomplete robustness for broad, unconstrained scaling. [52]
- Reporting/validation infrastructure is still being refined (e.g., disengagement narrative sparsity and inconsistent reporting noted by USDOT's HASS COE), which is typical of systems not yet in ubiquitous, commodity-scale deployment. [28]

Together, these suggest the ecosystem is not yet at the "widely delivered competing products with clearly rising demand" threshold implied by level 7, especially for *routine autonomy across wide regions and conditions*.

### **Sub-component maturity breakdown and aggregation**

- **Geofenced Level 4 robotaxi services (driverless, curated ODDs):** ~6
- Supported by commercial authorization and large-scale safety analysis at tens of millions of driverless miles. [53]
- **Highway Level 3 consumer availability (narrow ODD, strict conditions):** ~6
- Supported by deployment permitting that explicitly allows public offering under defined conditions (not just testing). [21]
- **Safety assurance / validation toolchain maturity (standards + reporting regimes):** ~6
- Strong standardization (SOTIF, scenario-based evaluation, safety case standards, modeling assumptions) and mandatory incident reporting; still evolving, but clearly institutionalized. [54]

- **Robustness in extreme weather & remote exception handling:** ~4–5
- Active research shows performance limits in poor visibility and ongoing dependencies on remote assistance design and procedures, suggesting incomplete robustness for broad ODD autonomy. [52]
- **OTA-driven scaling processes (engineering formalization):** ~6
- ISO 24089:2023 indicates mature process standardization for software updates, a prerequisite for safe fleet-scale iteration. [9]

**Aggregation approach:** This ART is a bundle where the core “driverless road vehicle” functionality is shared across variants but deployed unevenly by ODD and vehicle class. The score uses a **practical weighted view**: commercially delivered driverless services and regulated Level 3 offerings justify level 6, while weather/edge-case robustness and broad-area generalization remain below the level-7 threshold. [55]

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[1] [5] [9] [15] <https://www.iso.org/standard/77796.html>

<https://www.iso.org/standard/77796.html>

[2] [29] [32] [54] <https://www.iso.org/standard/77490.html>

<https://www.iso.org/standard/77490.html>

[3] [30] <https://www.iso.org/standard/78951.html>

<https://www.iso.org/standard/78951.html>

[4] [23] [34] [39] [52] <https://www.mdpi.com/1424-8220/24/1/14>

<https://www.mdpi.com/1424-8220/24/1/14>

[6] [20]

[https://www.shopulstandards.com/ProductDetail.aspx?productId=UL4600\\_2\\_S\\_20220315](https://www.shopulstandards.com/ProductDetail.aspx?productId=UL4600_2_S_20220315)

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[7] [38] [46] <https://arxiv.org/abs/2504.18328>

<https://arxiv.org/abs/2504.18328>

[8] <https://standards.ieee.org/ieee/2846/10831/>

<https://standards.ieee.org/ieee/2846/10831/>

[10] [11] [41]

<https://assets.publishing.service.gov.uk/media/62ff438c8fa8f504cdec92df/cam-2025-realising-benefits-self-driving-vehicles.pdf>

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[12] [14] [18] [19] [27] [47] [49] [53] [55] <https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-approves-permits-for-cruise-and-waymo-to-charge-fares-for-passenger-service-in-sf-2023>

<https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-approves-permits-for-cruise-and-waymo-to-charge-fares-for-passenger-service-in-sf-2023>

[13] [https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen\\_20240010\\_en.pdf](https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen_20240010_en.pdf)

[https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen\\_20240010\\_en.pdf](https://www.legislation.gov.uk/ukpga/2024/10/pdfs/ukpgaen_20240010_en.pdf)

[16] [25] <https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-07/report-congress-research-rulemaking-automated-driving-systems-july-2025-tag.pdf>

<https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-07/report-congress-research-rulemaking-automated-driving-systems-july-2025-tag.pdf>

[17] [21] [43] [51] <https://www.dmv.ca.gov/portal/news-and-media/california-dmv-approves-mercedes-benz-automated-driving-system-for-certain-highways-and-conditions/>

<https://www.dmv.ca.gov/portal/news-and-media/california-dmv-approves-mercedes-benz-automated-driving-system-for-certain-highways-and-conditions/>

[22] <https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/autonomous-vehicle-collision-reports/>

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[24] [40] [50] [https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01\\_2025.pdf](https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01_2025.pdf)

[https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01\\_2025.pdf](https://www.nhtsa.gov/sites/nhtsa.gov/files/2025-04/third-amended-SGO-2021-01_2025.pdf)

[26] [33] [48] <https://pubmed.ncbi.nlm.nih.gov/40378124/>

<https://pubmed.ncbi.nlm.nih.gov/40378124/>

[28] [36] [https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS\\_COE\\_Understanding\\_Safety\\_Challenges\\_of\\_Vehicles\\_Equipped\\_with\\_ADS\\_Aug2024.pdf](https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS_COE_Understanding_Safety_Challenges_of_Vehicles_Equipped_with_ADS_Aug2024.pdf)

[https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS\\_COE\\_Understanding\\_Safety\\_Challenges\\_of\\_Vehicles\\_Equipped\\_with\\_ADS\\_Aug2024.pdf](https://www.transportation.gov/sites/dot.gov/files/2024-08/HASS_COE_Understanding_Safety_Challenges_of_Vehicles_Equipped_with_ADS_Aug2024.pdf)

[31] <https://pubmed.ncbi.nlm.nih.gov/39114012/>

<https://pubmed.ncbi.nlm.nih.gov/39114012/>

[35] [https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304\\_V1.1.pdf](https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304_V1.1.pdf)

[https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304\\_V1.1.pdf](https://citainsp.org/wp-content/uploads/2023/04/IAMTS0004202304_V1.1.pdf)

[37] [https://users.ece.cmu.edu/~koopman/pubs/Koopman2023\\_UL4600\\_Safety\\_Case.pdf](https://users.ece.cmu.edu/~koopman/pubs/Koopman2023_UL4600_Safety_Case.pdf)

[https://users.ece.cmu.edu/~koopman/pubs/Koopman2023\\_UL4600\\_Safety\\_Case.pdf](https://users.ece.cmu.edu/~koopman/pubs/Koopman2023_UL4600_Safety_Case.pdf)

[42] [45] <https://elib.dlr.de/204846/>

<https://elib.dlr.de/204846/>

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## ART 05.030 Drone Swarms & Aerial Robots

### 1. ART extraction

**A. Primary capability:** Enabling autonomous *drone swarms* – fleets of UAVs that coordinate in real time to cover large, complex 3D environments without fixed infrastructure. Such swarms can be rapidly deployed and self-navigate with minimal human control, achieving tasks more flexibly and robustly than any single large drone.

### B. Key sub-components/variants:

- **Multi-UAV coordination algorithms:** Methods for real-time sharing of maps, sensor data, and tasks among drones, with dynamic task allocation and collision avoidance (each drone adjusting its path based on others).
- **Autonomous navigation & perception:** Onboard vision/range sensors and localization enabling each drone to avoid obstacles and operate without GPS or external markers (vital for cluttered or GPS-denied spaces).
- **Heterogeneous drone fleets:** Integration of different-sized aerial robots or even mixed air/ground/underwater vehicles working together, including high-altitude “mothership” drones guiding lower units and varied sensor payloads on different drones.
- **Communication networks:** Reliable, secure links (mesh networks, 5G, etc.) for inter-drone communication and swarm command, including infrastructure for beyond-visual-line-of-sight (BVLOS) control and data sharing.
- **Human-swarm interfaces & fail-safes:** High-level supervisory control systems for one operator to oversee many drones (defining objectives and boundaries), with autonomous fail-safes to handle communication loss, drone failures, and comply with airspace safety rules.
- **Power and endurance management:** Strategies to mitigate limited battery life (e.g. automated recharging/docking, optimal task sequencing, use of long-endurance nodes) so that swarms can persist on long missions despite individual drones’ short flight times.
- **Regulatory compliance frameworks:** Operational protocols and emerging regulatory provisions that allow swarm deployments (e.g. waivers for one-to-many drone control) while ensuring public safety and privacy in civilian airspace.

**C. Maturity indicators:** Key evidence of progress would include **field trials and pilot deployments** of multi-drone swarms performing useful tasks (e.g. disaster response, surveillance, mapping) under real-world conditions. **Proof-of-concept demonstrations** showing multiple drones autonomously coordinating (with minimal human input) to achieve objectives – especially in GPS-denied or hazardous environments – would signal high plausibility. **Prototype systems and products** reaching end-users (e.g. military exercises, industrial inspections) and **regulatory milestones** (such as waivers or new rules enabling

swarm operation) indicate rising maturity. Also, the emergence of **multiple well-funded companies or programs** competing in this space, and **metrics** like number of drones in a coordinated mission, autonomy in complex environments, or one-operator-to-many-drone control ratio, would demonstrate both technical feasibility and steps toward scalable deployment.

## 2. Evidence (10–20 recent, reliable sources)

- **Zhou et al., Zhejiang Univ. – Science Robotics (May 2022): “Swarm of micro flying robots in the wild.” (Peer-reviewed)** Demonstrated a swarm of palm-sized drones autonomously navigating a dense bamboo forest with on-board sensing and no external infrastructure. A new trajectory planner enabled inter-drone collision avoidance and obstacle evasion in real time, achieving complex 3D flight as a coordinated group – a task previously infeasible for swarms in such cluttered environments[1][2]. This real-world field trial confirms the plausibility of self-directed drone swarms operating in GPS-denied, hazardous terrain.
- **Gui et al., Def. Innov. Inst. (China) – MDPI Drones 7(6):337 (May 2023): “Decentralized Multi-UAV Cooperative Exploration Using Dynamic Centroid-Based Area Partition.” (Peer-reviewed)** Proposes an algorithm for a team of UAVs to efficiently explore unknown areas by dynamically partitioning the 3D space among drones. Each drone autonomously maps its region and shares minimal data (poses/weights) over a 5G Wi-Fi network. In simulations and a **3-UAV indoor experiment**, the method reduced redundant coverage and improved collective mapping speed[3][4]. The successful practical trial of three drones collaborating in real time to map an area demonstrates a solved sub-problem (coordinated exploration) and serves as a proof-of-concept for swarm autonomy in search-and-rescue scenarios.
- **U.S. GAO – Science & Tech Spotlight: Drone Swarm Technologies (Sep 2023): (Government report)** A high-level assessment of drone swarms’ status, noting that algorithms and AI have recently improved swarm decision-making, and swarms of “at least three and up to thousands” of drones coordinating with limited human control are now technically feasible[5][6]. However, GAO emphasizes that current real-world use of swarms is still very limited – mostly constrained to simple, pre-planned tasks like entertainment light shows – and more dynamic missions (e.g. real-time target tracking with many drones) remain challenging. The report also flags that **regulations lag behind**: as of now, U.S. federal rules don’t allow one operator to control multiple drones without a waiver[7]. This highlights that while the science is proven and prototypes exist, routine deployment is held back by safety, security, and regulatory hurdles rather than fundamental technology gaps.
- **NASA ESTO & Clemson Univ. – FireSense Project Overview (2022): “AI-Enabled Drone Swarms for Fire Detection, Mapping, and Modeling.” (Agency program announcement)** Describes a newly funded NASA project to develop heterogeneous drone swarms for wildfire monitoring[8]. The planned system uses a **hierarchical fleet** – high-altitude UAVs as command relays and many lower UAVs with thermal and visual sensors – to continuously map fires and predict spread. It focuses on on-board AI for real-time collaborative perception (to overcome bandwidth limits) and will create a **digital twin** environment for testing swarm strategies[8][9]. The project’s goals (e.g. multi-UAV autonomous coverage of a wildfire over long durations with minimal human input) indicate that major research agencies find the concept plausible and are actively working to mature it. This is evidence of accelerating progress towards field-ready swarm systems, with emphasis on software updates, simulation training, and integration into existing communication infrastructure.
- **VTT (Finland) – FireMan Project News (Aug 2022): “Using drone swarms to monitor and combat future wildfires.” (Research consortium update)** Reports on a Finnish R&D project

developing a **semi-autonomous swarm** for wildfire surveillance. Early simulations show drones can collectively encircle a fire and adapt their formation based on wind and fire spread – for example, sharing positions and automatically spacing themselves into an elongated ellipse downwind to avoid hazardous smoke[10]. Initial test flights in 2022 validated basic capabilities, and a full multi-drone demo in a controlled burn is planned for 2024[11][12]. Researchers aim to allow **one firefighter to supervise multiple drones**: “one pilot to operate several drones with the support of swarm intelligence,” rather than today’s one-drone-per-pilot paradigm[13]. This international effort underscores both the promise (faster, safer situational awareness for wildfire response) and the remaining work in human-swarm interfaces and trust. It also suggests that within a few years, such systems could transition from prototype to real deployments in public safety.

- **Wu, Rastgaar, Mahmoudian – IFAC-PapersOnLine Vol.58(20) (2024): “Heterogeneous Multi-Robot (UAV-USV-AUV) Collaborative Exploration with Energy Replenishment.” (Peer-reviewed)** Explores **heterogeneous swarm coordination**, extending aerial swarms to work jointly with unmanned surface and underwater vehicles. The authors present a dynamic programming approach to decide the optimal mix of drones, surface vessels, and underwater drones for a mission, given each platform’s speed and battery/endurance (including mobile charging stations)[14]. A genetic algorithm then plans coverage paths for the multi-vehicle team, and Dijkstra’s algorithm helps route them around obstacles (like islands or reefs) to ensure UAVs can periodically recharge without human retrieval[14]. Although primarily a simulation study, it indicates that *systems-of-systems* thinking (air, sea, sub-sea robots in concert) is already at play. This broadens the value proposition of drone swarms (e.g. a UAV swarm relaying data to an autonomous boat) and shows technical feasibility of coordinating different robot types – a capability likely necessary for truly scalable, long-term autonomous operations in the next decade.
- **UK Ministry of Defence (Dstl) – Press Release (May 2023): “World first as UK hosts inaugural AUKUS AI and autonomy trial.” (Official trial report)** Describes a **tri-nation field trial** where AI-enabled drones from the UK, US, and Australia were networked into a collaborative swarm that autonomously detected and tracked military targets in real time[15]. Notably, the swarm AI was flexible: during the exercise, the drones’ machine-learning models were *re-trained on the fly* and models were shared among partner nations’ drones, a world-first achievement[15]. This indicates a high level of swarm autonomy and adaptability in an operational environment. The success of this trial – part of the AUKUS defense pact’s advanced capabilities program – demonstrates rapid progress toward militarily viable swarms. It also highlights that multiple countries are now actively testing swarm robotics for practical use, which implies both technological maturity (at least at prototype level) and strong institutional investment.
- **Auterion (industry) – Autonomy Global News (Jan 2026): “Swarm Forge: Auterion Powers First Kinetic Live Swarm Strike on US Soil.” (Vendor technical news)** Documents a landmark **live-fire demonstration** conducted with the U.S. DoD: a single human operator successfully commanded a swarm of 3 autonomous drones to simultaneously strike 3 separate targets with explosive warheads[16]. The drones, equipped with Auterion’s open-source “Skynode” autopilot and swarm AI, coordinated their flight paths, avoided conflicts, and hit all targets under software control – proving a true “one-to-many” combat capability in a realistic scenario[16][17]. The demonstration validates that one operator can wield a coordinated attack by multiple drones, a clear advantage over the traditional one-drone-per-pilot model. In the same report, Auterion’s CEO notes “the one-pilot, one-drone model is obsolete”[18], and it’s revealed that **over 30,000** of Auterion’s swarm-capable autopilot kits have been shipped to Ukraine[19], indicating scaled deployment. Together, this is strong evidence of both engineering feasibility and a fast-moving path to real-world use, at least in defense contexts.



- Lockheed Martin & Verizon – 5G Drone Swarm Trials (C4ISRNet, Sep 2022): (Industry/Gov test report)** Describes joint tests where a *swarm of drones* equipped with ISR (intelligence, surveillance, reconnaissance) sensors were linked via **5G networks**[20]. In May and Sept 2022 demos, the drones were able to securely share real-time video and signals data over a private/public 5G, and an AI analytics system fused the data to detect and geolocate very low-power radio frequencies (simulating enemy communications or jamming devices)[20][21]. Army and Air Force observers noted the ability of 5G to handle the high bandwidth and low latency needed for swarm coordination. This demonstrates that existing telecom infrastructure (5G) can be leveraged to network drone swarms, enhancing their sensing range and reliability. It also showed a concrete battlefield application (electronic surveillance) where a multi-drone system outperforms a single platform. The success of these trials is a positive sign for the *scalability* of swarms – suggesting that as 5G/6G networks roll out, swarms could operate with robust connectivity and without deploying bespoke communication hardware.
- Shield AI – Tech Demo via AFWERX (Potomac Officers Club, Aug 2023): (Industry press)** Reports that Shield AI's autonomy software (*Hivemind*) piloted a **3-drone team of “V-BAT” UAVs** in a demonstration for the U.S. Air Force[22]. The drones worked together to detect, identify, and track objects during a simulated wildfire scenario, without GPS or constant comms – showcasing multi-UAV teamwork in a communications-denied environment[22]. This demo was the capstone of a U.S. AFRL program, and according to Shield AI it put their system on track for operational deployment of drone swarms by 2024. Shield AI (a well-funded startup) and others like it are in a competitive race to deliver deployable swarms for military use. The fact that the **same autonomy** (*Hivemind*) has also been flown on different platforms including quadcopters and even a fighter jet, reflects a push toward software-defined capabilities for swarms. This is evidence that multiple actors are refining the technology from prototype stage toward field-ready products, indicating a maturation from experimental to pre-production phase.
- Exyn Technologies – Field Deployment Case (Aug 2022): “Autonomous Cavity Monitoring in a German Salt Mine.” (Vendor field report)** Documents a commercial *multi-mission autonomous drone deployment* in an operating mine. Over three days, Exyn's drones flew **multiple fully autonomous flights** into large, hazardous underground cavities to map them, capturing high-resolution 3D point clouds **in a fraction of the time** of conventional survey methods[23]. Critically, this was done with no GPS and no human pilot in the mine – the drones made all navigation decisions and avoided obstacles (e.g. wires, narrow openings) on their own[24]. While these flights were one drone at a time (not a simultaneous swarm), Exyn's system is designed for one operator to supervise sequential autonomous missions. The success illustrates the growing *real-world adoption* of high-autonomy aerial robots in industry. It validates that the autonomy and sensor tech developed for swarms also delivers value with single drones today (e.g. improving safety and efficiency in mapping), and lays groundwork for near-future scenarios where **multiple such drones could operate concurrently** to further boost productivity.

### 3. Maturity score (1–7) and reasoning

**A) Maturity Score: 5** (on the 1–7 scale for the overall “Drone Swarms & Aerial Robots” technology bundle).

**B) Justification:** The evidence shows that drone swarm technology has progressed well beyond theoretical models (Levels 1–2) and lab prototypes (Level 3). **Working prototypes and PoCs (Level 4)** have been **successfully demonstrated in demanding real-world environments** – for example, fully autonomous multi-drone navigation through a dense



forest[1][2], and a 3-UAV team performing target searches without GPS[22]. These achievements prove that the once-“blocking” challenges (like inter-drone collision avoidance, decentralized mapping, etc.) can be solved in practice, meeting core functionality requirements. Furthermore, multiple projects have shown clear **benefit over single-unit operations**, such as faster area coverage and reduced risk to humans[23]. This satisfies much of Level 4.

Importantly, we now see **several well-capitalized actors racing to develop production-grade swarm systems**, which is characteristic of **Level 5** maturity. Evidence for this includes: **competition in the defense sector** (e.g. Shield AI, Auterion, Lockheed, and others are actively testing swarm capabilities[16][22]) and **significant government programs** (NASA, Dstl, DARPA, etc.) funding swarm R&D[8][15]. There are also initial signs of commercialization – for instance, Auterion shipping thousands of swarm-enabled drone kits to an active conflict[19], and Exyn selling autonomous drones to mining clients – indicating that prototype solutions are moving towards deployment and scaling. The **pace of progress is rapid** and recent: the first live-fire swarm strike was achieved just now in 2026[16], and multiple field trials in 2022–2023 broke new ground (AI swarms re-planning on the fly, multi-UAV wildfire monitoring, etc.). All this rules out Level 4: we are *beyond* a single proven PoC; rather, there’s momentum in turning prototypes into operational products.

At the same time, the technology hasn’t yet reached full **Level 6** commercialization where products are widely delivered to many customers with growing demand. Current deployments are **niche or pilot** in nature – e.g. military experiments, one-off emergency response demos, or confined industrial use with one-drone-at-a-time. Civilian regulatory constraints (one operator per swarm requires special waivers[7]) and unresolved issues like limited endurance still **prevent mass rollout** or routine everyday use. We have not seen broad adoption across industries or truly “increasing amounts” of swarm units purchased commercially (outside military urgent needs). Thus, the evidence does *not* yet show multiple competing off-the-shelf swarm products being adopted at scale – which would be needed for Level 6.

In summary, **Level 5** best fits the overall maturity: **drone swarms are in the late-prototype to pre-production stage**, with intense development activity and early customers in specialized markets, but not yet a ubiquitous product.

**C) Sub-component variation:** This ART encompasses several aspects (military swarms, civilian autonomous inspection drones, heterogeneity, etc.) that are maturing at slightly different paces. For instance:

- *Military lethal drone swarms* – rapidly advancing with substantial investment, arguably approaching early Level 6. The live swarm strike demo and large orders for swarm tech[19] show that defense customers are beginning to acquire these capabilities now.
- *Civilian swarm applications* (like firefighting, infrastructure monitoring) – closer to Level 4–5. We see convincing prototypes (e.g. the FireMan project’s semi-autonomous wildfire scouting in tests[13][25]), but regular commercial services are still a few years out, awaiting regulatory and safety milestones.
- *Enabling technologies* (autonomy algorithms, comm networks) – largely at Level 5: recent breakthroughs (e.g. robust decentralized mapping[3], 5G-enabled control[20])

solved key hurdles and are being integrated into trial systems now, but further refinement and validation are in progress.

Given these differences, **the chosen score 5 reflects an average** of the bundle. The core functionality – autonomous multi-drone coordination – is essentially proven (warranting >4), and in certain domains we see near-term transition to product delivery (pushing toward 6). But until the technology achieves routine use under broad conditions (which would merit 6) across its variants, Level 5 is the appropriate overall assessment. This level is reinforced by strong evidence of ongoing fast-paced development and competitive investment, which are hallmarks of a technology on the cusp of widespread commercialization.

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<https://pubmed.ncbi.nlm.nih.gov/35507682/>

[3] [4] Decentralized Multi-UAV Cooperative Exploration Using Dynamic Centroid-Based Area Partition | MDPI

<https://www.mdpi.com/2504-446X/7/6/337>

[5] [6] [7] GAO-23-106930, SCIENCE & TECH SPOTLIGHT: DRONE SWARM TECHNOLOGIES

<https://www.gao.gov/assets/gao-23-106930.pdf>

[8] [9] AI-Enabled Drone Swarms for Fire Detection, Mapping, and Modeling - NASA Earth Science and Technology Office

<https://esto.nasa.gov/firetech/ai-enabled-drone-swarms-for-fire-detection-mapping-and-modeling/>

[10] [11] [12] [13] [25] Using drone swarms to monitor and combat future wildfires — FCAI

<https://fc.ai/news/2022/8/15/using-drone-swarms-to-monitor-and-combat-future-wildfires>

[14] Heterogeneous Multi-Robot (UAV-USV-AUV) Collaborative Exploration with Energy Replenishment - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S2405896324018020>

[15] World first as UK hosts inaugural AUKUS AI and autonomy trial - GOV.UK

<https://www.gov.uk/government/news/world-first-as-uk-hosts-inaugural-aukus-ai-and-autonomy-trial>

[16] [17] [18] [19] Swarm Forge Program – Auterion Powers First Kinetic Live Swarm Strike on US Soil - Autonomy Global

<https://www.autonomyglobal.co/swarm-forge-program-auterion-powers-first-kinetic-live-swarm-strike-on-us-soil/>

[20] [21] Lockheed, Verizon testing 5G-linked drone swarm for intel collection

<https://www.c4isrnet.com/battlefield-tech/it-networks/5g/2022/09/28/lockheed-verizon-testing-5g-linked-drone-swarm-for-intel-collection/>

[22] Shield AI's Hivemind Pilots Three Unmanned Aircraft During Technology Demo - Potomac Officers Club

<https://www.potomacofficersclub.com/shield-ais-hivemind-pilots-three-unmanned-aircraft-during-technology-demo/>

[23] [24] Autonomous Cavity Monitoring in a German Salt Mine

<https://www.exyn.com/news/autonomous-cavity-monitoring-in-german-salt-mine>

## ART 05.031 Humanoid and General-Purpose Robots

### 17. ART extraction

18. **Primary capability:** Robots with a human-like form and dexterity that can operate in human environments and use human tools autonomously. They navigate spaces built for people (doors, stairs) and perform a wide range of tasks from physical labor to precise manipulations, reducing the need for constant human presence.

### 19. Key sub-components/variants:

- *Locomotion & Mobility:* Bipedal/legged platforms with agile walking, running, stair-climbing, and dynamic balance (e.g. Boston Dynamics' Atlas[1], Agility's Digit). Some designs use wheels or hybrid mobility for efficiency.
- *Manipulation & End-Effectors:* Multi-DOF arms and multi-fingered hands with force/tactile feedback for human-level object handling. Advanced prototypes have ≥11–20 DoF hands (e.g. Sanctuary's Phoenix has 20-DoF hands with haptic sensors[2]; Tesla Optimus Gen2's hands grew from 11 DoF to 22 DoF in one year[3]).
- *Sensing & Perception:* Rich sensor suites – stereo/RGB-D vision for 3D mapping, IMUs, force/torque sensors, often LIDAR[4]. Onboard perception builds real-time 3D models and recognizes people/objects. Some incorporate large vision-language models (e.g. Figure 02 has six RGB cameras and a vision-language model for visual reasoning[5]).
- *AI, Autonomy & Learning:* Onboard and networked AI for task planning, environment mapping, and human-robot interaction. Robots can take high-level instructions (speech or gestures) and learn new tasks via demonstration or simulation training. Notably, generative AI and LLMs are being integrated for higher-level reasoning and dialogue (e.g. Sanctuary's Phoenix uses a cognitive AI system with ChatGPT for understanding commands[6]; Figure 02 uses OpenAI's tech for natural language conversation[7][5]).
- *Human-Robot Interaction & Safety:* Interfaces for commanding robots include voice, wearables, and standard APIs. Safety-rated controls limit force and unsafe motions around people. Efforts are underway to develop ISO safety standards for legged robots[8]. Early deployments keep humanoids in controlled or isolated tasks to mitigate risk[9].
- *Power & Endurance:* Battery technology and power management are critical constraints. Current humanoids typically run 1–2 hours per charge[10], though

rapid charging or battery swapping is in development (Agility's next-gen Digit has a battery "backpack" giving 90 min runtime and a 9 min full recharge[11]). Most cannot yet work an 8-hour shift continuously; managing downtime and charging logistics in deployments is an active challenge[12][13].

- **Production & Cost:** Early units are complex and expensive (comparable to luxury vehicles or industrial machines). Scaling production involves securing supply chains for high-torque actuators, sensors, batteries, etc. Companies are investing in dedicated factories (e.g. Agility Robotics' new Oregon "RoboFab" can scale to >10,000 humanoids per year[14]). Simpler or smaller variants (e.g. 47 kg, 180 cm "Unitree H1" in China) trade off capability for lower cost[15].

20. **Maturity indicators:** Evidence of **working prototypes and field trials** (robots performing non-trivial tasks in real-world or mock-industrial settings) and **early commercialization efforts**. Key indicators include: multi-function demos beyond lab conditions (e.g. handling objects, tool use, navigating clutter)[16]; **pilot deployments** in workplaces or public environments (with safety measures)[17]; **investments in production** (factories, supply chain scaling, pre-orders)[14][18]; **multiple competing actors** (big tech, startups, government programs) advancing the technology in parallel[19]; and any **initial product sales or deliveries** to paying customers (even in limited volumes, as a step toward broader adoption). Evidence of improving cost-performance (e.g. runtime, payload, reliability) and concrete roadmaps for scaling up manufacturing would also signal maturity.

## 21. Evidence (10–20 recent, reliable sources)

22. **Agility Robotics opens factory for mass-producing humanoids** – Agility Robotics (press release) – Sep 2023[14][18]. Describes the launch of "RoboFab," a 70,000 sq ft facility in Oregon capable of building over 10,000 bipedal Digit robots per year. Agility anticipates "hundreds" of Digits produced in the first year and first deliveries to pilot customers in 2024, with general availability in 2025. This marks the transition from prototypes to production scaling, a pivotal step for commercial maturity.
23. **Humanoid Robots Aren't Scaling (yet)** – IEEE Spectrum (feature by E. Ackerman) – Sep 2025[19][20]. Analyzes the emerging humanoid industry boom: multiple well-funded companies (Agility, Tesla, Figure, etc.) plan aggressive production – e.g. Agility expects to ship hundreds of Digits in 2025 and built a factory for >10k/year[21]; Tesla aims for 5k Optimus in 2025 and 50k in 2026[22]. However, it notes current deployments are only "small handfuls" of robots in controlled pilots[23], and identifies key hurdles (battery life, reliability, safety) that must be solved before thousands of units can be truly useful[20]. This highlights both fast-paced progress and the gap to real-world scale.
24. **NASA's Valkyrie humanoid deployed for offshore facility tests** – NASA/Johnson Space Center (news release) – Jul 2023[24][25]. Reports a NASA project sending a Valkyrie humanoid robot to Western Australia under a partnership with Woodside Energy. The goal is to develop remote dexterous manipulation for maintaining uncrewed offshore oil & gas facilities[24]. NASA engineers delivered Valkyrie and trained Woodside staff, and the robot will be tele-operated to perform inspection and maintenance tasks in a hazardous, real-world environment[25]. This is a field trial by a government lab to mature humanoid capabilities for industrial use and gather data on performance outside the lab, underscoring the plausibility of humanoids in remote, dangerous jobs.
25. **Sanctuary AI's general-purpose humanoid in commercial pilot** – SiliconANGLE (tech news) – May 2023[2][26]. Describes "Phoenix," a humanoid robot (170 cm, 70 kg) launched by Canadian startup Sanctuary AI. Phoenix has 20-DoF hands with haptic feedback and can carry

25 kg, with a top walking speed ~4.8 km/h[2]. It runs on the company's "Carbon" AI control system (which integrates modern AI including GPT-based models) and is designed for "labor-as-a-service" work. The article notes a successful pilot where an earlier prototype completed 110 different tasks (about 40% of all tasks performed by staff) during a week-long trial in a retail store (Mark's, in Canada)[26]. This demonstrates a humanoid performing a broad task repertoire (stocking, cleaning, tagging, etc.) in a real commercial environment, indicating technical feasibility of general-purpose function and providing early evidence of value (freeing workers for higher-value tasks).

26. **Figure 02 humanoid: AI integration and BMW partnership** – Popular Science – Aug 2024[27][28]. Covers Figure AI, a well-funded US startup, and its second-generation humanoid Figure 02. The Figure 02 (a 5 ft 0 in, ~60 kg biped) has five-fingered hands (16 DoF) with "human-equivalent strength"[29] and a 2.25 kWh battery for ~7.5 hours runtime[28] – a 50% improvement over their first model. Figure 02 is equipped with OpenAI's language models for voice dialog and vision processing (six onboard cameras), enabling it to converse with humans and perform visual reasoning on the fly[7][5]. The piece notes that multiple Figure 02 units were tested at a BMW car factory moving automobile parts on an assembly line, as part of a pilot partnership[30][31]. While the demo tasks (carrying and positioning parts) remained relatively scripted, the integration of advanced AI and a real factory pilot highlight rapid advances toward autonomous, interactive robots in industrial settings.
27. **Rapid learning of complex tasks via human-in-the-loop AI** – Science Robotics (via UC Berkeley press/TechXplore) – Aug 2025[32][33]. Researchers at UC Berkeley demonstrated a training system (HiL-SERL) that enables robots to master complicated, multi-step tasks within 1–2 hours of real-world practice[34]. By combining human feedback (corrective teleoperation) with reinforcement learning, their robot achieved 100% success on challenging manipulation tasks like "Jenga block whipping," flipping a fragile egg, assembling a shelf and a car's dashboard, and even inserting chips on a motherboard[33][35]. This represents a major leap in robot skill acquisition, reducing the demonstrations or time needed by ~85–90% compared to earlier methods. Such progress in fast, robust learning algorithms makes it more plausible that general-purpose humanoids could be taught new tasks on the fly (or update their skill libraries remotely) – a critical aspect of the ART's vision.
28. **Xiaomi's "CyberOne" humanoid prototype** – IEEE Spectrum (news by E. Ackerman) – Aug 2022[36]. Reports that Chinese tech giant Xiaomi unveiled CyberOne, a full-size bipedal humanoid robot as a technology demo. CyberOne stands 177 cm tall, 52 kg, with 21 degrees of freedom and a curved OLED "face" display[36]. Xiaomi equipped it with vision and environmental sensors (it can create 3D maps and purportedly recognize human emotions), but acknowledged it as an R&D showcase rather than a near-term product[37][38]. The significance is that major companies globally (China, in this case) are investing in humanoid robotics, leveraging their manufacturing prowess. CyberOne's debut, while not delivering new functionality, underscores worldwide interest and the engineering feasibility (a consumer electronics firm built a functioning humanoid in-house) – though also illustrating that practical utility and durability remain hard, as noted by the skeptical tone of experts[39].
29. **Boston Dynamics' Atlas robot demonstrates tool use and agility** – New Atlas (tech review) – Jan 2023[16][1]. Describes the latest feats of Atlas, a cutting-edge humanoid from Boston Dynamics. In a 2023 demo, Atlas (1.5 m tall, 89 kg, 28 hydraulic joints[40]) was tasked with assisting at a mock construction site. It autonomously picked up a plank to bridge a gap, carried a heavy tool bag up stairs and across the plank, then threw the bag to a higher level – all while maintaining balance – and finally performed an inverted 540° aerial flip off a platform[16]. Engineers noted the flip pushes "the limit of what the robot can do"[41]. This showcases state-of-the-art locomotion and manipulation: dynamic balance, coordination under load, and



*whole-body motions that were purely aspirational a few years ago. Atlas is not a commercial product, but its technical achievements validate feasibility for many human-like movements (jumping, lifting, tool use), albeit with expensive hardware and still limited operating time.*

30. **Tesla's Optimus humanoid: from prototype to production plans** – SmartBot (academic review) – Mar 2025[42][43]. Summarizes milestones of Tesla's Optimus (also called Tesla Bot). A first prototype shown in 2022 (approx. 173 cm, 56 kg) performed basic tasks like walking, watering plants, and carrying small objects[42]. By 2023, Optimus "Gen 2" achieved stable walking in Tesla's factory environment and could remain balanced while lifting or manipulating objects[44]. It uses Tesla's self-driving vision algorithms for perception and navigation, and Tesla has publicly stated plans to deploy Optimus at large scale in industry, services, and homes[45]. Indeed, Tesla projects building thousands of units in the next couple of years (internal communications and investor events in 2023–24) – an ambition backed by its new dedicated robotics teams and heavy investment. No independent field data is available yet, but the presence of a major automaker committing resources to humanoids (including custom actuators and AI chips) and iterating prototypes quickly is a strong indicator of maturity: it suggests the concept has moved out of research and into serious development, with an eye toward cost reduction and manufacturability (Tesla aims for a sub-\$30k unit price in the future, akin to a car[46]).
31. **General progress and global efforts (academic review)** – SmartBot journal (Sheng et al.) – 2025[47][15]. A comprehensive review notes that many actors worldwide are now in the humanoid race. In the US, startups like Figure (which showed a humanoid making coffee and tidying objects) are integrating large-language models for instruction following[48]. In China, multiple universities and companies have prototyped humanoids: e.g. Unitree unveiled an 180 cm, 47 kg humanoid (H1) in 2023 that can run and climb stairs, and a smaller 127 cm version with a dexterous 3-fingered hand in 2024[15]. Established robot firms like UBTECH released the Walker biped that walks and navigates autonomously in indoor spaces[49]. Even auto companies (Xpeng, Xiaomi) and appliance makers (Fourier, Dreame) have revealed humanoid designs[50]. This breadth of R&D, spanning academia, government, and industry across North America, Asia, and Europe, reinforces that the core technical barriers are being addressed, and there is a consensus that general-purpose humanoids are within reach – driving a competitive, well-funded environment.

### 32. Maturity score (1–7) and reasoning

#### Proposed Maturity Score: 5 (out of 7).

**A) Justification of score:** The evidence shows that humanoid/general-purpose robots have **passed the proof-of-concept stage (Level 4)** and are now in an **early commercialization and scale-up race**. Multiple well-capitalized companies and research teams have working prototypes that solve key functionality challenges (dynamic bipedal walking, basic manipulation, autonomous navigation) beyond what earlier robots could do. For example, Tesla Optimus and Sanctuary's Phoenix have demonstrated stable locomotion and useful task execution (e.g. picking and placing objects) in real settings[44][26] – this rules out Levels 1–3, which correspond to mere theory or isolated lab demos. **Level 4** is also exceeded: we have *full-scale prototypes meeting many commercial requirements*. Agility's Digit, Figure 02, and others show **human-sized robots performing industrial tasks** with reliability sufficient for pilot deployments[26][31]. Critically, the step to **Level 5** is evident in the rapid progress toward production: Agility Robotics opening a factory for mass-producing Digits[14], Tesla planning thousands of units[51], and multiple startups (Figure, 1X, Apptikon, etc.) raising significant funding to build the first market-ready humanoids. There is clear *competition*

among well-funded actors to develop production prototypes, which is the hallmark of Level 5. Progress is fast-paced, with successive prototype generations in 1-year cycles and improving capabilities (e.g. Optimus Gen2 to Gen3 within a year, doubling hand DOF and adding capabilities[3], and Figure going from a rough Version 01 to an AI-equipped Version 02 in ~18 months[27]).

**B) Why not a higher score?** We stop short of **Level 6 (products delivered in increasing volumes)** because true commercial rollout is only just beginning. **Few robots have been delivered to paying customers** so far – deployments are mostly pilots or internal tests (e.g. Sanctuary’s 110-task trial at a store[26], NASA’s single Valkyrie at an oil facility[24], a few Digits to research partners). No company yet has hundreds of humanoids performing daily work for customers in the field – the market remains “almost entirely hypothetical” at scale[23]. Moreover, key practical hurdles like battery endurance, safety certification, and long-term reliability are still being worked out (e.g. ensuring <1% downtime in factories[13], and drafting new ISO safety standards for legged machines[8]). Economic viability is not proven at scale – although unit costs are projected to fall with volume, currently these robots are expensive bespoke systems. Thus, while **the trajectory toward Level 6 is clear** (with initial manufacturing capacity now in place[14] and large pre-orders envisioned[22]), the **evidence of actual scaled adoption is not yet present**. Reaching Level 6 will require seeing dozens-to-hundreds of humanoids reliably working in industry, which is likely a couple of years away.

**C) Sub-component breakdown:** This ART combines several subsystems at different maturity levels, but they coalesce into one integrated product (the humanoid robot). Key sub-elements:

- **Mobility (locomotion & balance):** *Maturity*  $\approx$  4–5. Robots like Atlas and Digit have demonstrated human-comparable mobility (running, jumping, uneven terrain) in demos[1][52], solving many research obstacles. The remaining gap is hardening these capabilities for low-cost, everyday use (current systems are expensive and can still fail in unstructured settings).
- **Manipulation (arms & hands):** *Maturity*  $\approx$  3–4. Sophisticated robot hands exist (20+ DOF with touch sensing[2]), and recent AI advances let robots perform complex manipulations (assembly, tool use) with high success rates[33][16]. However, real-world robustness and human-level dexterity (especially for tiny objects or high precision) are still emerging. Many humanoids use relatively simple grippers or limited-finger hands in practice for reliability.
- **Autonomy & AI:** *Maturity*  $\approx$  4. There’s been striking progress in cognitive capabilities – vision, planning, and learning. Robots can follow voice instructions and learn new tasks from one demo or a few hours of training[34][7], which was infeasible until recently. Yet, *general* autonomy (the ability to adapt to arbitrary new tasks and environments with minimal help) is not fully achieved; most deployments require structured tasks or human oversight (teleoperation or engineers on call).
- **Power and hardware reliability:** *Maturity*  $\approx$  3. This is a limiting factor: current battery tech yields ~1–2 hours of work per charge[10], and frequent charging or swapping is needed for continuous operation[53]. High-performance actuators tend to heat up or wear, and maintenance needs in 24/7 settings are unproven. Efforts like quick-charge batteries[54] and efficient all-electric designs are underway, but field reliability over months/years is not demonstrated.
- **Manufacturing & cost:** *Maturity*  $\approx$  5. Surprisingly, this aspect is being tackled head-on now:



Agility's factory and Tesla's planned production indicate that building thousands of units is viewed as *feasible with existing supply chains* (they note humanoids can leverage supply chains of industrial arms and EVs)[55]. **Investment and scaling plans are in place**, even if the market demand side is uncertain[56].

Given these sub-scores, the overall maturity is around **4+**, but we weight the higher end because the *integrated system* is what defines the ART's impact. The various subsystems are rapidly converging into viable products due to the intense engineering efforts currently underway. The **presence of multiple competitors and active prototypes tips the scale to a solid Level 5** – the project is beyond proof-of-concept, firmly in the stage of refining prototypes into products, with clear momentum toward initial market entry. In summary, humanoid/general-purpose robots are **plausible and partially demonstrated (Level 4)** and are now **on the cusp of real-world deployment with major backing (Level 5)**, but **not yet broadly adopted or proven at scale (not Level 6)**.

[1] [16] [40] [41] Atlas robot takes a major leap in perception and object manipulation

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## ART 05.032 Soft Robotics & Bio-Inspired Machines

1. **ART extraction**
2. **Primary capability:** Enables robots with deformable, compliant bodies that safely interact with fragile objects, humans, and tight or cluttered spaces by mimicking the soft movement and adaptability of biological organisms. These soft robots can absorb impacts and conform to their environment, performing gentle manipulation or navigation tasks that would damage or trap conventional rigid robots.
3. **Key sub-components or variants:**
4. *Soft structures & materials:* Flexible polymers, elastomers, gels, textiles, and composites form the robot's body and joints, allowing it to bend, stretch, and squeeze as needed.
5. *Bio-inspired actuators:* Fluidic or pneumatic networks and "artificial muscle" actuators (e.g. air muscles, electroactive polymers, shape-memory alloys) produce motion without hard skeletons, often inspired by muscle or hydraulic systems in animals.
6. *Distributed soft sensors:* Flexible tactile and strain sensors embedded throughout the robot detect pressure, texture, force, or shape changes, feeding data to on-board controllers.
7. *Embedded control & AI:* On-board processors run real-time control algorithms that use data-driven models and bio-inspired gait/grasp patterns. Robots can learn motions via imitation of human demonstrations or reinforcement learning, simplifying programming.
8. *Human-friendly interfaces:* Instead of manual joint-by-joint coding, users can command the robot through high-level APIs, voice or gesture controls, making operation intuitive (the robot's "mechanical intelligence" handles low-level coordination).
9. *Specialized fabrication:* New manufacturing methods (soft lithography, multi-material 3D printing, fabric weaving of actuators) enable scalable production of complex soft robotic components, though requiring specialized tools and materials.
10. *Variants:* Soft robotic grippers and manipulators (for gentle picking in factories or agriculture), wearable soft exosuits (assistive apparel for human mobility or rehabilitation), soft mobile robots (e.g. snake-like or vine robots for search-and-

rescue, soft drones or underwater vehicles for exploration), and hybrid rigid-soft systems that combine a firm base with soft end-effectors.

#### 11. **Maturity indicators:**

12. Field demonstrations of soft robots performing tasks in real-world conditions (e.g. factory lines, disaster sites, medical trials), showing they can reliably operate outside the lab.
13. Functional prototypes solving previously intractable problems (gentle handling of delicate food, navigating collapsed buildings, assisting human gait) and meeting key performance benchmarks (speed, force output, endurance) beyond what human workers or rigid bots can achieve.
14. Early commercial products and startups: e.g. soft gripper tools being sold and deployed in industry, or soft exosuits entering pilot clinical use – indicating progress from research to market.
15. Investment and competition: multiple startups and major firms (robotics companies, automation suppliers) developing soft robotics solutions, significant venture funding or corporate R&D programs, and emerging industry consortia/standards (including safety certifications for robots working near people).
16. Signs of scalable manufacturing and maintenance: development of durable materials (e.g. self-healing or fatigue-resistant elastomers) and modular designs, as well as training programs or documentation that allow broader adoption by non-experts.
17. **Bottlenecks to watch:** improvements in actuator power-density (for faster, stronger motion untethered), longer material lifespan (fatigue, tear resistance), portable power sources, and formal safety testing – progress on these will mark readiness for wide deployment.

#### 18. **Evidence (10–20 recent, reliable sources)**

19. **Festo HPSX Soft Gripper** – *Festo (vendor technical doc, 11/2023)* – Industrial automation company Festo released the **HPSX soft gripper**, a hygienic, food-grade gripper with soft modular silicone fingers. It comes in three sizes and can gently handle items from strawberries to melons without damage. The design’s soft compliance and ISO-standard robot mount make it easy to integrate on collaborative robots, addressing delicate handling needs in food, pharmaceuticals, and cosmetics[1][2]. (This shows a commercial soft robot end-effector meeting industry safety and cleanliness standards.)
20. **Soft Robot Tech (SRT) soft grippers** – *SRT company profile (China, 2023)* – Beijing-based startup SRT, founded 2016, reports its **soft robotic grippers** can mimic human hand motions to grasp ~96% of object shapes encountered in industry[3]. SRT claims over **500 customers worldwide across 30+ countries**, deploying soft grippers in fresh food handling, electronics assembly, semiconductors, agriculture, rehabilitation devices, etc.[4]. (This indicates significant early commercial adoption of soft robotics, with broad industry and geographic reach.)
21. **Soft Robotics mGrip in produce packing** – *Photonics Spectra (trade magazine, Winter 2022)* – Describes an automated packing line for sweet potatoes where a **Soft Robotics Inc. “mGrip” soft gripper** was installed to handle produce of varying shapes[5]. Competing rigid grippers struggled with the irregular produce, but the pneumatic mGrip fingers (made of food-safe elastomer) gently grasp items without manual tuning. After integration, the system saw immediate improvements – even delicate baked goods could be picked “without breaking them,” which was previously impossible[6]. A 3D vision system guides the soft gripper to consistently fill boxes, eliminating labor-intensive packing and product damage.

(Demonstrates a real-world deployment where soft robotics outperformed conventional automation in gentle handling and adaptability.)

22. **Soft Robotics mGripAI commercial adoption** – *NVIDIA Blog (01/2023)* – Reports that **Soft Robotics (USA)** has developed the mGripAI system (soft grippers + 3D vision + AI) for food processing lines[7]. Major food companies like Tyson Foods and Johnsonville are using this technology to pick and place meats and produce at high speeds (up to 100 picks/min) without bruising or contamination[8]. The company received **\$26 M Series C funding** led by food industry investors to scale up production[9], and its tools are helping alleviate labor shortages and injury risks in poultry packaging. (Shows that soft robotic solutions have progressed to **scaled industrial pilots and attracted substantial investment**, meeting throughput demands in a billion-dollar sector.)
  
23. **EU–Japan “CURSOR” rescue robots** – *Horizon Magazine (EU R&I, 06/2025)* – Describes the **SMURF (Soft Miniaturised Underground Robotic Finder)** developed in a 2019–2023 EU-Japan project for disaster search-and-rescue[10]. This small two-wheeled soft robot carries cameras, two-way audio, and a chemical sensor “SNIFFER” that detects human breath markers (CO<sub>2</sub>, ammonia). In field simulations, multiple SMURFs could be **deployed into rubble via drones** to locate trapped survivors while keeping first-responders out of harm’s way[11]. The SMURF’s **chemical sensor proved reliable amidst smoke and rain**, distinguishing live victims from remains[12]. (Evidence of a successful **prototype field trial**: soft robots with advanced sensing functioning in unpredictable, hazardous environments, highlighting both feasibility and remaining challenges before real deployment.)
  
24. **MIT’s SPROUT vine robot** – *TechXplore/MIT News (04/2025)* – Researchers at MIT Lincoln Lab and Notre Dame demonstrated **SPROUT**, a “vine” robot for urban search-and-rescue[13][14]. SPROUT is an **inflatable soft robot** that “grows” a flexible tube through debris by air pressure, allowing it to maneuver around obstacles and snake through narrow voids. It can currently extend ~10 feet (aiming for 25 ft) and is teleoperated via a simple joystick interface[15]. The team solved challenges in controlling the robot’s deformable body (steering via internal air pressure, minimizing friction) so that first responders can deploy it without expert knowledge[16]. (This prototype addresses the key **niche of navigating confined, unsafe spaces**, and is being developed with user-friendly control for eventual field use by emergency personnel.)
  
25. **“WalkON” soft robotic exosuit** – *Tricomi et al., Nature Machine Intelligence (10/2024)* – A peer-reviewed study of **soft robotic shorts (exosuit)** that assist hip motion in walking. The device uses lightweight textile braces and cable/tendon actuators to add force during hip flexion. In outdoor tests, young adults walking uphill with the powered shorts expended **17.8% less energy**, and in a separate trial older adults on level ground saw a **~10.5% reduction in metabolic cost** while wearing the exosuit[17]. Participants maintained a high sense of natural control (rating ~6.1/7) over their gait. These results, achieved in real-world environments (hiking trail, outdoor track), show that soft wearable robots can **meaningfully improve mobility and endurance** for users, beyond laboratory settings. (Demonstrates a **proof-of-concept exoskeleton** nearing practical viability for assisting human locomotion, with comfort and efficiency gains.)
  
26. **Untethered soft actuator advances** – *Park et al., Nature Communications (2024)* – A comprehensive review of recent progress in soft robotics notes that while soft robots offer extraordinary compliance and safety, they historically suffer from **limited force output and reliance on tethers** (external pumps/wires for power)[18]. It highlights emerging solutions: e.g. **pump-free pneumatic actuators** using phase-changing fluids to generate pressure internally, and soft actuators driven by external stimuli like magnetic fields, light, or wireless

electricity[19]. Such approaches have demonstrated increased force and motion speed without bulky air hoses, inching soft robots toward fully untethered operation. (This underscores that the field has **moved beyond fundamental principles** – researchers are actively solving engineering roadblocks like power and force density, which is crucial for real-world deployment.)

27. **Durability testing of soft actuators** – Bui et al., *Frontiers in Materials* (05/2023) – Investigated the longevity and performance drift of a **silicone fabric-reinforced pneumatic actuator** under extended use. Through cyclic tests, the team found the actuator’s motion stabilized after an initial “break-in” (~160 inflation cycles) despite some hysteresis, and it withstood **over 1,280 actuation cycles** before failure in pressure tests[20]. This indicates current silicone soft actuators can operate through hundreds of cycles with repeatable performance, but also highlights the need to improve material fatigue life. (Provides empirical data on **soft robot reliability**, showing progress in understanding and extending the lifespan of soft components to meet practical service requirements.)
28. **Soft robot in the deep sea** – Li et al. via *Nature Communications* (11/2023) – Reports a breakthrough wherein a **soft robotic fish**, inspired by the deepest-living snailfish, was successfully tested at extreme ocean depth. The untethered robot, using dielectric elastomer “muscle” actuators and a soft body, survived pressures of **110 MPa (Mariana Trench depth)** without a rigid vessel[21]. It swam effectively in a pressure tank and achieved free-swimming at >3,000 m depth, even performing at **~10,900 m** in field trials. This world-first demonstration of a soft robot operating at such depth validates the approach of using compliant materials to withstand high pressure, and paves the way for gentle deep-sea exploration of fragile marine life. (Shows **scientific feasibility proven in extreme conditions**, a strong plausibility signal for soft machines where rigid ones fail.)
29. **SofaGym simulator for soft robots** – Schegg et al., *Soft Robotics journal* (04/2023) – Introduces “**SofaGym**,” an open-source platform that connects a physics-based soft robot simulator (SOFA) with the standard OpenAI Gym reinforcement learning interface[22]. The authors provide 11 example environments (different soft robot morphologies and tasks) and demonstrate how learning algorithms can be applied to optimize control and motion planning for soft robots[23]. By offering a common toolkit for training soft robotic control policies and easing sim-to-real transfer, this work lowers the barrier for researchers and companies to develop **intelligent, adaptive behaviors** in soft robots. (Evidence of ecosystem maturation – tools for simulation, learning, and programming are emerging, which will speed up development and deployment of soft robotics applications.)

### 30. Maturity score (1–7) and reasoning

**Assigned Score: 5 (Early commercial prototypes with growing investment and competition)**

**A) We score Soft Robotics & Bio-Inspired Machines as a 5**, reflecting an **intermediate maturity**: key proofs-of-concept have been demonstrated and several startups and industry players are actively pushing toward production and scale, but full commercial maturity in all areas isn’t yet achieved. Notably, **multiple well-funded actors** are involved (e.g. Soft Robotics Inc., SRT, Festo, plus academic spinoffs), and **early products** like soft grippers are on the market, which goes beyond a lab prototype (ruling out Levels 1–3). For instance, Festo’s and SRT’s soft grippers are being delivered to customers for gentle handling in factories[1][24], and Soft Robotics’ systems have secured significant industry funding for expansion[9], indicating we are past the one-off demo stage. This collective momentum



satisfies many Level 5 criteria: **proof-of-concept prototypes clearly solving real problems, with investment to commercialize and fast-paced progress** in recent years.

**B) Why not a 6 or 7?** The technology as a whole isn't fully at Level 6 because widespread production use is still *nascent and fragmented*. **Some sub-fields (like soft gripper end-effectors)** are approaching Level 6 – they have paying customers and scaling demand (500+ clients in SRT's case) – but other aspects remain in prototyping. For example, **soft wearable exosuits and soft mobile robots** are only in pilot testing or limited trials (e.g. the WalkON exosuit showed real-world efficacy[17] but is not yet a sold product, and vine robots like SPROUT are functional demos, not deployed equipment[15]). Fundamental technical gaps such as **power and durability** also persist: most soft robots still rely on external pumps or tethers and have lifespan issues[18][20], which companies are actively addressing but not fully solved. These gaps mean that, although demand is rising and niche adoption is underway, we have not seen **broad, off-the-shelf commercialization across the board** that would merit Level 6. To reach the next level, we would expect to see robust untethered soft robots operating at scale in multiple industries, formal safety certifications in place, and primarily internal (revenue-driven) R&D rather than grant-funded – evidence which is still emerging.

### C) Sub-component breakdown:

- **Soft grippers/manipulators (industrial automation):** *Maturity ~6*. They are **commercially deployed in production environments**. Companies like Soft Robotics and SRT have products handling food, electronics, etc., with hundreds of end-users[24]. Major firms (Tyson Foods, etc.) are investing in these for immediate operational use[9]. This segment sees **competition and early economies of scale**, inching toward Level 6.
- **Soft wearable robots (exosuits, medical devices):** *Maturity ~4*. Functional **prototypes have been validated in relevant scenarios** (assisting mobility with measurable benefits[17]). Some start-ups and collaborations (e.g. through rehabilitation trials) exist, but products are not widely available yet – they are at proof-of-concept/pre-commercial stage.
- **Soft mobile robots (search-and-rescue, exploration):** *Maturity ~3–4*. There are **working prototypes** (vine crawlers, soft rescue bots) demonstrating unique capabilities in field tests[10][14], which proves feasibility (Level 3). A few are moving toward advanced pilot demonstrations (bordering Level 4), but none are in routine practical deployment due to ongoing R&D on reliability, control and regulatory approval for use in safety-critical situations.
- **Core soft robotics technology (materials, actuators, control software):** *Maturity ~3*. The scientific principles are proven and there are many lab demos (Level 2 achieved long ago), and importantly some **previously blocking challenges have been partially solved in the lab** – e.g. new actuators without tethers[19], or soft robots surviving extreme conditions[21] (indicative of Level 3). However, many components are still in the optimization stage and not yet at a cost or robustness suitable for mass production.

Taking an **average view of these components**, the overall area stands at **Level 5**. We chose an average-based score because the “soft robotics” bundle spans diverse applications – from factory grippers to medical devices – that are maturing at different rates and largely serve different markets (the value is distributed across various use-cases rather than one unified product). **In summary, the strongest evidence (industrial adoption and multi-million-dollar investments) pushes the score above 4**, but full maturity is tempered by other sub-fields lagging behind. Achieving a solid Level 6 will require further convergence of

these advances: untethered operation, proven durability, regulatory safety frameworks, and profitable scale in more than one domain – all of which are in progress, but not uniformly realized yet.

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## ART 05.033 Fully Autonomous Drones, Robots & Underwater Vehicles

### 33. ART extraction

**A) Primary capability:** The ART envisions robotic vehicles (drones, ground robots, underwater vehicles) that can operate *fully autonomously* in environments dangerous or inaccessible to humans. The key capability is long-duration, reliable sensing and manipulation in remote areas with **minimal human supervision**. These systems aim to maintain presence and perform tasks (inspection, transport, assembly) in harsh conditions where human operation would be risky or impractical.

### B) Key sub-components or variants:

- **Autonomous aerial drones (UAVs):** Uncrewed aircraft with advanced autopilots and on-board AI, able to take off, navigate, and land with little oversight. They carry modular sensor or cargo payloads for missions at high altitude or over long distances.
- **Autonomous ground robots (UGVs):** Wheeled, tracked or legged robots that can traverse challenging terrain (rubble, stairs, remote sites) on their own. Often designed with **modular bases** and attachable tools (arms, cameras) to perform inspections or manipulate objects (e.g. opening valves).
- **Autonomous underwater vehicles (AUVs):** Submersible robots with pressure-tolerant hulls, capable of deep or long-duration underwater missions without tether or constant contact. They use sonar, inertial navigation, etc., to map and operate in the ocean depths.
- **Sensor fusion & real-time mapping:** All variants rely on combining inputs (cameras, LiDAR/radar, sonar, IMUs, GPS or alternative positioning) to perform SLAM (simultaneous localization and mapping) in unknown or GPS-denied environments. High-powered onboard computing and AI enable them to build detailed maps on the fly and avoid obstacles or adapt to changes without human intervention.
- **Swarm coordination:** Many units can work in **fleets or swarms**, sharing data (maps, sensor findings) and dividing tasks. A small number of human operators can oversee a large autonomous fleet. Swarm algorithms and V2V communication allow cooperative behaviors (e.g. distributed surveying, target search) even if external comm links are lost.
- **Human-robot interaction:** Humans interact at a high level via dashboards, mission planning software, or even natural-language commands. The robots handle fine-grained control autonomously. Human input is supervisory (setting goals or checking status), rather than manual teleoperation in real time.

### C) Maturity indicators to look for:

- **Field demonstrations and deployments:** Evidence of these robots operating autonomously in real-world conditions (e.g. disaster sites, industrial facilities, polar regions, open ocean) for extended periods, performing useful tasks.
- **Prototype → product transition:** Reports of functional prototypes meeting key requirements (endurance, navigation, payload use) and moving toward commercialization – e.g. pilot programs, proof-of-concept trials, or initial products delivered to early customers.
- **Competitive development and investment:** Multiple well-funded companies, defense programs, or research consortia developing such systems (and, ideally, competing to

improve them), indicating a broad push toward scalable products.

- **Scaling and production metrics:** Signs of scaling up, such as **units produced or deployed**, manufacturing partnerships, or large pre-orders. Also, standards or certifications (for safety in shared spaces, explosion-proof operation, etc.) enabling wider use.

- **Performance milestones:** Concrete achievements that surpass traditional approaches – e.g. missions lasting days or weeks without human intervention, multi-robot cooperation in complex tasks, autonomous manipulation successes, or endurance in extreme environments (high winds, deep sea).

- **Regulatory and operational integration:** Evidence of regulatory approvals or waivers (like beyond-visual-line-of-sight flight waivers, autonomy in public spaces) and of end-user adoption (military or industry integrating these robots into regular operations).

#### 34. Evidence (10–20 recent, reliable sources)

35. **Autonomous cargo drone in extreme environment (British Antarctic Survey):** “*Ice World Exploration: Pilotless Uncrewed Aerial Vehicle Arrives in Antarctica*” – Press release, British Antarctic Survey – Feb 2024. [1][2] Describes field testing of the Windracers ULTRA, a fully autonomous twin-engine UAV (10 m wingspan) that carries 100 kg over 1000 km. It can take off, fly, and land with only minimal operator oversight using a patented autopilot. Built with redundancies for harsh conditions, it’s being trialed in Antarctica to extend scientific reach. The project also envisions deploying **multiple ULTRA drones as a coordinated swarm**, demonstrating feasibility of sustained autonomous operations in one of Earth’s toughest environments. This shows both the *plausibility* (rugged autonomous flight proven in the field) and emerging *maturity* (government-funded trial of a near-production system).
36. **Large-scale autonomous drone network for utility inspection (Percepto/FPL):** “*Percepto unveils world’s largest autonomous commercial drone deployment at leading US electric utility*” – Press Release, Percepto (drone-in-a-box vendor) – Apr 2022. [3][4] Florida Power & Light, a major utility, is deploying a network of autonomous “drone-in-a-box” units for statewide grid monitoring. Phase 1 rolled out 13 autonomous drones, with **hundreds more planned over five years**, making it the world’s largest commercial autonomous drone project. These drones live on-site in weatherproof docks, run missions beyond visual line of sight under an FAA waiver, and even withstood Level 5 hurricane winds in testing. This evidences *maturity*: a well-capitalized end-user moving beyond pilots to scale up autonomous drone operations (a strong indicator of level 5–6, with real deployments and regulatory integration). It also underscores the technology’s value in reducing manual inspections and emergency response time.
37. **AI-coordinated drone swarm with minimal comms (Airbus & Quantum Systems):** “*Airbus and Quantum Systems make progress in autonomous swarm technology*” – Joint industry press release (Airbus Defence & Space, Quantum Systems) – Aug 2024. [5] Reports a successful field test in Germany of **seven drones controlled by a single AI-driven mission system** as part of a defense research program. Heterogeneous UAS (fixed-wing and multirotor) were autonomously coordinated even under GPS jamming and communication loss. All drones’ sensor data were fused in real-time to form a common situational map, and the AI autopilots dynamically adjusted roles to complete reconnaissance and target-location tasks without direct human control. This demonstrates the *feasibility* of multi-robot autonomy at a tactical scale (each drone adapting to others and to degraded conditions) and indicates growing *technical maturity* in swarm control algorithms (relevant to the ART’s vision of swarm operation in harsh, comm-denied environments).

38. **Long-endurance autonomous underwater vehicle (Kongsberg, Norway):** “*Mission accomplished for the world’s first HUGIN Endurance*” – Vendor technical news (Kongsberg Discovery) – Mar 2024. [6][7] Announces that Kongsberg’s new HUGIN Endurance AUV (launched 2021) completed sea trials and was delivered to its first customer. This large AUV can operate **up to 15 days and 2200 km** on one mission, with modular payload bays for sonar, cameras, and environmental sensors. The first production unit passed factory and sea acceptance tests by early 2024 and demonstrated all capabilities to the customer. This marks a key *maturity milestone*: a formerly experimental long-range AUV is now a commercial product, meeting the endurance and autonomy requirements for real-world use (military and industrial interest is noted). The robust navigation and power systems needed for multi-week unsupervised operation at sea validate the ART’s plausibility in the underwater domain.
39. **Five-week fully autonomous undersea mission (UK research):** “*Autosub Long Range 1500: A continuous 2000 km field trial*” – A.B. Phillips *et al.*, *Ocean Engineering* (peer-reviewed) – July 2023. [8] Documents a record-breaking mission by the UK’s National Oceanography Centre: their Autosub Long Range 1500 AUV conducted a **5-week (2000 km)** unaccompanied deployment from Plymouth into the North Atlantic and back. The vehicle operated continuously beyond visual or communication range, using only half its battery capacity over 2000 km. This experiment demonstrates the *feasibility* of truly persistent autonomous presence underwater. Achieving multi-week autonomy, robust navigation in open ocean, and power management over such distance showcases that the core technical barriers (energy, navigation, reliability) can be overcome in practice. It pushes the platform toward operational readiness (between lab prototype and full production, i.e. ~level 3–4 maturity for this specific model).
40. **Extra-large unmanned submarine delivered to Navy (Boeing Orca XLUV):** “*U.S. Navy Accepts Delivery of First Extra Large Unmanned Undersea Vehicle*” – U.S. Navy PEO USC official news – Dec 2023. [9][10] The U.S. Navy took delivery of its first Orca XLUV “autonomous submarine” from Boeing, marking the transition from development to fleet integration. The Orca is a 15.5 m diesel-electric UUV with a modular payload section for different missions (e.g. mines, sensors). It is designed for **long-endurance autonomous operation**, carrying out undersea missions with minimal human contact. This event indicates substantial *maturity*: a decade-long R&D program culminating in an operational prototype now in the hands of an end-user (level 4→5). The Navy’s plan to field five Orcas, and the platform’s flexibility to adapt to new payloads, underscores both the commitment of a major institution and the plausibility of unsupervised vehicles performing complex tasks (critical undersea missions) reliably.
41. **Autonomous legged robots entering industry (ANYbotics, Switzerland):** “*World’s Only Scalable Ex-proof Robot Inspection Solution Now Available to Industry*” – Press release, ANYbotics – Sep 2022. [11][12] Announces the commercial launch of the **ANYmal X** quadrupedal robot – a fully autonomous, explosion-proof inspection robot for oil & gas facilities. The manufacturer opened orders after successful early deployments, highlighting that over **500 units were already reserved** by early adopters and production was being scaled with manufacturing partners. First customer deliveries began mid-2023. This shows a rapid move from prototype to production, with *strong market demand* in a niche (hazardous environment inspection). ANYmal X uses AI-based locomotion and navigation to climb stairs and traverse complex plants autonomously, tasks that fit the ART’s vision of robots in hard-to-reach or dangerous spaces. The volume of pre-orders and compliance with strict safety certifications (ATEX/IECEX for explosive atmospheres) signal a ~level 5–6 maturity for autonomous ground robots in industry (multiple units in real operation, supported by significant investment).

42. **Widespread deployment of quadruped robots (Boston Dynamics Spot):** “*Robot Police Dogs Are on Patrol, But Who’s Holding the Leash?*” – Undark (science magazine) – Sep 2023. [13] Reports that **over 1,000 Boston Dynamics Spot robots** were operating across 35 countries by 2022, according to a company blog post. Spot is a commercially available autonomous quadruped that can be teleoperated or run missions autonomously (e.g. routine patrols, data capture). This statistic provides concrete evidence of *scaling*: competing products in the autonomous robot space are being delivered globally in significant numbers. It underscores that the core technology is beyond the lab/prototype stage – real customers are investing in these robots for diverse applications (from power plants to police departments). Such multi-continent adoption and iterative product improvements (Spot has seen hardware/software upgrades) reflect a maturity level trending toward **6**, although full unsupervised use in public space remains limited by policy.
43. **Multi-robot autonomy in complex terrain (DARPA Subterranean Challenge):** “*Team CERBERUS Wins the DARPA Subterranean Challenge: Technical Overview*” – M. Tranzatto *et al.*, arXiv preprint (ETH Zurich, others) – July 2022. [14] Details the winning approach in a major robotics competition, where a team deployed a “**system-of-systems**” of **legged and flying robots** to explore underground tunnels and caves with no GPS and unreliable comms. The CERBERUS team’s robots leveraged sensor fusion and resilient autonomy to map and navigate perilous terrain, all while one human supervisor merely gave high-level commands. The robots could dynamically replan and overcome obstacles (like rubble or vertical shafts) without direct teleoperation. This is a compelling *feasibility proof*: it shows that multiple heterogeneous robots can autonomously coordinate to perform search and mapping in real time, exactly the kind of hard, unmapped environment envisioned by the ART. The success in DARPA’s challenge (final event in 2021, documented 2022) indicates the technology for robust autonomy exists at least at prototype level (TRL ~6 for that context), though transitioning this to everyday commercial use is ongoing.
44. **Drones autonomously building structures (Nature cover story):** “*New bee-inspired drone fleet works together to build 3D objects*” – UCL & Imperial College London, *Nature* (covered in UCL News) – Sep 2022. [15][16] Describes a research demonstration where **flying drones cooperatively 3D-printed a cylinder 2.05 m tall** (72 layers) and another structure out of cement-like material, all autonomously. A team of “BuilDrones” deposited material while “ScanDrones” measured progress; the drones adjusted their paths in real-time to ensure the structure met the blueprint specs. They required no human intervention during the build, aside from a monitoring operator. This achievement highlights the *versatility and precision* that modern autonomous robots can attain – not only navigating, but actively manipulating the environment (constructing or repairing structures). It reinforces plausibility for tasks like assembly or disaster-repair that the ART foresees. While this was a controlled experiment (≈ level 3–4, lab prototype), being published in *Nature* with plans to work with construction firms suggests a path toward field trials of autonomous construction swarms in coming years.
45. **Maturity score (1–7) and reasoning**

**Proposed Maturity Score: 6** (out of 7) – *Early commercial rollout and scaling.*

**A) Why not lower:** The collected evidence shows that we are well beyond theoretical or lab-only stages (levels 1–3). Multiple **working prototypes have been proven in demanding environments** – e.g. a 5-week undersea mission with no human contact[8], autonomous drones mapping Antarctic ice[1], legged robots performing industrial inspections[11]. In fact, several of these technologies have reached **Proof-of-Concept and productization stages (levels 4–5)**: for instance, the first Orca XLUV was delivered to the Navy in 2023[9][10], and

ANYbotics is fulfilling orders for dozens of ANYmal X units to oil & gas clients[12]. We also see **well-capitalized actors and competition** in each domain – from big defense contractors (Boeing, Airbus) to specialized robotics firms (Boston Dynamics, ANYbotics) – investing heavily and vying to deploy autonomous robots. These are strong signs that the field has progressed into the *production prototype and initial deployment phase*. Real customers are using the technology, validating its value by ordering more (e.g. FPL planning hundreds of drones[3]). This clearly rules out levels 1–4 and even level 5: we have moved beyond one-off demos and isolated prototypes to **small-scale commercial fleets and multi-unit deliveries** across different regions.

**B) Why not higher:** The overall ART spans multiple platforms (air, ground, underwater) which are each at slightly different maturity points – but none have fully achieved level 7 ubiquity yet. **Autonomous drones** for inspection and surveying are the closest to mature: thousands are in operation[13], and major expansions (like the utility deployment) are underway.

**Autonomous ground robots** (like quadrupeds) are a nascent market with hundreds of units being adopted in industrial settings[11], but they are not yet as common or trusted as, say, industrial vehicles. **Autonomous underwater vehicles** tend to lag a bit in volume – advanced models exist and have *just* started to see operational use (e.g. Kongsberg’s 15-day AUV in 2024), but these are still specialized deployments rather than widespread fleets. Moreover, *fully* unsupervised operation in open public environments remains limited by regulations and technical edge cases (safety, reliability under all conditions). For example, drones still often require special waivers for beyond-line-of-sight flight[17], and robotic trucks or ships aren’t yet driving among the general population without oversight. To reach **level 7**, we would expect to see *competing products in broad, rising demand* and largely self-sustaining growth. The current evidence shows strong progress but mostly in **targeted domains** (military, industrial, research) rather than everyday life. In short, the technology is transitioning from early adopter phase to wider adoption, but hasn’t fully broken into a mass-market or multi-industry mainstream usage with “rising demand” across the board. Key missing pieces to justify level 7 include: ubiquitous safety certification frameworks (allowing routine unsupervised use in shared spaces), larger scale manufacturing driving down costs (units are still as expensive as specialized equipment), and longer track records of reliability that would spur *unhesitating* customer demand.

**C) Sub-component breakdown:**

- **Aerial autonomous drones:** *Maturity*  $\approx$  6. Small and mid-size autonomous drones have active competition and deployment. Evidence: utility and industrial inspections using fleets of drones (Percepto/FPL)[3], government research investing in multi-drone swarms[5], and numerous vendors (DJI, Skydio, etc.) selling autonomous navigation drones. Drones benefit from decades of R&D in autopilots and now AI, so many tasks (mapping, surveillance) can be done with minimal human input.

- **Ground robots (UGVs):** *Maturity*  $\approx$  5–6. Mobile robots that navigate human environments autonomously are emerging from pilot stage. The data of 1000+ quadrupeds deployed[13] and new models like ANYmal X selling hundreds of units[12] show a commercial foothold. However, ground robots face more regulatory/social hurdles (e.g. public perception, dealing with people and obstacles in cluttered spaces) – their use is currently mostly in controlled industrial sites or pilot programs (factories, warehouses, military exercises).

- **Underwater robots (AUVs):** *Maturity*  $\approx$  4–5. Technically, some AUVs are very advanced (multi-day endurance, deep-ocean autonomy proven in trials[8]). Agencies and companies



are now procuring these (e.g. Navy's Orca in 2023[9], Kongsberg's deliveries in 2024), which is a leap from purely experimental models. Still, the number in operation is limited, and each unit is often bespoke or low-volume production. The underwater sector is likely a step behind aerial drones in commercialization pace, due to higher costs and narrower use-cases (scientific surveying, naval missions).

Taking an **average** of these sub-scores (driven by the fact that they address different environments and markets), the bundle as a whole sits around **level 6**. In essence, *the enabling technologies are all demonstrated and one by one entering real use, with active players pushing them toward scalable products*. The score of 6 reflects that **multiple autonomous robot types are already being delivered to paying users and scaled up**, though not yet a completely mature, ubiquitous commodity. The evidence above shows recent rapid progress, and with continued R&D and investment (and some regulatory evolution), this ART is on the cusp of broad impact within the next decade.

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[14] [2207.04914] Team CERBERUS Wins the DARPA Subterranean Challenge: Technical Overview and Lessons Learned

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[15] [16] New bee-inspired drone fleet works together to build 3D objects | UCL News - UCL – University College London

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## ART 05.034 Supportive Infrastructure for Autonomy

### 46. ART extraction

**A) Primary capability:** “*Supportive Infrastructure for Autonomy*” aims to turn physical environments into structured, robot-friendly spaces. The core capability is embedding an **intentional infrastructural layer** in buildings, vehicles, and public areas that actively assists autonomous robots. This makes environments **legible, predictable, and serviceable** for fleets of mobile robots and robotic manipulators, rather than forcing each robot to handle arbitrary, unstructured settings. It enables high-density, **coordinated multi-robot operations** that are safer and more reliable by offloading perception, navigation, and coordination tasks to the environment itself.

### **B) Key sub-components/variants:**

- **Robot-readable markers & surfaces:** Physical tags or standardized markings (e.g. visual fiducials, QR codes, reflective strips) embedded in floors, walls, or objects to convey position or identity information to robots, simplifying perception and navigation.
- **High-precision localization fields:** Installed infrastructure (like ultra-wideband beacons, Wi-Fi/UWB anchor grids, or vision-based reference points) that provides **centimeter-level positioning** for robots indoors where GPS is unavailable[1]. This allows robots to localize quickly and accurately without expensive onboard sensors.
- **Standardized docking & payload stations:** **Universal charging docks, battery swap stations, and load transfer points** built into the environment, enabling any compliant robot to autonomously recharge or exchange payloads. These are designed for interoperability (common connectors or wireless charging) so different vendors' robots can use the same infrastructure.
- **“Coordination posts” & traffic control units:** Distributed computing nodes or cloud services that manage multi-robot traffic and safety. They enforce **shared “rules of the road”** (right-of-way, speed limits, collision avoidance) for heterogeneous robots in the area, often by



monitoring positions and orchestrating movements via V2X (vehicle-to-everything) communications. Robots can request access to certain lanes or zones through these coordination points, which negotiate priorities and prevent deadlocks.

- **Digital interfaces & APIs:** A unified **environment API** through which robots query the infrastructure for map data, reserve corridors or elevators, get dynamic updates (e.g. construction zones or human worker presence), and obey environment-specific constraints. This requires common protocols/standards so robots from different manufacturers can all communicate with the infrastructure.

- **Human interaction & oversight tools:** Clear **physical cues** (lights, signals, designated robot lanes) that let people intuitively understand robot operating zones and statuses. **Call buttons or request stations** for humans to summon or dispatch robots. Central **fleet operations dashboards** for human supervisors to monitor robot activities in real time, inspect their status, and intervene or override if needed – ensuring all autonomous behavior is transparent and interruptible by people.

### C) Maturity indicators to seek:

- *Field demonstrations or pilot deployments* where environments have been retrofitted with robot-support infrastructure (e.g. warehouses, factories, hospitals, or campuses instrumented with markers, beacons, central controllers) and shown measurable improvements in robot efficiency or safety.

- *Interoperability standards or consortia* – evidence of industry-wide efforts (standards bodies, working groups) defining common interfaces for robot/environment communication, docking hardware, or fleet management protocols (for example, a standard for sharing a charging station or traffic data between different robots).

- *Prototype to product transition:* Existence of commercial **products or platforms** offering infrastructure-based solutions – e.g. companies selling multi-robot management systems, “autonomy through infrastructure” sensor networks, or standardized docking stations. Competing well-funded startups or consortium projects would indicate momentum toward commercialization.

- *Performance metrics beyond classical autonomy:* Data showing that with supportive infrastructure, robots achieve **higher reliability or lower cost** than standalone autonomy – e.g. simpler robots navigating with infrastructure assistance, precise indoor localization (few cm error) achieved via installed beacons, or denser robot traffic with no collisions under a coordination system.

- *Investment and scaling signals:* Reports of major facility upgrades for robot infrastructure (e.g. a factory spending capital on installing sensors or markers), or multiple deployments in “high-utilization zones” (like busy warehouses, airports, or hospitals) indicating that the value justifies the cost in certain scenarios. Funding rounds or partnerships (robot makers teaming with infrastructure providers, large end-users trialing the tech) would also reflect maturity.

#### 47. Evidence (10–20 recent, reliable sources):

48. **“Infrastructure to support robots: a practical, scalable model for comparative evaluation of design choices”** – G. McFassel, D. Shell (Texas A&M University); *IROS 2023, peer-reviewed conference paper; 10/2023. Link: [PDF][2]. Researchers formalize the notion that structured environments make robots more effective. They introduce a quantitative model (MDP-based) to evaluate adding infrastructure (markers, sensors, etc.) around robots. The model computes how many robots are needed for an infrastructure investment to pay off, when installation costs are recouped through performance gains, and how robot behaviors improve with such*

environmental modifications[3]. This provides a theoretical foundation to justify investing in robot-friendly infrastructure and helps identify break-even points, reinforcing the plausibility that such infrastructure can yield net economic and performance benefits.

49. **“An Experimental Evaluation of Indoor Localization in Autonomous Mobile Robots”** – O. Dagdeviren et al.; *Sensors (MDPI)*, peer-reviewed; 04/2025. **Link:**[4]. Compares indoor positioning technologies for mobile robots and finds Ultra-Wideband (UWB) outperforms Wi-Fi and BLE by a wide margin. With just 4 UWB anchors covering a 431 m<sup>2</sup> area, the system achieved <13.1 cm error (static) and ~28–30 cm error for moving robots[1] – an 88% accuracy improvement over Bluetooth and 93% over Wi-Fi. The study notes that UWB’s high precision, few anchors needed, and dropping hardware costs make it a prime candidate for “dominating technology in indoor tracking systems in the near future”[5]. This validates the feasibility of the “high-density localization fields” aspect of the ART: robust, infrastructure-based localization is technically mature and can reliably guide robots with centimeter accuracy indoors.
50. **“Positional inaccuracy investigation and innovative connection solution for robotic construction of load carrying structures”** – C.P. Chea, Y. Bai, Y. Fang; *Journal of Infrastructure Intelligence and Resilience*, peer-reviewed; 06/2025. **Link:**[6]. Describes a multi-robot construction experiment where two mobile robots and robotic arms collaboratively assembled a structure. The team embedded AprilTag fiducial markers in the environment as a positioning system to align the mobile robots and target components during assembly[6]. By using these robot-readable markers with an RGB-D camera, they quantified the positioning accuracy and even developed a magnetic self-alignment mechanism to counter minor errors. The successful automated assembly demo shows that adding simple visual infrastructure (tags) can significantly aid robot navigation/precision in complex tasks, underscoring the ART’s claim that “autonomy-native” modifications (like markers) make previously infeasible automation tasks viable by reducing robots’ cognitive burden.
51. **BMW Group’s Dingolfing Factory Pilot – Autonomy through Infrastructure** – BMW Group with Seoul Robotics & Embotech; BMW Press Release; 07/2022. **Link:**[7]. BMW deployed a pilot system where newly produced cars navigate autonomously through a factory area guided entirely by infrastructure sensors and a central controller (no onboard LIDAR/vision in the vehicles). The route (170 m) is equipped with cameras and LiDARs running Seoul Robotics’ perception software for vehicle localization and environment recognition, plus Embotech’s motion planning software to steer/brake the vehicles via V2X commands[7]. This “Automated Factory Driving” project (AFW) lets cars drive themselves from assembly to dispatch, using fixed infrastructure as the “eyes and brain.” It was slated to run through 2023 and then scale to more production lines[8]. Why it matters: This is a real-world proof-of-concept of the ART – a major OEM installed a shared infrastructure layer to automate vehicle movement\*, achieving Level-5 autonomy on private grounds without expensive vehicle sensors. It demonstrates both plausibility (technology works: the environment can safely choreograph multiple driverless vehicles) and progress toward maturity (a leading carmaker invested >€300 million in factory upgrades including this system).
52. **“VDA 5050 Explained – An Overview of the Evolving AGV Communication Standard”** – BlueBotics (Switzerland) tech blog; 08/2024. **Link:**[9][10]. Industry associations in Germany (VDA & VDMA) have developed VDA 5050, a standard interface to allow heterogeneous AGVs/AMRs and a central fleet software to communicate regardless of manufacturer. Version 2.0 was published in Jan 2022[9], expanding the standard to support sending actions (e.g. “slow down”) and for robots to share a detailed capability “fact sheet.” The blog notes that VDA 5050 is still in pilot/testing phase – it’s a “proposed” standard expected to evolve over 2–5 years, and currently no robot is fully compliant since the spec isn’t final[10]. Some early adopter projects have integrated mixed fleets via VDA 5050, but these required significant

custom coding for each new robot type and will need rework once the standard finalizes[10]. Relevance: This shows active efforts to achieve widely accepted interoperability standards – a key ART enabler – but also highlights that in 2022–2024 the process is ongoing. It indicates multiple vendors and end-users (e.g. BMW, which is cited as using VDA 5050) are collaborating to make shared infrastructure (like fleet managers, shared chargers, traffic control) a reality, even if full plug-and-play interoperability is a couple years away.

53. **“Multi-robot orchestration software focused on logistics improvement launched”** – Plant Engineering magazine; 03/2023. Link:[11][12]. Reports on the U.S. launch of CoEvolution’s AI-powered multi-robot orchestration platform at ProMat 2023. This software can control different brands and types of robots simultaneously, coordinating them “as a homogeneous fleet”[11]. By unifying control, it allows robots that traditionally operate in separate zones to work together in the same space, greatly improving space utilization and efficiency in warehouses[12]. The platform provides centralized traffic management and task orchestration across AMRs that handle various functions (forklifts, shelf carriers, etc.). CoEvolution cited that demand for multi-fleet orchestration is skyrocketing (projected 138% CAGR globally through 2027), as large warehouses seek to optimize mixed robot operations[13]. Significance: This is evidence of a commercial solution directly addressing the “coordination layer” of the ART. Multiple vendors (CoEvolution, and others like InOrbit, see below) are now competing in this space, indicating the transition from concept to market. The product’s value proposition – higher density robot traffic without chaos – aligns exactly with the ART’s goal of “dense, choreographed machine activity” enabled by shared rules and scheduling.
54. **“Scalable and heterogeneous mobile robot fleet-based task automation in crowded hospital environments – a field test”** – R. Valner et al. (Univ. of Tartu, Estonia); *Frontiers in Robotics & AI*, peer-reviewed; 08/2022. Link:[14]. Documents a real-world deployment of an open-source Robotics Middleware Framework (RMF) to coordinate a mixed fleet of service robots in a busy hospital. In Tartu University Hospital, the team deployed multiple mobile robots to transport lab samples through narrow, human-crowded corridors. The system used RMF as the interoperability and scheduling layer for different robots and IoT devices, handling task distribution and navigation in a human-aware manner[14]. They report lessons learned from this heterogeneous fleet automation and provide source code. Notably, RMF (developed by Open Robotics) is described as “highly capable... yet to reach full maturity,” meaning some integration challenges had to be overcome[14]. Why important: This is a field validation of the ART concept in a complex, unstructured environment (a hospital). It shows that with a coordination framework and some infrastructure (the robots share maps and schedules via RMF, and integrate with building elevators/doors), autonomous delivery can work even around crowds. It also underscores current limitations – continuous calibration/safety adjustments were needed, echoing the ART’s note that such infrastructure requires ongoing assurance as layouts and usage change.
55. **Human Oversight & Interoperability Platforms – (InOrbit, Meili Robots)** – Singh et al., FORMIGA project; *Frontiers in Robotics & AI*, 2025. Link:[15]. A 2025 robotics article reviews state-of-the-art fleet management systems and notes that commercial “RobOps” platforms now exist to supervise robot fleets with human-in-the-loop control. For example, InOrbit provides cloud-based dashboards for real-time fleet monitoring, incident alerts, and intervention, and includes tools to handle autonomy exceptions (like localization failures) remotely[15]. Likewise, Meili Robots offers an interoperability platform with features like shared maps, traffic control, and support for standard protocols (HTTP/MQTT, etc.) to link diverse robots[15]. These systems emphasize scalability (managing dozens to thousands of robots) and transparency, allowing operators to visualize and optimize fleet behavior. This evidences the “human interface and oversight” part of the ART: robust supervisory control products are

*emerging to make machine behavior inspectable and interruptible by humans, which is crucial for safety and trust. It also shows focus on interoperability – multiple robot types can be integrated via such platforms, aligning with the need for environment-level coordination across vendors.*

56. **“Autonomous Multirotor UAV Docking and Charging: A Comprehensive Review”** – I. Petrovic et al.; *Symmetry* (MDPI), peer-reviewed; 11/2025. **Link:**[\[16\]](#). Although focused on drones, this review highlights a broader infrastructure issue relevant to all robots: the lack of standardized docking/charging systems. It notes that current autonomous docking solutions are fragmented, and “a standardized system needs to be implemented to provide industry standards for docking systems in accordance with charging protocols and safety regulations.”[\[16\]](#) In other words, researchers call for uniform design of charging contacts, battery swap interfaces, and safety interlocks so any robot can use any compliant dock. Relevance: The ART’s vision includes standardized energy and payload transfer nodes; this source affirms that as of 2025, the community sees standardization as an unmet need (docking is still mostly proprietary). It underscores a current maturity gap: while one-off solutions exist (various vendors have made auto-chargers), an agreed standard would greatly accelerate deployment of such infrastructure at scale.

#### 57. Maturity score (1–7) and reasoning

**Overall Maturity Score: 5 (out of 7)** – The technology bundle “Supportive Infrastructure for Autonomy” is at **Level 5: early commercial prototypes with active industry competition, but not yet broadly adopted or scaled.**

**A) Why it’s not lower:** Multiple lines of evidence show we’ve moved past pure theory (Levels 1–2) and lab demos (Level 3). There are **functioning prototypes and pilots in real operational environments**, which is characteristic of Level 4 and above. For example, BMW’s 2022 pilot in a factory used infrastructure sensors to autonomously maneuver real vehicles[\[7\]](#) – a significant Proof-of-Concept in an industrial setting. Similarly, the Tartu hospital trial (2022) successfully integrated a heterogeneous robot fleet using a centralized framework[\[14\]](#), and startups like CoEvolution have demonstrated orchestration of mixed robot fleets in warehouses[\[12\]](#). These achievements show that the key blockers (like multi-robot traffic control and precise indoor positioning) **have been solved in prototype form**. Importantly, we also see **active funding and industry collaboration**: well-capitalized companies and consortia are working on standards (MassRobotics AMR group, VDA 5050 in 2022[\[9\]](#)) and launching products (e.g. multi-fleet management software in 2023[\[11\]](#)), indicating a commercial drive that goes beyond isolated experiments. This rules out Level 4; the field is no longer at a single proof-of-concept – it’s now about **refining and converging prototypes for broader deployment**, which aligns with Level 5.

**B) Why it’s not higher:** Despite progress, the **infrastructure is not yet widely deployed or standardized** – keeping it below Levels 6–7 (which require competing products delivered at scale and rising customer demand). The evidence highlights ongoing challenges that must be resolved before mass adoption: for instance, the need for **widely accepted standards** is still a bottleneck. The VDA 5050 case shows that while a version exists, full interoperability “promise is still out of reach” in 2024 without custom engineering[\[10\]](#). Likewise, the MDPI review (2025) explicitly calls out the absence of standard docking protocols[\[16\]](#) – meaning each new environment retrofit today often requires bespoke solutions, limiting scalability. There have been only *selective deployments* in high-utilization settings (one car factory pilot, a few warehouses/hospitals in trials), and those tend to be **costly, custom integrations**



rather than off-the-shelf rollouts. No evidence yet shows broad customer adoption or large production orders of “autonomy infrastructure” as a product – most projects are still pilots or early-stage deployments, and many existing robot installations still rely on robots’ onboard autonomy rather than instrumented environments. In short, the concept is proven viable (robots *can* benefit enormously from infrastructure support), but the ecosystem is in an **early commercialization phase**: multiple players are racing to define standards and offer solutions, and end-users are just beginning to test these in live operations. This fits Level 5, where well-funded actors are converging on production prototypes but market penetration remains limited.

**C) Sub-component breakdown:** *The ART comprises a bundle of technologies with different maturity levels, so we assessed each and averaged:*

- **Precision localization infrastructure: Level 6.** Technologies like UWB beacons and fiducial markers are quite mature – they’re already used in industry for indoor robot navigation (e.g. UWB-based RTLS is being shipped with ~10 cm accuracy[11]). Many warehouses use floor tags or reflectors for AGV guidance. The capability to localize robots via environment aids is essentially a solved problem technically and is in commercial use, although often in siloed, vendor-specific ways.
- **Robot coordination & fleet management systems: Level 5.** We see multiple startups and platforms (InOrbit, Meili, CoEvolution, Open-RMF) providing the “traffic control and scheduling” layer[11][15]. This segment has active competition and initial customers (especially in warehousing and logistics), and standards like VDA 5050 are being collaboratively developed[9]. However, the market is still shaking out – interoperability between systems is limited and many deployments are in pilot phase. The presence of at least **half a dozen players** and rapid growth forecasts for multi-robot orchestration show that the race is on (a hallmark of Level 5), even if a dominant design isn’t settled yet.
- **Standardized docking & physical infrastructure hardware: Level 3–4.** While automatic charging stations and tool-changing docks exist, there is **no widely adopted standard** (confirmed by calls for standardization in 2025[16]). Each vendor has its own approach (for example, one AMR might use QR codes for docking alignment, another uses Lidar), and retrofitting a facility with universal docking nodes is still mostly experimental. Some prototypes demonstrate >90% autonomous docking success in labs[17], but cross-compatibility and cost-effectiveness remain issues. This sub-component lags others; it’s around proof-of-concept to early prototype stage.
- **Human oversight interfaces: Level 5.** Fleet operations dashboards and robot supervision tools are available (InOrbit’s platform, for instance, is a product used by companies to manage robotics deployments[15]). The integration of humans into the loop (through control centers, alert systems, or “call buttons” in facilities) is being built into most commercial fleet software. It’s not fully standardized, but essentially every serious multi-robot solution now considers human interaction, indicating this aspect is keeping pace with the coordination systems above (around Level 5).

Given these differences, the **overall functionality is only as strong as its weakest links** – a fully “autonomy-native” environment requires all components (localization, coordination, docking, standards, HMI) to work together. Right now, some pieces (like localization) are ready to deploy, while others (like universal docking and true multi-vendor plug-and-play) are

still emerging. Therefore, we aggregate to **Level 5** as a balanced score. This reflects that *in limited high-value domains the infrastructure is moving into deployment*, but a comprehensive, standardized rollout across industries is a few steps away. Achieving Level 6/7 will require ironing out standards and reducing retrofit costs so that such supportive infrastructure can be installed broadly rather than only in bespoke, high-cost projects – a transition we expect to see as current pilots prove value and drive wider adoption.

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## ART 05.035 Optical/Microwave Power Beaming for Persistent Robotics

### 58. ART extraction

59. *Primary capability*: Enabling robots and remote devices to receive electric power via directed energy beams (laser or microwave), freeing them from bulky onboard batteries or frequent manual refueling. This promises **persistent operation over long durations** by delivering power wirelessly over line-of-sight distances, much like an “energy Wi-Fi” that can keep drones aloft or sensors active continuously.

60. *Key sub-components/variants*:

- **Optical (laser) power beaming** – high-intensity laser transmitters paired with photovoltaic receivers (specialized solar cells) to convert light to electricity. Offers tight beam focus and small receiver size, but performance can degrade in fog/rain and requires eye-safety measures.
- **Microwave/millimeter-wave power beaming** – phased-array microwave transmitters and rectenna receivers (antenna + rectifier) to convert RF to DC. Better penetration through weather and potentially safer power densities, but needs larger antennas for long range and faces spectrum regulation[1][2].
- **Beam tracking and relay networks** – gimbal or phased-array beam steering systems, plus sensors and software for active tracking of moving targets (drones, vehicles) to maintain alignment. May include airborne relay platforms to extend range beyond line-of-sight[3][4].
- **Safety & control subsystems** – fail-safes that cut off power if an object enters the beam, and power-density limits to avoid harming people, wildlife, or other equipment[5][6]. Also, software interfaces to allocate and schedule power delivery across multiple receivers (analogous to communication network management).

61. *Maturity indicators (evidence)*: We would expect **experimental prototypes and field trials** that demonstrate powering of real robots (e.g. keeping a drone flying for hours via beam). Key evidence includes: high-power transmissions over significant distances with efficient conversion; **continuous operation tests** (not just momentary lab experiments); integration of tracking and safety in realistic environments; **multiple organizations investing** (defense agencies, space agencies, companies) and moving from lab demos to deployable systems. Indicators of maturity would be **working proof-of-concept systems** meeting mission requirements (power level, range, safety)[7][8], and efforts to scale up (e.g. plans for operational pilots, commercial products, or standardization efforts).

62. **Evidence (10–20 recent, reliable sources)**

63. **DARPA long-distance laser power beaming record – May 2025 (U.S. DoD) – DARPA News Release**. DARPA’s POWER program set a new benchmark by delivering **>800 W of optical power over 8.6 km** in tests at White Sands, using a novel receiver with dozens of photovoltaic cells and a parabolic concentrator[9][10]. Over 1 MJ of energy was beamed in total, **shattering previous records** (previously 230 W at 1.7 km)[11]. This demonstrated unprecedented range and power, proving feasibility for powering remote sites or drones from the ground. It also validated >20% end-to-end efficiency



at shorter range with the new receiver design[12], showing that practical conversion efficiencies are achievable. This is a major plausibility milestone, indicating that high-intensity laser links can be maintained over tactical distances.

64. **NRL “SCOPE-M” microwave beaming demo (1.6 kW over 1 km) – Apr 2022 (U.S. Navy)** – *Navy Research Lab Press Release*. A Naval Research Laboratory team achieved **1.6 kW wireless power transfer across 1 km** using a 10 GHz microwave beam, the most significant power beaming demo in nearly 50 years[13][14]. Conducted at an Army range in Maryland, it exceeded the 1-kW target by 60%. Importantly, it stayed within internationally defined safety limits – the power density was low enough to be intrinsically safe for birds and people, without needing an interlock shutdown[5][6]. NRL also demonstrated the system at a second site (MIT), showing higher average power delivery over time[15]. NRL’s Paul Jaffe stated this work is **“very close to demonstrating a system we can deploy”**, highlighting that the remaining issues are being solved to move from experiment to usable field system[16]. This validates engineering feasibility for microwave beaming (which works in all weather) and shows military interest in near-term deployment to power remote bases or equipment.
65. **NTT/Mitsubishi 1-kW laser wireless power trial – Nov 2025 (Japan industry)** – *Technical news (Science Japan)*. In a public outdoor experiment, Nippon Telegraph & Telephone (NTT) and Mitsubishi Heavy Industries beamed a **1.035 kW laser over 1 km** to a silicon photovoltaic receiver, yielding ~152 W DC output (15% efficiency)[17][18]. They maintained the link for **30 minutes continuously**[18] under strong atmospheric turbulence (near-ground horizontal path), using beam-shaping optics and a beam homogenizer to counter intensity distortions[19][20]. This is the world’s highest reported efficiency for laser power transfer with a silicon PV under turbulent conditions[21]. It shows that **commercial players are tackling real-world issues** (beam spreading, atmospheric interference) and achieving stable power delivery over substantial distances. The success suggests viability for powering “remote locations where cables are hard to use,” with envisioned applications from isolated islands to drones and even satellites[22].
66. **Caltech Space Solar Power Demonstrator (MAPLE) – June 2023 (U.S. academia)** – *Caltech News*. Caltech’s Space Solar Power Project launched a prototype to orbit in Jan 2023, which **wirelessly transmitted power in space and to Earth** for the first time[23][24]. The MAPLE experiment consisted of a flexible array of microwave transmitters with custom chips. In March 2023 it lit up onboard LEDs via wireless transfer in free space, and in May 2023 it **beamed a detectable microwave signal down to a Caltech ground station**[25][26]. Though only a very small amount of power was received on Earth, this proves that a lightweight phased array can survive launch and operate in space as intended. It marks a crucial plausibility step for space-to-ground power beaming, validating that key components (flexible arrays, beam steering) work in the harsh space environment[24][27]. This boosts confidence in the underlying science and informs next designs, even as terrestrial applications are pursued in parallel.
67. **First power beaming from a moving aircraft – Nov 2025 (Overview Energy, U.S.)** – *IEEE Spectrum (reporting on startup demo)*. Startup Overview Energy demonstrated optical power beaming from a **moving airplane to ground receivers** – a Cessna aircraft at 5,000 m beamed near-infrared power while in flight[28][29]. Only a small

amount of power was transmitted (a “sprinkling”), but it used the same hardware the company plans for space solar satellites[30]. This is the **first-ever airborne moving-platform power beaming test**, showing that pointing and tracking can work in a real flight with turbulence and crosswinds. It validates a key capability needed for dynamic “power-at-a-distance” networks. Notably, former DARPA program manager Paul Jaffe joined the company, citing that the approach “gets around a lot of the showstoppers” and **appears technically viable for scaling up**[31][32]. This indicates growing expert confidence and the involvement of experienced talent to transition the tech beyond lab.

68. **Airbus “Power Beaming” lab demonstration – Sept 2022 (EU industry) – Airbus Newsroom (Innovation web story).** Airbus’ X-Works lab built a pilot system illustrating space solar power: in a demo for policymakers, they used **microwave beaming over 36 m** indoors to transmit energy from a “Space” transmitter to an “Earth” receiver, which in turn **produced green hydrogen and powered a model city**[33]. The setup used a ~5.8 GHz beam (with ~1.9 m antennas per reports) and represented a satellite sending power to ground[34]. While small-scale, it showcased end-to-end functionality (conversion of beam power to useful work like hydrogen generation) and was **successful in impressing stakeholders**[33]. Airbus estimates that by the early 2030s, operational prototypes could be in use, following a stepped approach from ground tests to aerial, then orbital systems[35]. They emphasize that at scale, the economics could rival large terrestrial energy projects, and that power-beaming could be a “game changer” for aircraft and energy distribution[36][37]. This demonstrates serious interest in Europe and the convergence of aerospace and energy sectors to push the technology.
69. **Emrod and ESA long-range WPT demonstration – Sept 2022 (NZ/EU startup collaboration) – Energy Global trade article.** New Zealand startup Emrod, with funding from ESA and Airbus, conducted **Europe’s first long-range wireless power demo for space solar applications**[38][34]. At Airbus’s site in Munich, Emrod’s system beamed power **over 36 m at 5.8 GHz** using a phased array ~1.92 m in size on both transmitter and receiver[34]. This achieved the conversion efficiency and alignment needed to convince ESA to propose a program (SOLARIS) to pursue space-based solar power[38]. ESA’s tech director noted this as a showcase of WPT as an emerging technology to solve sustainability challenges[38]. Emrod’s CEO announced they are now planning a larger terrestrial use-case demo and preparing for in-orbit tests[39]. The event underscores that **startups and agencies are actively de-risking the tech**, and that moderate-range microwave beaming is already functioning in a prototypical form.
70. **PowerLight “Infinite Flight” laser charging system – Dec 2025 (U.S. company) – Company Press Release.** PowerLight Technologies (formerly LaserMotive) unveiled a fully integrated **ground-to-air laser power beaming system** for drones, developed under a U.S. CENTCOM-sponsored program[40][41]. The system couples an autonomous high-power laser transmitter (with precision optical tracking and multi-layer safety interlocks) and a lightweight onboard receiver that converts the beam to DC to recharge the UAV’s battery in flight[42][43]. In testing, it has delivered “kilowatt-class power over kilometers” and successfully tracked moving UAS targets in real time[44][45]. By late 2025 it moved from component tests to integrated system tests, and **full flight demonstrations are scheduled for early 2026** on an ultra-long-

endurance drone platform[46]. This marks a true **proof-of-concept prototype aimed at operational use**, with a specific customer (DoD) in mind. The presence of safety-certified features and plans for imminent flight trials indicate the technology is transitioning out of the lab.

71. **Army STTR solicitation for powered UAVs – Apr 2023 (U.S. government) – U.S. Army SBIR Topic A23B-T023.** The U.S. Army issued a call for small-business R&D to develop a **power-beaming system for Group 1 drones** (under ~20 lb)[47][8]. The objective is a prototype that can deliver >100 W continuously to a drone at 500 m or more, ideally enabling indefinite flight (>200 W for unlimited endurance)[8]. The topic notes prior demos (e.g. a laser link to a UAV in a wind tunnel) and the need to progress to a more “relevant outdoors” demonstration with the drone in flight[48]. It highlights technical challenges: keeping a high-power beam locked on a moving target despite turbulence, ensuring eye safety, and managing the added weight/heat on the drone[49]. This solicitation is evidence that **military end-users see enough promise to invest in accelerating the technology**. It defines concrete performance targets (100–200 W at multi-hundred-meter range, eye-safe operation) that align with real mission requirements (doubling or eliminating the need for battery swaps)[8]. The funded effort will push lab successes toward field-capable prototypes, indicating the field is moving beyond academia into applied engineering development.

## 72. Maturity score (1–7) and reasoning

### Proposed Maturity Score: 4 (Proof-of-Concept demonstrated)

**A) Why not lower:** The core feasibility of optical/microwave power beaming is **well past theoretical and lab validation (Levels 1–2)**. In the last few years we’ve seen **multiple full-system demonstrations (Level 3)** that solved key hurdles: e.g., NRL’s microwave demo showed kW-level delivery over 1 km with safety and efficiency managed[13][5]; DARPA’s laser test achieved unprecedented range/power, breaking misconceptions about distance limits[9][50]. Importantly, we now have at least one **integrated prototype at or near operational conditions (Level 4)** – the PowerLight laser-UAV system with autonomous tracking and safety, slated for flight testing of “infinite” endurance in 2026[44][46]. That system combines all necessary pieces (high-power source, beam steering, airborne receiver, energy storage) and is backed by end-user interest, indicating it meets many functional requirements for real deployment. Likewise, Airbus and Emrod’s 2022 demos, though small scale, integrated generation, transmission, and usage (even making hydrogen), underscoring that the concept works end-to-end[33]. These achievements rule out Levels 1–3: the technology is beyond theory and isolated lab experiments – it **exists as functional prototypes tackling real-world conditions** (atmospheric turbulence, mobile targets, etc.).

**B) Why not higher:** The leap to Level 5 or above would require evidence of **multiple competing commercial products or near-products** and rapid scaling toward market. We are not quite there yet. While well-funded players are involved (DARPA, ESA, Airbus, CENTCOM, etc.), and startups like PowerLight, Emrod, and Overview are in the mix, we don’t yet see **products being sold or widely deployed (Levels 6–7)**. There is not yet a **fleet of robots powered by these systems in continuous use**, only one-off demos and pilot projects. No public evidence shows multi-company competition delivering units to customers at scale – most efforts are still government-sponsored trials or prototypes. To reach Level 5, for example, we’d expect several companies racing to finalize production-ready systems or clear plans for commercial launch. Instead, we see one company (PowerLight) just entering flight demo phase[46] and another (Emrod) preparing a terrestrial pilot[39]. **No off-the-shelf power-beaming infrastructure exists yet**; regulatory frameworks

(especially for high-power lasers/microwaves) are still in development. In short, the concept has been proven viable (hence Level 4), but it **has not reached commercial rollout**. Further evidence needed for the next level would include things like year-long field deployments powering real autonomous platforms, multiple vendors with turnkey systems, or significant private investment scaling manufacturing – none of which has been fully realized as of now.

**C) Sub-component considerations:** This ART comprises two main technical variants – **laser-based and microwave-based power beaming**. Both aim at similar functionality (untethered power delivery) and are at comparable maturity: each has seen successful prototypes but no wide adoption yet. Laser systems (optical) have achieved higher beam precision and have a clear path for drone applications (e.g., PowerLight’s kW-class laser charger nearing field test[51][46]). Microwave systems have demonstrated larger distances and weather-robust operation (e.g., NRL’s 1-km/1.6 kW and the Airbus/Emrod demo)[13][34], which is promising for infrastructure-scale use. **Neither variant is fully mature alone**, but together they reinforce the overall concept’s viability. Since their **functionality overlaps (each can service similar use-cases) and progress is parallel**, we treat the bundle’s maturity as a whole. Both sub-techs are roughly in the PoC/prototype stage, so averaging their maturity still yields  $\approx 4$ . We therefore assign **Level 4** as the composite score – **working prototypes exist proving the concept’s value, but commercial exploitation is still in its infancy**. The score reflects that the fundamental technology is demonstrated and on the cusp of practical deployment, while acknowledging that the transition to widespread, competitive products is the next step still to come.

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## ART 05.036 Gecko-Inspired Dry-Adhesion Mobility & Manipulation

### 1. ART extraction

- **Primary capability:** Enable strong yet residue-free adhesion on surfaces (even smooth or inverted) using micro-/nano-structured “gecko” pads that grip via van der Waals forces rather than suction or glue. This allows robots to **attach, climb, or grip objects** securely and **quickly release** by switching adhesion off, even in vacuum or low-pressure environments where conventional suction fails.

- **Key sub-components/variants:** Advanced **dry adhesive materials** (arrays of micro/nanofibers or wedges inspired by gecko setae) providing high shear and normal adhesion; **mechanical switching mechanisms** (controlled preload, shear or angle orientation, stiffness-tunable backing) to turn adhesion on/off; **embedded sensors** (e.g. capacitive or piezo sensors in the adhesive backing) to detect contact area and adhesion force in real time; **actuated mounts** (robotic fingers, tiles or track modules) that apply and peel the adhesive under software control; and **manufacturing techniques** (microfabrication, 3D printing, roll-to-roll processes) to produce large-area, durable adhesive pads. Application variants include gecko-like **robotic grippers** for smooth or delicate objects, **wall-climbing robots** or perching drones for vertical/overhead surfaces, and adhesive anchoring devices for space or industrial use.

- **Maturity indicators:** Evidence of **lab prototypes solving prior blockers** (e.g. rapid



switching adhesion, self-cleaning of dust, sensing integration), **field demonstrations** (robots using gecko adhesives in real environments like the International Space Station or factories), and **early commercial adoption**. Indicators include functional **proof-of-concept devices** meeting practical load and cycle-life requirements; **industry products or pilot programs** (e.g. an adhesive gripper sold for automation tasks); ability to **manufacture** adhesive pads in quantity with consistent performance; **multi-cycle durability** (tens of thousands of attach-detach cycles without failure); and **investment or partnerships** (multiple companies, including major materials or robotics firms, investing in or bringing products to market, signaling competition and scaling efforts).

## 2. Evidence (10–20 recent, reliable sources)

73. **Gecko-inspired self-sensing adhesive for intelligent adhesion – S. Li et al. (North Univ. of China & Xi'an JITU)** – *Chemical Engineering Journal*, 11/2025 (peer-reviewed)[1][2].  
*Researchers demonstrate a dry adhesive pad with an integrated flexible capacitive sensor backing, mimicking gecko skin's tactile feedback. The system can measure adhesion force in real time and achieved reliable sticking even on angled surfaces by using a compliant backing layer, addressing the lack of feedback and off-angle performance in earlier gecko adhesives.*
74. **Gecko Toe Pad-Inspired Robotic Gripper with Rapidly and Precisely Tunable Adhesion – S. Li et al.** – *Research (AAAS Open Science Journal)*, accepted 04/2025 (peer-reviewed)[3][4].  
*Presents a robotic gripper that uses gecko-inspired pads and a self-peeling mechanism to switch adhesion on/off in under 0.5 s, allowing it to pick up and release objects like glass sheets, silicon wafers, and flexible films. The gripper can modulate adhesion strength from 0 up to ~82.8 kPa by adjusting pad peeling angle, enabling fast handling of thin, fragile or heavy objects without residue. This indicates a major step in precision industrial grippers using dry adhesion.*
75. **Gecko-Inspired Controllable Adhesive: Structure, Fabrication, and Application – J. Liu et al.** – *Sensors & Actuators (Review)*, 03/2024 (peer-reviewed)[5][6]. *Comprehensive review of gecko-inspired adhesion technologies, covering designs like shape-memory polymer adhesives, magnetically switchable microstructures, and tunable backings, as well as fabrication methods (photolithography, 3D printing, etc.). It notes that while lab prototypes show high adhesive strength, scaling up production to large-area adhesives efficiently remains a challenge, and integrating all the gecko-inspired mechanisms into one product is a future goal. This underscores both the breadth of R&D in the field and the remaining hurdles in manufacturing and integration[6].*
76. **Testing Gecko-Inspired Adhesives with Astrobee Aboard the ISS – T. G. Chen et al. (Stanford/NASA Ames)** – *IEEE Robotics & Automation Letters*, 2022 (peer-reviewed)[7].  
*Reports the first on-orbit tests of a gecko-adhesive gripper on NASA's Astrobee free-flying robot inside the International Space Station. In early 2021, the adhesive gripper reliably perched on surfaces in microgravity, providing ~3.15 N of holding force for the robot[7]. The gecko materials performed as expected even after long storage in space, demonstrating functionality in vacuum/low-pressure and raising the technology's TRL for space applications. This validates the plausibility of dry adhesives for anchoring robots in environments where suction or magnets don't work.*
77. **OnRobot Gecko Gripper (SP Series)** – *OnRobot A/S (Denmark) product technical info*, 2023 (vendor technical doc)[8][9]. *A commercially available robotic gripper using gecko-inspired dry adhesive pads. It requires no cables, electricity, or air supply to operate[8]. The gripper comes in three sizes (SP1, SP3, SP5) named by payload (1–5 kg) and can lift smooth, shiny, or even*

perforated objects (like circuit boards or mesh) without marking the surface[9]. The adhesive leaves no residue on high-gloss materials, eliminating post-process cleaning, and can repeatedly attach/detach in manufacturing tasks. This product shows that dry adhesion has matured into a **deployable tool in industry**, handling use-cases where traditional vacuum grippers fail (e.g. grabbing objects with holes or sensitive surfaces).\*

78. **Surface Adaptable and Adhesion Controllable Dry Adhesive with Shape Memory Polymer – S. H. Lee, M. K. Kwak et al.** – *Macromolecular Rapid Comm.*, 04/2022 (peer-reviewed)[10]. Demonstrates a shape-memory polymer (SMP) based dry adhesive that achieves ~332.8 kPa of shear adhesion on various surfaces, yet “turns off” to a low ~3.7 kPa when released by changing its shape[10]. The SMP micro-structures can conform to uneven surfaces and then recover, enabling both strong grip and easy release. The authors used this adhesive in a prototype glass-handling system to effortlessly pick and place an ultra-thin glass film, showing its potential for high-throughput electronics manufacturing. This validates the feasibility of mass production line use, with high adhesion strength and rapid switching comparable to – or exceeding – conventional methods.
79. **geCKo Materials Dry Adhesive (micro-wedge technology)** – geCKo Materials, PBC (startup) technical spec sheet, 2024 (vendor technical doc)[11][12]. A U.S. startup (spun from Stanford research) offers a micro-wedge dry adhesive that is ultra-strong, reusable, and residue-free. The product can hold about 120 kPa of shear stress and needs effectively zero force to attach or detach, mimicking gecko toe function[12]. It attaches/detaches within milliseconds and is rated for up to 120,000 reuse cycles with no performance loss[11]. The company reports having developed a scalable manufacturing process (proprietary) to produce the adhesive in quantity[13]. This indicates that **industry-grade durability and lifetime** (hundreds of thousands of cycles) are being achieved, and efforts are underway to **mass-manufacture** dry adhesive components at viable cost.\*
80. **LIZARD in-orbit adhesive experiment (TU Berlin)** – 14th IAA Small Satellites Symposium (conference paper), 05/2023[14]. Describes the “Long-term Investigation of Zero-g, Vacuum and Radiation on Gecko materials” (LIZARD) experiment: a CubeSat mission scheduled for launch in 2024 to test gecko-inspired adhesive samples in space for 1 year. It will measure how vacuum, thermal cycling, UV radiation, and atomic oxygen exposure affect adhesion performance over time[14]. Multiple dry adhesive material variants will be repeatedly pressed and peeled from a surface in orbit, with load cells recording grip forces. This large-scale durability study, supported by European research agencies, shows a push toward qualifying gecko adhesives for real-world deployment (e.g. satellite docking or debris capture), examining longevity and failure modes in operational environments.
81. **Shin-Etsu Chemical to acquire Setex (gecko adhesive company)** – *Indian Chemical News*, 04/23/2024[15][16]. Reports that Shin-Etsu Chemical, a global industrial materials firm, acquired Setex Technologies – a startup commercializing gecko-inspired adhesives (formerly NanoGriptech, maker of Setex “Geckotape”). Shin-Etsu plans to combine Setex’s micro-fibrillar adhesive (which provides strong friction/adhesion via a gecko-like surface) with its own materials to create “ShineGrip” solutions[15]. Target applications include semiconductor manufacturing processes and other industries requiring repeated attach-detach without residue[16]. This is evidence of a **well-capitalized market actor investing in dry adhesion tech**: a major chemical company is betting on scaling up and applying gecko adhesives in high-value manufacturing, which signals confidence in the technology’s commercial potential.\*
82. **Controlled Dry Adhesion of Bio-Inspired Fibrillar Polymers: Mechanics, Strategies, and Recent Advances** – M. Alizadehyazdi et al. – *Bioengineering (MDPI)*, 2023 (peer-reviewed



review)[17][18]. Survey of recent advances in switchable fibrillar adhesives focusing on engineering challenges like contamination and repeatability. It highlights an approach by Alizadehyazdi et al. where a piezoelectric element was embedded with a gecko-inspired adhesive to actively shake off dust particles and concurrently serve as a contact force sensor[17]. This setup allowed the adhesive to be “turned off” via ultrasonic vibration for cleaning/tuning adhesion. Another case discussed is a hierarchical gecko-like adhesive with embedded magnetic particles that achieved self-cleaning and could even handle ultra-light objects when activated by a magnetic field[18]. These examples show that researchers are solving practical issues (dust fouling, mode of release) and integrating adhesives into multi-functional systems, improving reliability for real-world conditions.

### 3. Maturity score (1–7) and reasoning

#### Overall ART maturity score: 5 (Prototype/Demonstration phase).

**A) Justification of score:** The accumulated evidence shows that gecko-inspired dry adhesion has **progressed beyond laboratory proofs (Levels 2–3)** to working prototypes and initial commercial products. For example, a **market-ready gecko gripper is being sold and used in industry** (OnRobot’s device) – a strong sign that the core technology works under real conditions, **surpassing a mere proof-of-concept**[8][9]. Multiple academic groups have recently demonstrated **key performance breakthroughs** such as rapid switchable adhesion[3], integrated sensing[1], and extreme durability ( $10^5+$  cycles)[11], indicating that previously blocking issues (slow release, lack of feedback, short lifespan) are being solved. These achievements collectively **rule out maturity Levels 1–3** (the concept is well beyond theory or single lab tests). The technology as a bundle is now around Level 5: there are **functioning prototypes meeting functional requirements** and clear advantages over incumbents, with **active investment to commercialize them**. For instance, the Shin-Etsu acquisition of Setex in 2024 shows that **well-capitalized industry players are entering the race**[15], aiming to scale production and deploy gecko-adhesive solutions in manufacturing – behavior characteristic of Level 5. Recent field trials, like NASA’s ISS demo, further validate the technology in challenging environments[7], signaling that gecko adhesives are no longer confined to the lab.

However, evidence for Level 6 (broad product delivery and scaling) is still **emerging rather than fully realized**. While one or two products exist, we do not yet see **wide competition with multiple suppliers or high-volume adoption across industries**. The OnRobot gripper addresses niche use-cases and startups like geCKo Materials and Setex are just transitioning to scale; we don’t have reports of millions of units shipped or sharply dropping costs yet. Furthermore, **certain sub-systems remain at prototype stage** – e.g. wall-climbing robots using these adhesives are still mostly experimental, and full integration of sensing + adhesion in a commercial device is likely a next step. Thus, the ART hasn’t reached Level 6 “customer-delivered products in increasing volumes” across the board. Its trajectory is upward, but **some reliability and generality challenges (rough surface performance, self-cleaning, etc.) are still being actively researched**[17][18], preventing a jump to mass deployment in all scenarios. The score of **5** reflects a technology bundle on the cusp: proven in demos with clear use-case value, supported by significant R&D and early commercialization, but still maturing in manufacturing scale and breadth of adoption needed for the next level.

**B) Sub-component breakdown:** Since the ART consists of multiple integrated elements (materials, mechanisms, applications), their maturities vary:

- **Dry adhesive materials: Level 6.** The core adhesive films/pads themselves are quite advanced – one company has delivered them as a product (Setex’s Geckotape, OnRobot pads) and achieved large-scale fabrication runs. They offer high strength (100+ kPa) and long lifetimes[12][11]. The **acquisition of Setex by a major chemical company**[15] underscores that adhesive *materials* are entering commercialization and being internally funded by industry (a Level 6 trait).
- **Adhesive-based grippers/manipulators: Level 5–6.** OnRobot’s gecko gripper (launched ~2019 and updated through 2023) is being sold worldwide, indicating a working **production prototype** in use. No direct competitor product is widely known yet (OnRobot is somewhat unique), but the presence of at least one **established vendor shipping units** and startups preparing competing offerings (e.g. ShineGrip from Shin-Etsu) suggests a transition from Level 4 to **Level 5+** for manipulation applications. This segment benefits from relatively controlled environments (flat parts, indoor factories), making commercialization easier.
- **Climbing robots / mobility systems: Level 3–4.** Attaching robots to walls or ceilings via dry adhesion has been demonstrated in labs (e.g. *Stickybot*, *UNiclimb*) and specialized trials (astronaut tests on ISS) but **not yet productized** for broad use. Issues like uneven surfaces, dust, and safety have kept this sub-application mostly in prototype stage[17][18]. No off-the-shelf wall-climbing robot using gecko pads is on the market as of 2025. Thus, mobility use-cases lag behind grippers, roughly at proof-of-concept Level 3–4 (working demos, but not routine deployment).
- **Sensing and control integration: Level 3.** The fusion of dry adhesives with embedded sensors and smart control (for auto-tuning preload, etc.) is very new – e.g. the self-sensing pad from 2025[1]. This is at a **lab prototype** stage (TRL 3) with clear functionality shown, but not yet in products. It will likely advance in the next few years as these intelligent adhesives are tested in pilot projects.

Considering these sub-scores, the **overall functionality spans from mid/high to early stages**. The **core adhesive tech and basic gripper use** are at a higher maturity (approaching early commercial rollout), while more complex integrated systems (climbing robots, smart adhesives) are a step behind. The **total value of the ART comes from combining these elements**, so the bundle’s maturity is best represented by an **average** of the parts rather than the maximum. By averaging the above:  $(6 + 5.5 + 3.5 + 3) \approx$  **approximately 5**, we arrive at a composite Level 5. This aggregation reflects that the **fundamental capability is proven and entering the market (thanks to sub-components at ~5–6), but full integration and widespread adoption are still in progress (due to components at ~3–4)**.

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## Group 6 – Additive, Agile & Digital Manufacturing

### ART 06.037 Multi-Material & Hybrid 3D Printing

#### 83. ART extraction

84. *Primary capability:* Additive manufacturing systems that can **print complex parts using multiple different materials in one build**, combining polymers, metals, ceramics, and conductive inks in a single 3D printing process. This enables fabrication of entire functional assemblies in one step, with integrated mechanical, thermal, and electrical features that traditionally require separate manufacturing and assembly steps.

85. *Key sub-components/variants:*

- **Polymer–Metal Hybrid Printing:** Processes that print plastic and metal together (or sequentially) to create lightweight parts with embedded metal reinforcement or circuitry. For example, using dual extrusion or print-and-plate techniques to integrate conductive metal pathways into polymer structures.

- **Multi-Metal & Graded Alloy Printing:** Techniques (e.g. multi-material powder bed fusion or directed energy deposition) that combine different metal alloys in one part or create functionally graded metal components (one metal transitioning to another), providing locally tailored strength, conductivity, or heat resistance.
  - **Polymer–Polymer & Composite Multi-Material:** Multi-nozzle or multi-resin printers that deposit different polymers (rigid, flexible, elastomeric, colored, etc.) in one object, as well as composite printers that embed continuous fibers (carbon, glass, Kevlar) into thermoplastic parts for enhanced stiffness.
  - **Embedded Electronics Printing:** Integrating conductive inks, pastes or wires during printing to embed **electrical circuitry, sensors, antennas, or connectors** directly inside structural parts. This often involves hybrid systems (e.g. combining material extrusion with direct-ink writing or aerosol jetting) to print insulating structural material and conductive traces in one job.
  - **Hybrid Additive–Subtractive Systems:** Machines that **combine 3D printing with secondary processes** like CNC milling, laser machining, or pick-and-place. These hybrids can deposit material and then mill surfaces or drill channels in situ, enabling precision features, smooth finishes, or insertion of components during the build.
86. *Maturity indicators:* Evidence of **working prototypes and commercial systems** that print multiple materials in one go (e.g. demo parts with integrated metals and polymers, or electronics). Reports of **functional parts printed with multi-material AM** (e.g. a 3D-printed device with embedded circuits or a graded metal part with improved performance) indicate scientific feasibility. The emergence of **commercial printers or spin-offs** offering multi-material capabilities, **pilot production or field demonstrations**, and **multiple companies investing in development** would signal progress toward commercialization. Key milestones include proof that multi-material parts meet performance requirements (strength, conductivity, etc.) and that **process control challenges (bonding between materials, calibration)** are being solved, as well as evidence of **investment, partnerships, or early customer adoption** of such systems.
87. **Evidence (10–20 recent, reliable sources)**
88. *Fraunhofer IKTS / AMAREA – Multi-Material Jetting Platform (Press release, 09/2023):* Researchers at Fraunhofer IKTS (Germany) spun off a company (AMAREA Technology) to commercialize a **multi-material inkjet 3D printer** that can combine up to **six different materials (ceramics, metals, glass, polymers, etc.) in one print**. They demonstrated convincing prototypes for industrial clients and plan a 2024 market launch of a printer with six printheads (achieving ~70–100 µm accuracy and 8–12 cm<sup>3</sup>/h per head). An optional in-line laser module will even polish or machine surfaces during printing[1][2]. *This shows a well-supported effort to bring multi-material printing (including ceramics and metals together) to commercial reality, with funding and a roadmap for scaling.*
89. *Lithoz CeraFab Multi 2M30 – Metal/Ceramic/Polymer Printer (Trade news, 10/2023):* Lithoz (Austria) unveiled a new multi-material 3D printer (CeraFab Multi 2M30) capable of **printing ceramics combined with metals or polymers in one part, even within a single layer**[3]. They displayed **functional multi-material parts (including embedded electronic devices)** at Formnext 2023. *This provides evidence of an industrial AM machine achieving in-situ combination of vastly different material classes (e.g. insulating ceramic with conductive metal), indicating the technical feasibility of tightly interleaving materials during a single build.*

90. *DMG Mori LASERTEC 65 DED Hybrid – Multi-material metal + machining (Industry news, 10/2022)*: Machine-tool leader DMG Mori demonstrated a **hybrid directed-energy deposition (DED) machine** that can deposit metal and then mill it in the same setup. For example, a LASERTEC 65 DED Hybrid was used to 3D-print a copper or bronze core with internal cooling channels, **machine precision channels**, then deposit a tool-steel outer layer – all in one continuous process[4]. *This showcases multi-material metal printing (two different alloys in one part) combined with in-situ machining, proving out a key hybrid capability: making parts like molds with one metal embedded in another, something impossible via conventional methods.*
  
91. *Griffis et al. – Multi-Material Laser Powder Bed Fusion Demo (npj Adv. Manufacturing, 03/2025)*: A research team (Penn State and collaborators) **demonstrated multi-material laser powder bed fusion** by selectively depositing different metal powders in one build. They printed a complex gyroid structure composed of **904L stainless steel and bronze** in a single job, and analyzed the melt-pool, interface microstructure, and mechanical performance[5][6]. The study showed both the **opportunities and challenges** of MM-LPBF: such as achieving good bonding at the material interfaces and managing defects, with potential applications in thermal-management surfaces and biomedical implants. *This provides experimental proof that high-resolution metal 3D printers can fabricate graded or discrete multi-metal parts, though it also underscores remaining issues (e.g. cracks, property mismatches) when fusing dissimilar metals.*
  
92. *Zhu et al. – 3D Printed Soft Robot with Embedded Electronics (Science Advances, 12/2025)*: Researchers from Shanghai Jiao Tong Univ. and NTU Singapore reported an **integrated Digital Light Processing (DLP) + direct-ink writing** system to fabricate soft robots with electronics in one go. They printed soft silicone structures *and simultaneously* printed stretchable conductive inks as wires and sensors within the body[7]. The result was autonomous soft robots with **embedded tactile sensors, antenna for wireless communication, onboard actuators, and even obstacle avoidance capability**, all produced without manual wiring[8]. *This peer-reviewed work demonstrates the plausibility of printing functional devices (in this case, robots) that come out of the printer already containing working circuits and sensors, a key promise of multi-material AM.*
  
93. *Wilt & Lewis (Harvard) – Printed Soft Actuators with Internal Channels (Advanced Materials, reported 02/2026)*: A Harvard research team developed a **rotational multi-material printing method** using a single coaxial nozzle to deposit two materials at once[9][10]. They printed soft robot structures with a polyurethane elastomer as the exterior and a fugitive ink (poloxamer gel) as the interior. After printing, the sacrificial core was washed out, leaving **complex internal channels** in the part[10]. When these channels were pressurized, the structures achieved **programmable bending and motion** without any assembly[11]. *This innovation shows how multi-material deposition (structure + sacrificial material) can create integrated fluidic actuators in one step, eliminating the need for molds or assembly of soft robotic components.*
  
94. *Patadiya et al. – Multimaterial AM Review & Antenna Example (ACS Applied Eng., 2025)*: A comprehensive 2025 review on multimaterial additive manufacturing noted rapid progress in multi-nozzle and multi-ink systems. For instance, it describes a commercially available **nScript 3Dn-300 multi-material printer** (FDM plus micro-dispensing) that was used to fabricate a functional low-profile **antenna** by printing one dielectric material (polycarbonate) and simultaneously depositing a conductive silver ink trace[12]. *This example highlights real-world functionality: a fully printed RF device with integrated conductors, demonstrating that multi-material printers are already yielding working components (antennas) that meet electrical performance goals.*



95. *Nano Dimension DragonFly IV – 3D Printed Electronics System (Vendor technical doc, 06/2023)*: The DragonFly IV is a commercial additive electronics printer that **simultaneously deposits conductive metal (silver nanoparticle ink) and insulating polymer** to build complex circuit boards and radiofrequency devices layer by layer. Nano Dimension’s press release notes this system can **fabricate in-situ capacitors, coils, antennas and transformers** by printing conductive and dielectric materials together[13]. It has been adopted by research institutes (e.g. University of Stuttgart) for developing next-gen quantum sensor hardware. *This provides evidence of a shipping product enabling multi-material (metal-polymer) printing, albeit applied to electronics: it underscores that tightly integrated multi-material printing is commercially feasible in a niche (PCB/prototyping) and is now spreading to advanced R&D applications.*
96. *Zhang et al. – Continuous Fiber Composite 3D Printing (Composite Structures, 06/2023)*: A 2023 study optimized 3D printing of **continuous carbon fiber reinforced polymer** parts. By tailoring fiber orientation and topology, they achieved **256% higher stiffness and 305% higher strength** compared to standard Markforged printed composites[14][15]. Markforged’s existing printers already combine nylon with continuous carbon fiber to produce “**metal-strength**” composite parts, and this research shows the performance can rival aerospace-grade aluminum[15]. *This illustrates a mature subset of multi-material AM – continuous fiber reinforcement – which is commercially deployed. The ability to print a polymer part with embedded fibers for local strength is a concrete (and successful) example of tailoring material properties within a print, aligning with the ART’s claims.*
97. *Npj Review – Challenges in Metal-Polymer AM (npj Adv. Manuf., 2025)*: A recent review on heterogeneous metal–polymer additive manufacturing noted that **combining metals and polymers in one structure remains fundamentally challenging** due to their disparate properties (thermal expansion, melting points, etc.), which has historically limited progress[16]. Nonetheless, it highlights broad interest from aerospace to biomedical sectors in overcoming these issues[17]. *This underscores that while multi-material printing is scientifically plausible (as shown by lab demos), materials compatibility is a key hurdle. It validates the ART’s note that material compatibility windows and interface bonding are critical constraints, thus framing current R&D focus areas that need to be solved for full maturity.*

#### 98. Maturity score (1–7) and reasoning

#### Overall Maturity Score: 4 (Proof-of-Concept)

**A) Justification for score:** Multi-material & hybrid 3D printing has clearly moved beyond theory (Levels 1–2) and basic lab demos (Level 3) into the **proof-of-concept and early prototype stage (Level 4)**. Strong evidence shows **functional prototypes** and even niche commercial products: for example, researchers have printed working devices like antennas[12], electronic soft robots[7], and soft actuators[11] entirely via multi-material AM, proving the core functionality is achievable. Key technical barriers such as multi-material powder bed fusion have seen breakthrough demos (e.g. steel–bronze parts[5][6]), indicating that previously blocking problems (like fusing dissimilar metals) can be solved in principle – a hallmark of reaching Level 3. We even have **first-generation commercial systems**: continuous fiber printers and 3D electronics printers are on the market, and a six-material ceramic/metal printer is launching (Fraunhofer’s AMAREA, 2024)[1][2]. These achievements collectively **exceed Level 3** because they meet functional requirements in real applications (strength of composites rivaling metal[15], printed circuits functioning at GHz frequencies, etc.). However, the technology is **not yet widely adopted or broadly commercialized**, which holds it at Level 4. We do not see multiple major manufacturers shipping general-purpose

multi-material machines in high volume – instead, the field is still characterized by isolated specialized systems and ongoing R&D. There is growing investment and competition (a positive sign toward Level 5), such as new entrants (start-ups, spin-offs, and established AM companies like Lithoz, DMG Mori, Stratasys, Nano Dimension, etc.) developing multi-material capabilities. But these efforts are just coalescing now, with most products in beta or low-volume production. The **remaining gaps** (material incompatibilities, process stability, cost and speed limitations) are widely acknowledged[16] and no vendor yet offers a mature, turnkey “print-all-materials” solution for broad industry use. Thus, the evidence best fits a **Level 4 PoC stage**: the concept is proven viable with prototypes meeting key functionality, and it’s poised to move toward commercialization once scalability and reliability improve.

**B) Evidence ruling out lower levels:** The reported accomplishments clearly transcend a purely theoretical or early-experimental stage. Level 1/2 are ruled out by the numerous **experimental demonstrations in the last few years** – e.g. printing **fully integrated functional objects** (soft robots[7], RF antennas[12], multi-material lattice structures[5]) that work as designed. Level 3 (lab prototype solving a key hurdle) has been surpassed as well – for instance, the **DragonFly IV printer is already delivering multi-material electronic devices to paying customers**[13], and **Markforged’s multi-material composite printers are deployed in industry**, indicating viability beyond one-off lab prototypes. The breadth of actors (academic groups, government labs, start-ups, and established companies) all pushing this technology further also suggests we are beyond a singular prototype – the concept has momentum and **multiple proof-of-concept implementations** in different domains (electronics, aerospace, biomedical, etc.).

**C) What’s missing to reach higher levels:** To progress to Level 5 and above, we would expect to see **multiple well-capitalized firms racing to productize multi-material AM**, and evidence of reliable production-grade machines entering the market. While we do see early market entrants (spin-offs like AMAREA, and companies like Nano Dimension or Stratasys in specific niches), the field lacks a **general, high-volume solution** so far. There isn’t yet a fully **scalable, cost-effective multi-material printer** that can, for example, replace multi-step manufacturing lines for a broad range of parts – current machines are either limited in material combinations, have slow throughput, or require highly controlled conditions and expert operators (as noted in the ART description). To reach Level 5–6, the technology needs: improved material compatibility (strong bonding between disparate materials, without manual intervention)[16], **higher reliability and calibration** for complex builds (some evidence, like the need for careful control in metal-polymer printing, shows this is still being worked out[18]), and **economic viability** for more than specialized low-volume use. We would also expect to see **expanding adoption** – e.g. more companies purchasing multi-material machines for production, and perhaps standards or supply-chain integration – which has only just begun. In summary, the **functionality has been proven (Level 4)**, but **scaling and commercialization** are in early days; with continued progress, the technology could soon enter Level 5 (multiple competitive prototypes approaching market). For now, it remains a promising proof-of-concept with clear practical demonstrations but limited deployment.



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## ART 06.038 Digital Twin & Simulation-Driven Production

### 99. ART extraction

100. **Primary capability:** Real-time digital duplication of each significant manufacturing asset or process, allowing continuous monitoring and **simulation-driven optimization** of production operations. This enables testing of changes virtually (at accelerated timescales) before implementing them in the physical factory, thereby improving control over complex processes and decision-making.
101. **Key sub-components/variants:**
- High-fidelity *physics-based models* of equipment and processes, combined with data-driven surrogate/AI models to mirror and predict the system's behavior.
  - **Real-time sensor integration and data streaming** (Industrial IoT) from physical machines to their digital twins, providing up-to-date state information.
  - **Digital thread connectivity** linking physical and virtual counterparts (e.g. via industrial protocols) for bidirectional control and feedback.
  - **Simulation and virtual commissioning tools** that test process changes, new product introductions, scheduling scenarios, or maintenance actions in a virtual environment (including 3D visualizations and AR/VR dashboards) without disrupting real production.
  - **Automated control agents and AI** that can autonomously adjust process parameters within safety/quality constraints, using the twin to evaluate outcomes and continuously learn and calibrate models.
  - **Infrastructure and integration** elements such as edge/cloud computing resources to run simulations in sync with operations, and adapters for legacy equipment to participate in the digital twin ecosystem.
102. **Maturity indicators for evidence:**
- **Field pilots & deployments:** Documented *proof-of-concept demonstrations in actual production lines* or factories, showing that digital twin systems function at scale and yield improvements (e.g. reduced downtime, improved throughput or quality).
  - **Commercial platforms & industry adoption:** Availability of vendor-supported **digital twin platforms or toolkits** (from major industrial tech firms) and case studies of **multiple well-funded companies implementing digital twins**, indicating competition and investment in the technology.
  - **Performance benchmarks:** Empirical results showing the twin technology's feasibility (e.g. real-time co-simulation achieved, predictive accuracy improvements, optimization outcomes) and clear *benefits over traditional methods* (such as faster ramp-up or cost savings in production).
  - **Standardization and consortia:** Presence of **industry standards (ISO, etc.)** and large research or government programs dedicated to digital twins (signifying consensus on frameworks and significant R&D funding), as well as efforts to integrate the technology into **workforce training and best practices**.
103. **Evidence (10–20 recent, reliable sources)**
104. *Digital twin driven smart factories: real time physics based co-simulation using edge a.i. and federated learning* – V. Padmavathi et al., Scientific Reports (peer-reviewed), Dec 2025.  
**Findings:** Proposes an edge-computing digital twin framework for manufacturing that combines physics simulation with federated AI. In testing, it achieved **35% lower latency and**

**a 13.2% throughput increase** compared to a cloud-only baseline[1], demonstrating feasibility of real-time, scalable co-simulation for factory processes. (Shows plausibility of fast, AI-enhanced twins for on-site control.)

105. *A Digital Twins Platform for Digital Manufacturing* – **Maheshi Gunaratne et al. (Swinburne Univ.)**, *Electronics* (MDPI journal, peer-reviewed), Jan 2026. **Findings:** Introduces a comprehensive digital twin framework (physical twin + virtual twin + digital thread) and platform for production lines. A **case study in composite airframe manufacturing** is presented where sensor-fed AI models in the twin predicted product quality and **cut curing time for a composite part**, improving efficiency while maintaining quality[2]. (Demonstrates a working prototype that integrates real-time shop-floor data and modeling to optimize an advanced manufacturing process.)
106. *Digital twin system for manufacturing processes based on a multi-layer knowledge graph model* – **Chang Su et al.**, *Scientific Reports* (peer-reviewed), Apr 2025. **Findings:** Describes a knowledge-graph-based architecture to integrate heterogeneous data for a manufacturing digital twin. Validated in an **aero-engine blade production line**, the system improved part precision (maximum contour error reduced from 0.073 mm to 0.062 mm) and raised the yield (qualification rate from 81.3% to 85.2%) over 5 months[3]. (Shows a deployed digital twin improving quality control and anomaly detection in a real production process.)
107. *Digital twin key technology on rare earth process* – **Hui Yang et al.**, *Scientific Reports* (peer-reviewed), Aug 2022. **Findings:** Explores applying digital twins in the *rare-earth extraction* industry (a complex chemical process with nonlinear, coupled variables). The paper presents methods for soft-sensor measurements, process simulation, and control optimization within a digital twin of a cascade extraction process. A **model validation and case study** confirmed the twin's feasibility in simulating the process and predicting failures[4], suggesting the approach can improve efficiency and fault management in process industries.
108. *Digital Twins for predictive maintenance: A case study for a flexible IT-architecture* – **P. Mrzyk et al.**, *Procedia CIRP* (conference proceedings), 2023. **Findings:** Investigates a standardized, reusable software architecture for deploying digital twins in different scenarios. The team built a flexible IoT and service-oriented architecture and applied it to **two use cases (a compressor and a wind turbine)** for predictive maintenance. They demonstrated that much of the integration could be reused between cases, **reducing the effort to build new digital twins** by leveraging a common architecture[5]. (Supports plausibility by addressing integration costs, and shows progress toward scalable twin deployments across equipment types.)
109. *BMW Group scales Virtual Factory* – **BMW Group (press release)**, Jun 2025. **Findings:** Reports that BMW has **implemented digital twins for over 30 production sites worldwide** as part of its “Virtual Factory” initiative[6]. This virtual commissioning environment allows planners to simulate factory changes and new vehicle integrations entirely in software. A notable result is that a collision-check process which once took ~4 weeks of physical tests now takes **3 days via the digital twin**, and BMW projects **30% lower planning costs** using these tools[6][7]. (Demonstrates an advanced real-world deployment: digital twin technology is actively used at enterprise scale to reduce time and cost in production planning.)
110. *Manufacturing Digital Twin Standards* – **Guodong Shao (NIST)**, EDTconf 2024 (conference paper), Sept 2024. **Findings:** This paper (from the U.S. National Institute of Standards and Technology) surveys digital twin use cases and challenges in manufacturing, and reviews ongoing **standardization efforts**. It highlights the new **ISO 23247 Digital Twin Framework for Manufacturing** and maps out a standards roadmap[8]. (Significance: Indicates

that industry and standards bodies are actively defining interoperability and best practices for digital twins, a sign of maturing technology and consensus on implementation approaches.)

111. **CHIPS Manufacturing USA “SMART” Institute for Digital Twins – U.S. Dept. of Commerce/NIST press release**, Nov 2024. **Findings:** Announces a \$285 million award (as part of a \$1 billion public-private effort) to establish “**SMART USA**”, a national institute dedicated to digital twin technology in semiconductor manufacturing[9]. The institute’s goals include using twins to **cut chip production costs >35% and cycle times ~30%**, and training 100k workers on twin tech[10]. (This represents a major government-backed investment in scaling digital twins, underlining both the feasibility and the expected economic importance in a critical industry.)
112. *Economics of Digital Twins: Costs, Benefits, and Economic Decision Making – Douglas Thomas (NIST)*, NIST Advanced Manufacturing Series report, Oct 2024. **Findings:** Analyzes the cost-benefit tradeoffs of digital twin adoption in manufacturing. It concludes that under plausible conditions, implementing digital twins could yield on the order of **tens of billions of dollars in annual value** across the industry (estimated ~\$37.9 billion potential, with a median scenario of ~\$27 billion)[11]. (This provides an economic rationale for the technology, showing that even with uncertainties, the productivity and efficiency gains make a strong business case as the technology matures.)
113. *Digital Twin for Flexible Manufacturing Systems and Optimization Through Simulation: A Case Study – Adriana Florescu, Machines* (MDPI, peer-reviewed), Nov 2024. **Findings:** Describes creating a digital twin for a real flexible manufacturing cell (robotic machining of cylindrical parts). The virtual model mirrored each device in the cell, enabling both time-based and discrete-event simulations. This allowed the team to **identify equipment collisions and errors in the system and test optimized solutions (like adding collaborative robots) virtually**[12], before physical implementation. (Demonstrates practical *virtual commissioning*: using a digital twin to detect design flaws and improve a production system, proving the concept can prevent costly mistakes and optimize layouts in advance.)
114. **Maturity score (1–7) and reasoning**

**Score: 6** (on the 1–7 scale). This score reflects that *Digital Twin & simulation-driven production* is transitioning from successful prototypes and pilots into **early industry-scale adoption**, with multiple major players delivering solutions, but not yet a fully ubiquitous commodity across all of manufacturing.

- **Why not lower:** The technology is well past the basic research stage (Levels 1–3). **Lab validations and pilot projects** have been abundant – for example, high-fidelity digital twins with real-time control have been demonstrated in research (e.g. real factory testbeds achieving performance gains[1]). More importantly, there are now **real-world production implementations**. BMW’s deployment of digital twins in 30+ plants shows that full-scale operational prototypes are in use, yielding tangible benefits (faster retooling, cost savings)[6]. The emergence of multiple **commercial offerings and active competition** (Siemens, GE, Dassault, PTC, etc., all marketing digital twin platforms) and large investments like the \$1B SMART USA institute[9] indicate the field has moved beyond isolated PoCs into a race for scalable products. These facts rule out Levels 4–5, which correspond to one-off prototypes or single-actor development; we already see **multiple well-capitalized actors and early customer adoption**, consistent with Level 6.
- **Why not higher:** The technology hasn’t yet reached the point where *digital twin systems are a standard, widely-installed solution across industry*, which would correspond to Level 7. While

demand and interest are rising, current adoption is still **uneven** – mostly in large enterprises or specific high-value sectors (auto, aerospace, semiconductors) and often in pilot/initial deployment phases. There is not yet a “plug-and-play” ecosystem of competing off-the-shelf products used by the majority of manufacturers. Key challenges remain (as noted by NIST[13]) in integrating legacy equipment, ensuring data interoperability, and building trust in these systems. Those challenges are being addressed (via standards like ISO 23247 and consortia), but until digital twins are as common as, say, traditional SCADA/PLC systems on every factory floor, the technology falls short of the saturation implied by Level 7. **In summary**, we have strong evidence of viability and scaling (widespread pilots, some full production rollouts, multi-billion-dollar investments), but *not yet the broad, mature market penetration* that defines the highest maturity level.

- **Sub-component considerations:** This ART actually encompasses a spectrum of capabilities – some are more mature than others. For instance, **virtual factory modeling and offline simulation** for production planning is already quite advanced (e.g. BMW’s virtual commissioning system, a Level~6 deployment). In contrast, **closed-loop autonomous control** via digital twins (where AI agents continuously adjust a live process) is earlier in adoption, perhaps around Level 4–5 in practice (proven in prototypes like predictive-maintenance twins[5], but not yet routine). Because these facets share the same overall goal (a data-driven cyber-physical production system) and are converging, the *overall maturity score is taken as ~6*. We chose Level 6 (competing products starting to scale to customers) since the core functionality – using digital replicas to optimize production – is already being delivered in industry with clear benefits, even if full self-optimizing “lights-out” factories (the ultimate vision) remain a few iterations away.

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## ART 06.039 Reconfigurable & Agile Factories

115. **ART extraction**

116. *Primary capability* – “Reconfigurable & Agile Factories”: The ability to rapidly reconfigure production lines or workcells to handle different products or variations on demand, with minimal downtime or physical retooling. This enables factories to swiftly adapt to volatile demand, short product lifecycles, and high customization without sacrificing efficiency or quality.

117. *Key sub-components/variants*:

- **Modular robotic workcells** with standardized mechanical and digital interfaces. Each cell can incorporate robots, machine tools, conveyors, sensors, etc., as plug-and-play modules. End-effectors, fixtures, or process modules can be quickly swapped, and new “digital recipes” loaded, so the same physical cell can perform different tasks for different product families.
- **Rapid tool/changeover systems** (e.g. quick-release end-effectors, modular fixturing) that enable switching production tasks in minutes instead of lengthy line rebuilds. These hardware modules are supported by *universal interface standards* (akin to industrial “plug-and-play”) ensuring any new device or module can be integrated with minimal configuration[1][2].
- **Orchestration & planning software** that globally coordinates the modular cells. This includes model-based planning, optimization algorithms and digital **twin** simulations to schedule tasks, balance workloads, manage material flow, and automatically reconfigure the layout as needed[3][4]. The software leverages real-time data and AI to optimize production and can re-allocate resources on the fly when demand or conditions change.



- **Human-machine interfaces** that allow **high-level, intuitive control** of the factory. Instead of programming low-level machine code, human operators use visual dashboards, augmented reality (AR) overlays, or even natural language commands to specify desired outcomes and constraints. For example, voice- or text-based instructions to a Manufacturing Execution System have been tested (using large-language models) to execute multi-step production tasks[5][6]. AR overlays can guide technicians through reconfiguration or maintenance procedures visually.
  - **Infrastructure & standards** underlying the system: Reliable power and industrial networking are critical to link modules. New standards (e.g. the *Module Type Package, MTP*) are being adopted to define uniform **software interfaces** for modules, enabling true “plug & produce” integration across vendors[2][7]. Cybersecurity and safety frameworks are also crucial, given frequent reconfiguration could introduce new failure modes or attack surfaces.
118. **Maturity indicators/evidence to look for:** Concrete demonstrations of flexible factories in real settings (e.g. pilot production lines that make multiple products with quick changeovers), and **field trials or deployments** in industry. Key signs include proof-of-concept *pilot factories* or workcells showing hours→minutes reduction in changeover time, use of standardized module interfaces (with different equipment vendors interoperating), and **orchestration software** managing reconfiguration autonomously. Evidence of **commercial products** or platforms offering modular automation (and **investments** or competition between well-funded firms in this space) would indicate progression toward market readiness. Adoption of **standards** (like MTP or plug-and-produce protocols) by industry bodies, and **case studies** from manufacturing sectors (automotive, pharma, electronics, etc.) implementing such systems, would demonstrate both plausibility and growing maturity. Metrics such as reduced downtime, cost savings over product lifecycles, or smaller batch production made economically viable will be important. Also, watch for **government or consortium roadmaps** treating reconfigurable manufacturing as a strategic goal, and whether multiple suppliers offer compatible modular factory solutions (signaling an emerging ecosystem rather than a single lab prototype).
119. **Evidence (10–20 recent, reliable sources)**
120. **Assessment of design approaches for RMS (Rezaee & Moghaddam, *Computers & Ind. Engineering*, 2025) – Peer-reviewed journal paper (open access).** Proposes an integer linear programming model to optimally design and reconfigure a **Reconfigurable Manufacturing System (RMS)** over its life cycle based on demand changes[8]. Highlights the role of *modular reconfigurable machine tools* (RMTs) that can adjust capacity via module exchanges[9]. In simulation tests, predictive reconfiguration strategies (using accurate forecasts) minimized total costs, demonstrating that properly planned modular capacity adjustments can economically outperform static dedicated lines. This supports the *feasibility and cost benefits* of reconfigurable factories in coping with demand volatility.
121. **“A systematic methodology for changeable and reconfigurable manufacturing systems development” (Andersen et al., *J. of Manufacturing Systems*, 06/2024) – Peer-reviewed journal article (open access).** Presents a 4-step methodology for designing reconfigurable production systems, covering conception through implementation. Uniquely, it was **validated across seven real manufacturing companies**[10], integrating both existing and novel RMS design tools in collaboration with industry. The successful case studies demonstrate that companies in diverse sectors can adopt modular, changeable production methods in practice. This provides evidence of *practical feasibility*: the concept isn’t just



theoretical, but has been tested in industrial pilot projects, confirming that agile, reconfigurable factories can be realized with current technology and provide value across multiple environments.

122.     **Development of Reconfigurable Manufacturing (REKON Project, Denmark, 2020–2023)** – *Research consortium report (Aalborg Univ. & partners, funded by Danish Industry Foundation)*. A national initiative to help industries move from dedicated lines to **modular, platform-based production**[11]. Through pilot implementations in 7 companies (Phase 1) and broader dissemination (Phase 2), REKON developed a toolbox for designing reconfigurable production systems. Notably, it reports that prior research and pilot data showed reconfigurable production can **reduce capacity investment costs by up to 50%** compared to traditional dedicated lines, while still meeting demand uncertainty[12]. This economic result is compelling evidence that agile factories can significantly cut the cost of adapting to new products or volume changes, mitigating the risk of over- or under-capacity. (The project’s success also led to at least one journal publication from the team, underscoring its impact in both academia and industry.)
  
123.     **Audi Modular Assembly Pilot – Audi AG Press Release, July 2022** – *Industry press (automaker)*. Describes Audi’s implementation of the **world’s first modular assembly system** in automobile production as a pilot at Ingolstadt[13]. Instead of a fixed conveyor line, workers assemble door panels at independent “production islands,” with Automated Guided Vehicles (AGVs) delivering parts to each station on a flexible schedule. This modular approach allowed Audi to handle high product variability with ~20% efficiency improvement in the pilot (due to integrated logistics and inline quality checks)[14]. Crucially, it also enabled accommodating workers with different paces or disabilities by decoupling tasks from a rigid takt time. Audi’s pilot confirms the **technical plausibility** of reconfigurable production in a real factory: it achieved non-sequential, on-demand task routing and demonstrated improved flexibility and ergonomics. The fact that a major OEM invested in this and reported quantitative gains (20% efficiency) is a strong maturity signal (beyond lab demo, moving into production trial).
  
124.     **Automakers Embrace Modular Production for Flexibility (AMS, Aug 2025)** – *Automotive Manufacturing Solutions (trade publication)*. Reviews how major car manufacturers are adopting modular, “**matrix**” **production systems** to boost agility. For example, Jaguar Land Rover’s forthcoming Electrified Modular Architecture allows building a mix of EV and ICE vehicles on the **same assembly line**, enabling JLR to **pivot production in real time** as demand shifts without costly retooling[15]. Similarly, Audi’s use of flexible “production islands” served by AGVs is highlighted as a tangible result at its Ingolstadt plant[16]. The article notes multiple OEMs (BMW, Mercedes, Honda, Daimler Truck, etc.) now investing in such flexible manufacturing and supply chain setups[17]. This evidence shows *competition among well-capitalized actors*: the concept of reconfigurable/agile factories is being actively pursued by several global companies in parallel. It underscores that the industry views this as a key to resilience and efficiency (especially to handle EV transition and unpredictable markets), which speaks to increasing maturity (moving towards broad adoption).
  
125.     **“Plug and Produce — a review and future trend” (Khabbazi et al., Int. J. Adv. Manuf. Tech., Sep 2024)** – *Peer-reviewed review paper (open access)*. A comprehensive literature review of **Plug-and-Produce** concepts in advanced manufacturing control. It finds that over decades, researchers have greatly improved the *conceptual, logical, and physical* aspects of plug-and-produce, making integration of new machines or products ever faster and more seamless[18]. Modern implementations aim for **minimal downtime and no manual re-programming** when reconfiguring a production system – essentially treating manufacturing modules like plug-and-play peripherals[1]. The review identifies plug-and-produce as a

**foundational principle for future manufacturing**, aligning with Industry 4.0/5.0 goals, and notes that *standardization and industry consortia efforts are underway to support widespread adoption*[19]. In conclusion, it states the future of Plug & Produce is “promising” with active innovation and investment driving it forward as a key enabler of flexibility[20]. This source confirms the *scientific consensus* that the modular integration approach (a core enabler of agile factories) is feasible and maturing, backed by a growing body of experimental and standards-based progress.

126. **Festo Modular Automation & MTP (Festo AG, technical article, ~2023) – Vendor technical documentation (automation supplier).** Describes Festo’s solution for **decentralized, modular production systems** in process industries. Each process module is a standalone unit with its own control, capable of autonomous operation; modules connect via a standard interface called **Module Type Package (MTP)** that handles communication with a higher-level orchestration system[2]. This allows “plug & produce” flexibility – new modules (e.g. a filtration unit, reactor, filling station in pharma manufacturing) can be added or removed without reprogramming the whole system, and the orchestration layer automatically incorporates them[21][7]. The page highlights benefits like significantly faster commissioning (time-to-market *cut* ~50% in some cases) and easy capacity scaling by numbering-up modules instead of building a whole new line. It also notes Festo’s active role in standardizing MTP internationally (via VDI/NAMUR and IEC committees)[22], underscoring that major industry players are not only building products but also establishing *common standards* to make modular factories widely interoperable. This is concrete evidence of a *commercial toolset* for agile factories (Festo is delivering hardware/software for modular production), and the push toward standards shows an ecosystem forming (a hallmark of rising maturity).
127. **Merck & Siemens “Plug-and-Produce” Pilot Plant (NNE event brief, Oct 2022) – Industry case/consortium report.** Announces that **Merck KGaA** (a global pharmaceutical firm) is constructing a state-of-the-art production facility in Darmstadt using a *modular automation* approach[23]. The project, in close collaboration with Siemens, relies on the Plug & Produce concept with MTP and a Process Orchestration Layer (POL) standard. This initiative is presented in an industry event as a “gamechanger,” sharing real-world experiences of implementing MTP in a highly regulated environment. The significance here is that a *real production plant* (not just a demo cell) for pharmaceuticals – which demands high reliability and validation – is being built around reconfigurable, module-based automation. This indicates strong confidence in the technology’s **plausibility and readiness** for mission-critical applications. It also exemplifies cross-industry uptake (pharma, in addition to automotive), and suggests that by the mid-2020s, agile factory concepts are moving into *full-scale deployment* in at least pilot form.
128. **“Chat with MES”: Natural Language Control of Manufacturing (Yuan et al., J. of Manufacturing Systems, 2025) – Peer-reviewed experimental paper (open access).** Demonstrates an AI-driven interface where factory workers can interact with a Manufacturing Execution System using **natural language** (in this case, through a Large Language Model agent). The system, tested on a simulated garment factory, could interpret user requests (e.g. “change the production schedule” or “check machine status”) and break them into executable operations on the shop floor[5]. It achieved a **80% success rate** on 55 test queries, outperforming a baseline using raw GPT-4 (60% success)[6]. This proof-of-concept shows that emerging AI (LLMs) can make factory control more intuitive and “operator-friendly,” which is a key aspect of agile factories (operators specify high-level goals rather than low-level code). The results lend plausibility to the claim that *natural language or AR-based interfaces* can effectively augment human-machine interaction in reconfigurable production systems. While

still a research-stage result, it marks rapid progress in the HMI aspect, which will improve usability and reduce the expertise needed to reconfigure complex manufacturing setups.

129. **Digital Twin framework for Reconfigurable Manufacturing (Touckia et al., *Int. J. Adv. Manuf. Tech.*, Mar 2022)** – Peer-reviewed journal paper (open access). Introduces a **digital twin model** tailored for RMS, to aid in design and real-time reconfiguration of manufacturing systems[3]. The paper emphasizes that after COVID-19, companies recognize the need for quick reaction to market changes and see reconfigurable, agile manufacturing as a top priority[24][25]. It integrates advanced ICT (IoT, cloud computing, AI) to monitor the physical factory and simulate changes virtually, enabling faster adaptation (e.g., testing a new cell layout in the digital twin before physically reconfiguring). This is evidence of the *sophisticated software tools* being developed to support agile factories. It underscores plausibility: not only is the hardware being made modular, but the software (digital twin + AI) exists to validate and optimize reconfigurations, reducing risk and downtime. Such capabilities are essential for scaling up reconfigurable manufacturing, and the fact that this is an active research front (with industrial priority) indicates the field’s momentum.
130. **Essert “MicroFactory” Modular Automation Platform (Essert GmbH, product info, 2023)** – Vendor product documentation. Showcases a **commercial modular factory system** for the life sciences industry. The *MicroFactory Ecosystem* consists of process modules (“one process per module”) that can be docked together with a standardized **interface handling power, data, and logic** connections instantly[26]. This plug&produce design lets users start with a single automated module and expand to a full production line by adding modules as needed. Changeovers are very fast – the company claims adding or swapping a module can be done in **minutes**, whereas traditional changeovers take hours or days[27][28]. Importantly, when a new module is added, the rest of the line does not need re-validation, which is crucial for regulated manufacturing. This source is concrete evidence that *turnkey products* for reconfigurable, agile manufacturing are already on the market. An “award-winning” platform like this indicates that not only is the concept feasible, but it’s reaching customers (particularly in high-mix, high-complexity manufacturing like biotech/pharma) with promises of tangible benefits (faster scale-up, future-proof flexibility). It also exemplifies competition in the space – presumably, other firms will offer similar modular automation solutions if one company is successful, aligning with the emergence of an industry trend.
131. **Maturity score (1–7) and reasoning**

**Final Maturity Score: 5** (on the 1–7 scale).

**A. Justification – Evidence-to-Rubric Mapping:** The accumulated evidence places “Reconfigurable & Agile Factories” at **Level 5: early commercial prototype stage with multiple actors involved**. Lower maturity levels (1–3) are clearly surpassed – the core principles are *experimentally proven and demonstrated in working systems*. For instance, Audi’s 2022 pilot of a modular assembly line in a real factory environment shows a functional prototype solving prior blockers (flexibly decoupling assembly tasks from a fixed line) with measurable benefits[14][13]. Likewise, Merck’s collaboration with Siemens to build a modular production plant[23], and the existence of standardized module integration methods (MTP, Plug&Produce) adopted by industry, indicate that we are beyond isolated lab demos – the concept has moved into **practical trials and implementation**, satisfying at least Level 4 (Proof-of-Concept).

Several pieces of evidence push the assessment into **Level 5** territory. We see *multiple well-resourced organizations concurrently developing and investing in this technology*: e.g. major

automakers (Audi, BMW, JLR, Honda, etc.) are retooling production philosophies towards modular flexibility[17][16], major automation vendors (Siemens, ABB, Festo, Beckhoff) are offering products and standards for plug-and-produce[22][23], and even startups (like Essert's MicroFactory) are entering with modular automation solutions[26][28]. This competitive and collaborative momentum aligns with rubric Level 5, which is characterized by **well-capitalized actors racing to develop production-ready systems after a successful PoC**. Indeed, the evidence of cross-industry uptake (automotive and pharma pilots, among others) and the formation of consortia to standardize the approach shows that progress is recent and fast-paced. Each new prototype (e.g., the Merck modular plant or Audi's modular line) quickly motivates others, and standards like MTP are accelerating knowledge transfer – exactly the environment expected around Level 5 maturity. Notably, the technology also **meets or exceeds performance of conventional approaches in key areas**: e.g., Audi reported ~20% efficiency gains[14], JLR can avoid costly retooling by mixing models on one line[15], and modular systems can cut changeover time from days to minutes[28]. These advantages validate the commercial motivation and viability, suggesting the concept is on the cusp of wider adoption.

**B. Why not a higher score?** To reach Level 6 or 7, we would expect **broad market rollout and scaling**, with multiple competing products in regular industrial use and rapidly growing demand. While we have first products and pilots, *full production deployment is still limited*. Many of the implementations are pilot projects or initial phases (e.g., Audi's modular assembly was a trial in a sub-assembly, not yet an entire factory production, and Merck's plant is likely one of the first of its kind). We do not yet see evidence that hundreds of factories have converted to this paradigm or that “reconfigurable factory” solutions are routinely bought and installed at scale – rather, they are *in the introduction/early-adopter stage*. Additionally, some enabling sub-technologies are still maturing: for instance, **natural-language interfaces and AR control** for factories are just emerging from research (with a promising 80% success prototype[6], but not yet a standard feature on factory floors). Likewise, fully autonomous reconfiguration without expert engineers involved is not yet commonplace – some reconfiguration still requires careful planning (though digital twins and AI tools are coming, they are at early stages[4]). The need for further **validation, safety certification, and workforce training** in these systems means wide scale-up is likely incremental over the coming years. In short, the concept is proven and **entering commercialization (Level 5)**, but has not yet achieved the pervasive deployment or production volume growth that define Level 6.

**C. Sub-component maturity breakdown:** This ART is a bundle of several components, which are at slightly different maturity levels, though converging. The overall score **5** is mainly driven by the *core functionality* reaching a production-prototype stage, while acknowledging that some auxiliary aspects lag behind:

- **Modular hardware and integration platforms – Level ~5.** The physical modular workcells and the orchestration software that makes them function together have been demonstrated in industrial pilots and are offered by leading vendors. Evidence: Audi's and Merck's prototypes, Festo's and Siemens' module integration products, and the active standardization (VDI/VDE, IEC) indicate that the **industry considers this ready for near-term deployment**[23][2]. Multiple companies are building similar capabilities, confirming a competitive push at the cusp of commercialization.

- **Human-machine interface innovations** (AR, natural language control) – **Level ~3**. These are desirable for ease-of-use but not strictly required to achieve reconfigurable manufacturing. Current evidence (like the *Chat with MES* LLM interface) is at prototype stage in labs[6]. Some AR-assisted assembly or maintenance tools exist in factories, but natural-language operational control is not yet an established product. This sub-component is therefore less mature, around the stage of initial feasibility demonstrations (levels 2–3).
- **Autonomous planning and optimization (AI/digital twin) – Level ~4**. The software for automatically planning reconfigurations and optimizing production (using AI, simulations, digital twins) is under active development and has been piloted in some cases. For example, digital twin frameworks for RMS are being published and tested[3], and companies are using model-based scheduling in pilot projects. However, these tools are still advancing towards widespread robustness. They have cleared the basic R&D hurdle and shown clear utility, but need further refinement and integration for fully autonomous factory reconfiguration. This puts them at a proof-of-concept/early trial stage (around Level 4).

Considering these sub-scores, the *core capability* (modular, rapidly reconfigurable production) is solidly at **Level 5**, even if some supporting technologies trail slightly. The primary value of agile factories – quick physical reconfiguration and production agility – is already demonstrated with current industrial tech (robots, modular machines, orchestrators), and this justifies the higher weighting. The less mature aspects (like voice/AR control) don't prevent the concept's deployment; they will simply enhance it over time. Therefore, averaging the components would undervalue the fact that one can build a reconfigurable factory today using traditional HMIs and planning tools. **Hence, a score of 5 is assigned** – the concept as a whole is in the transition from proven prototype to early industry adoption. It's moving beyond the lab/PoC stage, but needs a few more years of scaling and ecosystem growth to reach full commercial maturation (Level 6).

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## ART 06.040 Circular & Sustainable Manufacturing

132. **ART extraction**

133. *Primary capability:* Transform industrial **waste and end-of-life products into new manufactured components** in a continuous, closed-loop process, reducing reliance on virgin raw materials. This involves treating waste as a **primary feedstock** rather than a disposal problem, thereby decoupling production from volatile material supplies and lowering environmental impact.

134. *Key sub-components/variants:*

- **Automated in-line recycling & additive manufacturing:** Integrated systems for **sorting, breakdown, and re-fabrication** of scrap. Waste materials are mechanically or chemically broken down, **sensed and characterized in-line**, then **additively reprinted** into new parts with predictable properties.
- **Bio-based & recyclable materials:** New **engineered polymers, composites, and binders** derived from renewable biomass (e.g. plant sugars, oils) that are designed for **easy recycling or biodegradation**. Complemented by **bio-engineered materials** (e.g. mycelium composites, bacterial polymers) produced via **fermentation, biofabrication, or enzymatic assembly**, tuned for high performance but circular life cycles.

- **Low-energy transformation processes:** Use of **low-temperature methods** (e.g. cold sintering, photopolymerization, enzymatic or electrochemical fabrication) instead of traditional high-heat, batch processing. These reduce energy consumption and preserve material quality through multiple cycles.
  - **Digital integration & traceability:** A software layer connecting **digital product passports**, design tools, and production planning. This enables automatic adjustment of designs and process parameters to accommodate **variable recycled feedstock**, and provides **real-time data on material origin, composition, and history** for compliance and optimization.
135. *Maturity indicators:* We would look for **working pilot plants or prototypes** that demonstrate the full circular flow (from waste to new product) under realistic conditions. Evidence such as **proof-of-concept integrations** of sorting + additive manufacturing, **field trials or small-scale production** using bio-derived recyclable materials, and **commercial investments or offtake agreements** in these technologies indicate progress. Key signs include **products meeting quality specs made from recycled/bio feedstocks**, **regulatory frameworks (e.g. digital product passports) being implemented**, multiple **well-funded companies or consortia** pursuing the technology, and clear **improvements in cost, energy use, or material performance** compared to the status quo.
136. **Evidence (10–20 recent, reliable sources)**
137. **Ultrasonic recycling of metal powder in additive manufacturing – Sojoodi et al., Univ. of Toledo (Shape Memory and Superelasticity, peer-reviewed) – Oct 2025.** Open-access review detailing an **ultrasonic plasma atomization (UPA)** method to recycle NiTi alloy powder for 3D printing[1]. It shows that scrap NiTi can be converted into **high-quality spherical powder (sphericity >0.9)** with stable composition, and outlines an **industrial roadmap** using machine learning and closed-loop recycling to integrate this into additive manufacturing[1]. This demonstrates **technical feasibility** of circular reuse in metal printing and plans for scaling, supporting the ART's plausibility.
138. **AI-enhanced circular plastic recycling – Valle-Basagoiti et al., IPN Mexico (MDPI Polymers, peer-reviewed review) – Jan 2026.** Reviews advances in **mechanical, chemical, and biological plastic recycling** and how AI is boosting efficiency. Reports that **intelligent sensing (FTIR, Raman, hyperspectral imaging, LIBS) with ML classifiers** now significantly improve material identification and sorting precision (fewer rejects)[2]. AI-driven models also optimize depolymerization processes (e.g. pyrolysis catalysts, enzyme design), and case studies in Europe/Asia/LatAm show **digital traceability and producer responsibility** schemes are pivotal for circular outcomes[3]. The authors conclude that AI has become a “**structural enabler**” for transparent, optimized recycling systems rather than just a lab tool[4][5] – evidence that many pieces (sensors, data, automation) are in place to make circular manufacturing viable at scale.
139. **DOE workshop on circular plastics (U.S. DOE BETO/AMMTO report) – June 2023.** An authoritative workshop report highlighting recent **pilot-scale and commercial developments** in circular manufacturing for plastics. It notes that traditionally hard-to-recycle materials are now being addressed: for example, a “**Materials Recovery for the Future**” pilot **demonstrated optical sorting of flexible plastic packaging** at a recycling facility, and industry partners (Dow and Waste Management) launched a **curbside film plastics recycling pilot**[6]. The report also discusses emerging **digital tools for traceability**, including the **HolyGrail 2.0** trial of digital watermarks on packaging in Europe and calls for **Digital Product Passports**, to improve sorting and supply chain transparency[7]. These show that multiple



stakeholders are actively piloting **integrated recycling technologies and data systems**, indicating progress toward real-world deployment.

140. **EU Digital Product Passport mandate – European Commission (Policy, ESPR law) – July 2024.** The EU's new *Ecodesign for Sustainable Products Regulation* requires a **Digital Product Passport (DPP)** for nearly all goods[8]. The DPP is a digital record of each product's materials, origin, repair history, and end-of-life handling, accessible electronically to support sustainability and compliance[8][9]. This regulatory move directly supports circular manufacturing by ensuring **traceability of materials and components** and enabling automated recycling or reuse decisions. It reflects a **government-backed push** for the digital integration aspect of the ART, and major companies are now preparing to implement these passports by 2026.
  
141. **Integrated circular prototyping for electronics – TECOS & partners (SMART CIRCUIT pilot, EU Interreg report) – Dec 2025.** Final report of an EU pilot where an SME and research center **combined additive manufacturing with structured digital traceability** to enable circular design in electronics[10][11]. They established fast design–print–test loops focusing on **modularity, repairability, and reuse**, and **trialed recycled and bio-based polymer filaments** in 3D-printed electronic enclosures[12]. The results showed these **recycled/bio materials were viable alternatives to virgin plastics**, and the improved process (with digital BOMs and part labeling for future recycling) **reduced scrap rates and defects** during prototyping[13][14]. This provides real-world evidence that **circular manufacturing principles (materials + digital integration)** can be practically applied in industry with immediate benefits.
  
142. **High-performance recyclable biopolymer development – Gilsdorf et al., NREL/Colorado State U. (Cell Reports Phys Sci, peer-reviewed) – May 2024.** Demonstrates a new **bio-based plastic (vinyl lactone acrylic polymer)** designed for full circularity[15]. The team shows their polymers (PMVL and PMDL, from plant-derived monomers) have **high functional performance** (better solvent resistance and higher glass transition temperature than PMMA plastic) *and* can be **chemically depolymerized back to monomer nearly 100% under mild conditions**[15]. They achieved **reversible upcycling** of the material and performed techno-economic and life-cycle analysis, finding that **with efficient recycling, the bio-plastic could be cost-competitive and eco-competitive with conventional plastics**[15][16]. This is a concrete leap in sustainable materials – a **closed-loop polymer** proven in the lab, supporting the ART's claim that new materials can maintain performance through many recirculation cycles.
  
143. **Mycelium bio-composites for construction – Bonenberg & Sydor, Poznan U. Tech. (Materials, MDPI, peer-reviewed) – Jun 2024.** Reviews the state of **mycelium-based composites (MBCs)** grown from fungal networks as sustainable materials. It cites recent experiments where **growing mycelium in a knitted textile scaffold dramatically improved the mechanical strength** of the composite, enabling larger structural components[17]. The resulting bio-composites have a **hierarchically porous structure with high energy absorption and very low thermal conductivity**, making them viable **lightweight insulation or foam replacements**[18][19]. Crucially, MBCs are produced from **agricultural waste feedstocks, require little energy, and are fully biodegradable/compostable at end-of-life**[20]. This validates a key ART element: **bio-fabricated materials with good performance** (fire-resistant, insulating, load-bearing in this case) that can replace conventional synthetics and **return safely to nature**, although scaling up cultivation and standardizing quality remain challenges.

144. **Low-temperature recycling of composites via cold sintering – Randall Group, Penn State (university R&D demonstration) – Jan 2026.** A research team at Penn State has **demonstrated a “cold sintering” process to recycle composite materials** (like battery electrodes and fiber composites) at low temperatures[21]. Cold sintering uses a transient liquid phase under pressure to densify materials below 200 °C. The group showed this method can **reprocess composite waste into new usable forms without significantly degrading properties**, which is traditionally very hard for thermoset composites[21]. This is important evidence of a **novel low-energy process** that could handle materials (carbon fiber composites, etc.) that today end up as waste, moving a step closer to circularity in high-performance sectors (aerospace, EVs) where recycling is minimal.
145. **Energy-efficient electrochemical 3D printing – Sandia National Labs (R&D technical note, R&D100 Award) – 2023.** Sandia developed “**Electro 3D**” additive manufacturing, which uses localized electrodeposition to 3D-print metals at **room temperature and ambient pressure**, instead of laser melting[22]. This technique essentially miniaturizes an electroplating process into a print nozzle, allowing **high-resolution metal part fabrication with no furnace, no post-processing, and greatly reduced energy use**[22][23]. The process can rapidly switch materials and print on sensitive substrates, all while consuming far less energy (lower embodied energy, less CO<sub>2</sub>) than traditional metal printing or casting[23]. This supports the ART by showing that **alternatives to high-heat manufacturing** are becoming real – here a lab-scale proven method that could cut energy and enable new circular fabrication approaches for metal components.
146. **Commercial scale-up of bio-circular polymer (PEF) – Avantium N.V. (industry press release) – Aug 2025.** Avantium, a Dutch sustainable chemicals company, announced the start-up of the world’s **first commercial FDCA plant** (5 kT/yr) – FDCA being the monomer for **polyethylene furanoate (PEF)**[24][25]. PEF is a new **100% plant-based, recyclable polymer** designed to replace PET in bottles and packaging. The plant was officially opened in 2024 and is now being commissioned; Avantium expects **commercial product sales to begin in Q1 2026 under existing offtake agreements**[24]. This is strong evidence of **well-capitalized, real-world deployment** of a bio-engineered material central to circular manufacturing. A major company is investing in production and has customers lined up, aiming to deliver a high-performance plastic that can integrate into recycling systems. It shows the ART’s materials component moving from labs and pilots into **full production and market adoption** in the very near term.
147. **Maturity score (1–7) and reasoning**

**Final maturity score: 4** (Proof-of-Concept demonstrated as viable, with clear recent progress toward commercialization).

**A)** We assess *Circular & Sustainable Manufacturing* as a **bundle of innovations** and find that it exceeds laboratory demonstrations (Levels 2–3) and is entering the **proof-of-concept and early prototype stage (Level 4)** on multiple fronts. The evidence above shows **key functionalities proven in pilot settings**: e.g. an integrated pilot line reusing waste in electronics with measurable success[12][14], new bio-based polymers achieving **commercial-quality performance and recyclability** in research[15], and **pilot/commercial facilities** (5 kT scale) being built for novel circular materials like PEF[24]. These accomplishments indicate that the core scientific principles are solved and **practical viability has been demonstrated** in relevant environments – ruling out Levels 1–3. The NiTi recycling and plastic upcycling examples show the concept is not only possible but can **meet or beat traditional material specs**[1][15].

**B)** However, the integrated vision has not yet reached widespread product deployment or competitive scaling, which limits it below Level 5. **Missing evidence for Level 5+** includes: fully operational **end-to-end factories** converting mixed waste streams into new products at scale, or multiple corporations selling turnkey “circular manufacturing” systems in the market. While we see significant investment and some first commercial launches (e.g. Avantium’s PEF plant) suggesting rising competition, much of this ART is still in **isolated pilot projects and niche roll-outs** rather than an established industry. We do not yet have multiple vendors delivering complete circular manufacturing platforms or a broad adoption by manufacturers – the **activity is fragmented across sub-technologies**. For instance, one company might focus on bio-materials, another on recycling tech, but they are not all integrated into one mature supply chain yet. Regulatory drivers (like digital passports) are only just being enacted, and standards for circular use are in early stages. These gaps mean the concept as a whole has not fully transitioned to production-prototype or early market (which would be Level 5).

**C) Sub-component breakdown:**

- **Advanced recycling & sorting processes:** *Maturity*  $\approx 5$ . In plastics and metals recycling, multiple **well-funded companies and consortia are at pilot or commercial rollout stages**. Evidence: the DOE report notes **pilot and even commercial-scale advanced recycling tech** (optical sorters for films, chemical recycling startups) and significant investments by major firms[6][26]. This indicates a competitive push to scale these processes (approaching production prototypes and initial products, thus around level 5).

- **Sustainable materials (bio-based & bio-fabricated):** *Maturity*  $\approx 4$ . Many new materials are proven in labs and some are moving to **first commercial production**, but broad market adoption is just beginning. For example, the **recyclable bio-polymer (vinyl lactone acrylic) is at lab PoC** with economic analysis[15], and mycelium composites are functional at pilot scale[17]. Meanwhile, **PEF and similar bio-polymers are entering initial production** (the 2024 FDCA plant)[24] – a major step toward commercialization. On average this domain sits at PoC/early prototype stage – some materials at level 4 pushing 5, others at level 3 moving into 4.

- **Integrated manufacturing systems (additive + in-line reuse + digital):** *Maturity*  $\approx 3-4$ . This is the least mature aspect. We have **laboratory and pilot demonstrations** (such as the EU Smart Circuit pilot[10][12], or Sandia’s energy-saving metal printer[22]), which show the concept works and yields benefits. But these are still **one-off prototypes**; fully integrated factories with continuous reuse flows are not yet delivered. No large-scale product line is running on entirely circular, recirculating inputs today, to our knowledge. Thus this integration aspect is around a proven prototype (level 3) edging into PoC (level 4) in the best cases.

Given the above, we weighted the sub-components to arrive at an overall **Score  $\sim 4$** . The **scientific and engineering feasibility is well established**, and importantly, **recent pilot projects have solved key blockers** (e.g. maintaining material quality after multiple cycles[1], ensuring bio-materials meet performance specs[15], automating waste sorting with AI[2]). This rules out the lower levels. The technology bundle is on the cusp of broader implementation, but still **needs integration and scaling**. To reach Level 5, we would want to see multiple complete systems being built with significant private financing – for example, several companies marketing **modular circular factories or services**, or existing manufacturers retrofitting facilities to circular methods in competition. Once we observe **competing products and rising customer demand** for circular manufacturing solutions (e.g.

equipment, materials, software as a package) – signs of Level 5–6 – the score would increase. For now, the evidence best supports **Level 4: proven functional prototypes and clear recent progress, but not yet a mainstream commercial reality.**

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## ART 06.041 Bio-fabrication technologies

### 1. ART extraction

**A. Primary capability** – Automated **bio-fabrication platforms** for producing human tissues and other biological products at useful scale. These systems integrate **3D bioprinting, engineered scaffolds, and controlled culture environments** to create living tissues with precise structure and composition, overcoming the limitations of manual cell culture.

**B. Key sub-components/variants** – - **High-resolution 3D bioprinters & bio-inks:** Print heads and “bioinks” (cells + biomaterials) to fabricate tissue constructs layer-by-layer with tunable architectures (including vasculature-mimicking channels).

- **Engineered scaffolds & biomaterials:** Supportive structures (hydrogels, polymers) that guide tissue formation, provide mechanical strength, and can be resorbed or integrated by cells.

- **Automated culture & bioreactor systems:** Incubators, perfusion bioreactors, and sensor arrays to maintain optimal conditions (nutrients, oxygen, temperature, mechanical stimuli) and scale up growth of printed tissues or organoids.

- **Integrated monitoring and control:** Sensors and software for real-time monitoring of culture parameters and automated adjustments to ensure reproducibility and quality (e.g. maintain sterility, prevent contamination, uniform cell growth).

- **Digital design & workflow software:** CAD-like tools for tissue design and recipe management, plus quality-control protocols. Remote updates can add new cell types, materials, or process workflows.

- **Product outputs:** *Tissue implants* (standardized patches, grafts, organoids with vascular channels and even embedded sensors), *cell-based reagents* (e.g. cultured cells or organoids for drug testing), and *bio-based materials* (engineered living or biomolecular products) produced with consistency and at scale.

**C. Maturity indicators** – Evidence to look for includes **peer-reviewed demonstrations of functional tissue prototypes** (solving prior blockers like vascularization or cell viability), **preclinical or clinical trials** of bioprinted tissues in animals or humans, **regulatory approvals or standards** emerging (e.g. first FDA clearances for bioprinted products, quality frameworks), and **commercial activity:** companies shipping bioprinters or tissue products, well-funded industry consortia, and multiple competitors racing to develop manufacturing platforms. Signs of maturity would be **production facilities** or “tissue foundries” coming online, **scaling metrics** (e.g. thousands of organoids produced automatically, large tissue constructs printed), and **investments/acquisitions** by major biotech or pharma firms indicating confidence in bio-fabrication technology.

### 2. Evidence (10–20 recent, reliable sources)

1. **From organoid culture to manufacturing: technologies for reproducible and scalable organoid production** – Dohui Kim et al. (*npj Biomedical Innovations*, review, 02/2026). This open-access review outlines the transition of organoid technology from lab technique to **industrial-scale manufacturing**. It details innovations for improving reproducibility and



throughput (e.g. micropatterned culture plates, droplet microfluidics, suspension bioreactors) and notes that regulators like FDA/NIH now recognize organoids as alternative preclinical models. It highlights that organoid-focused biotechs and pharma are rapidly adopting these platforms, marking a **pivotal shift toward standardized, high-fidelity organoid production with imminent clinical and commercial impact**[\[1\]\[2\]](#). It also describes emerging quality frameworks (OECD's GIVIMP) and the establishment of centers (NIH's SOM) to **promote robust, scalable organoid workflows**[\[3\]](#), underscoring the field's drive toward maturity.

2. **Semi-automated layer-by-layer biofabrication using rotational internal flow layer engineering technology** – Gwyneth West et al. (*SLAS Technology*, peer-reviewed, 04/2025). Researchers at University of Edinburgh demonstrate an **automation upgrade to a biofabrication process (RIFLE)** for building tubular tissues. The system automatically dispenses cell-laden hydrogel layers inside a rotating mold, achieving **high cell viability (>91% over 10 days)** and precise multi-layered structures (~14 µm thick cell layers) comparable to manual assembly[\[4\]\[5\]](#). This semi-automated platform reduced manual steps and human error in constructing vascular-like tubes, showing **progress in scaling up tissue engineering with reproducibility** and indicating that key technical barriers (layer resolution and viability at scale) are being solved in the lab.
3. **ARMI BioFabUSA “Tissue Foundry” Platform** – *Advanced Regenerative Manufacturing Institute (U.S. DoD Manufacturing USA program, info page updated 09/2024)*. ARMI's BioFabUSA consortium has developed the **first-ever scalable, modular, automated, and closed biofabrication line**, dubbed the Tissue Foundry[\[6\]](#). It consists of modules for each manufacturing stage of cell/tissue products, with robotics and sensors integrated for monitoring and controlling processes. The closed design (isolating the process from open air) minimizes contamination risk and reduces need for cleanroom facilities[\[7\]](#). This **prototype “tissue factory”** demonstrates the feasibility of end-to-end automation – from cell processing to tissue assembly – aiming to produce consistent, clinical-grade tissues at industrial scale. It validates the engineering integration described in the ART and shows that substantial capital investments (comparable to a mid-sized plant) are indeed being made to realize tissue manufacturing infrastructure.
4. **CollPlant and Stratasys Announce Pre-clinical Study for Regenerative Commercial-Sized Breast Implants** – *CollPlant Biotechnologies & Stratasys Ltd. (press release, 08/2024)*. This industry announcement details a collaboration in which a **bioprinted human-scale tissue implant (breast implant)** has been achieved. Using CollPlant's recombinant collagen bio-ink and a Stratasys Origin 3D printer, the team fabricated **200 cc volume implants** (approximate to an actual human breast) and began large-animal trials[\[8\]\[9\]](#). The goal is a regenerative implant that recruits the patient's cells to grow natural tissue and then biodegrades. Early preclinical results showed the 3D-printed implants can support **ingrowth of connective tissue and blood vessels** (neovascularization) and begin to biodegrade without adverse immune response[\[10\]](#). This demonstrates **scaling of biofabrication to clinically relevant sizes** and the involvement of well-capitalized partners; it underscores both the plausibility (functional tissues with vasculature printed) and advancing maturity (transitioning into preclinical trial stage for a commercial therapy).
5. **3D Systems launches Regenerative Tissue Program for personalized surgical reconstruction (press release)** – *3D Systems (corporate announcement, 02/2023)*. 3D Systems (a major 3D printing company) unveiled a program to commercialize **bioprinted human tissue solutions**, initially targeting a patient-specific **regenerative breast tissue scaffold (RBT™)** for post-mastectomy reconstruction[\[11\]\[12\]](#). The company leverages experience from its bioprinting of solid organs (ongoing projects on lung, liver, kidney) to create vascularized soft-tissue implants. The press release notes that in the past year they completed



multiple **large-animal proof-of-concept studies**, demonstrating an implantable scaffold that induces host tissue integration and blood vessel growth. Notably, they achieved both **host-mediated vascularization and direct surgical anastomosis of printed scaffolds** in these studies[13][14]. This indicates a **Proof-of-Concept (PoC) at commercialization criteria** – the printed adipose tissue scaffolds functioned well in vivo – and that a well-funded industry player is moving quickly toward a production prototype for clinical use.

6. **First-in-human trial of 3D-bioprinted ear implant (AuriNovo) – 3DBio Therapeutics & Microtia-Congenital Ear Institute (press release, 06/2022).** A clinical-stage biotech reported a **groundbreaking human surgery**: a 20-year-old patient received a 3D-bioprinted living ear implant (AuriNovo) made from her own cartilage cells, as part of an ongoing Phase 1/2 trial for microtia (ear deformity)[15][16]. The AuriNovo implant – a collagen hydrogel scaffold laden with the patient’s cells – was designed to precisely match her other ear. The FDA granted it Orphan Drug designation, and the trial aims to enroll 11 patients. This is **strong evidence of plausibility** (a complex living tissue implant successfully manufactured and implanted) and also a **maturity milestone**: it required a robust manufacturing and quality platform to meet FDA requirements. 3DBio had to develop processes for cell expansion, bio-ink formulation, a specialized sterile bioprinter, and temporary support structures[17], reflecting how the technology is advancing from lab prototype to a regulated therapeutic product in clinical evaluation.
7. **Dimension Inx’s 3D-printed bone graft (CMFlex™) – first FDA-cleared regenerative graft – Dimension Inx & Desktop Health (press release, 11/2023).** Dimension Inx, a startup, together with Desktop Health, announced that **CMFlex™, a 3D-printed synthetic bone graft, received FDA 510(k) clearance in Dec 2022 and has been used in its first patients**[18][19]. CMFlex is a biofabricated bone scaffold (comprised of hydroxyapatite and PLG polymer) printed with a micro-architecture that promotes bone regeneration. By late 2023 it was successfully implanted in multiple human surgeries (e.g. upper and lower jaw reconstructions and dental socket grafts) as a patient-specific graft that avoids the need to harvest the patient’s own bone[20][21]. Initially available to a few surgeons, it was slated for broader release in 2024[22]. **This is a fully commercial bio-fabricated product in clinical use**, demonstrating that at least niche tissues (bone grafts) have reached Level 6 maturity (regulated product delivered to customers). It provides concrete performance validation – surgeons reported the printed graft’s excellent handling and healing properties[23][24] – and signals that bio-fabrication can produce market-ready medical products.
8. **High cell density and high-resolution 3D bioprinting for vascularized tissues – Shangting You et al. (Sci. Advances, peer-reviewed, 02/2023).** This study tackled a crucial technical challenge: printing tissues that are **both densely cellular and finely detailed** (to support micro-vasculature). The team developed a method to reduce light scattering in a DLP bioprinter by adding iodixanol to bioinks, achieving **50 µm resolution prints at cell densities of 10<sup>8</sup> cells/mL**[25][26]. Using this approach, they fabricated thick, vascular-network-containing tissue constructs that remained **viable in perfusion culture, with embedded endothelial cells forming blood vessel structures after 14 days**[27][28]. This is a **pivotal feasibility result**: it shows that bioprinted tissues can incorporate dense living cells and capillary-scale channels, addressing the previous bottleneck of nutrient supply in larger tissues. Such advances in print fidelity and cell viability increase confidence that functional, larger tissues (with vascular support) can be produced for practical use.
9. **Systemic Bio opens facility for mass-producing bioprinted organ-on-chips – Systemic Bio (wholly-owned by 3D Systems), press release, 04/2023.** Systemic Bio opened a new Houston factory laboratory dedicated to manufacturing its **h-VIOS™ organ-on-a-chip platform** – bioprinted hydrogel scaffolds with human cells for drug testing. The facility includes a

cleanroom for **sterile production of thousands of organ-on-chip devices (plates and chips)**, an unprecedented capacity meant to supply multiple pharma partners in the coming year[29][30]. The h-VIOS system contains vascularized channels to sustain cells and perfuse drugs in a physiologically relevant way[31]. The CEO noted this marks a “**leap from experimental research to full-scale production**”, with automated Print-to-Perfusion technology now manufacturing high-quality tissue models at scale[30][32]. This is strong evidence of maturity on the **biologically-derived product side**: a commercial entity is producing and selling standardized bio-fabricated tissue models in quantity, indicating that reproducibility and scale-up challenges are being met for at least certain applications (drug discovery kits).

10. **Merck KGaA to acquire Hub Organoids (HUB) for organoid technology** – *Merck KGaA (announcement reported via Businesswire/Merck, 12/2024)*. Merck (Darmstadt, Germany) – a major pharma and life-science company – signed an agreement to **acquire Netherlands-based HUB Organoids**, a pioneer in organoid technology[33]. HUB, associated with the Hubrecht Institute, has been a leader in developing patient-derived organoid models (e.g. intestinal organoids). Merck’s acquisition (through its Life Science arm, MilliporeSigma) aims to **advance Merck’s next-generation biology and drug screening portfolio** using organoids. This corporate move underscores the **commercial and strategic value of scalable organoid production**. A top-tier pharma investing tens of millions into organoid capabilities indicates that the technology is viewed as scientifically credible and on the cusp of broader use. It also suggests emerging standards and IP consolidation, which typically occur when a field transitions from academic novelty to an applied biotech toolset.

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 5 (out of 7).

**B) Justification** – *Bio-fabrication technologies* as a whole are **beyond proof-of-concept (Level 4)** and moving into early commercialization, but have not yet achieved broad deployment or competition in end markets (necessary for Level 6 or 7). We have multiple indicators ruling out lower levels: fundamental feasibility is long proven (printing living tissues works in the lab – Level 2/3 achieved years ago), and importantly **functional prototypes have been demonstrated in biologically relevant contexts (Level 4)**. For example, a bioprinted ear implant has been successfully implanted in a human trial, showing real tissue function[15], and a 3D-printed bone graft has FDA clearance and is being used by surgeons, demonstrating **viability as a medical product** rather than just a lab demo (evidence of Level 5–6)[18][19]. Moreover, **well-capitalized actors are involved**: major companies (3D Systems, Merck KGaA, Stratasys, etc.) and consortia (ARMI BioFabUSA) are investing and competing to develop production platforms and scalable processes, which is characteristic of Level 5. The presence of an actual manufacturing facility for organ-on-chip devices and the first wave of commercial products (even if limited release) is a strong Level 5 signal.

However, the field has not yet reached full maturity (Levels 6–7) because **routine, volume production and widespread adoption are only beginning**. The evidence shows *initial* product launches and clinical trials, not a robust pipeline of competing products used at scale. For instance, the bone graft product (CMFlex) is only in limited rollout as of 2024[34], and custom tissue implants like the bioprinted ear are still in early clinical study – not yet broadly available therapies. The integrated “tissue factory” platforms (like ARMI’s Tissue Foundry) are at prototype stage, and many biofabrication successes are one-off or small-batch (e.g. thousands of organoids for testing, or a few patients treated). We **do not yet see**

**multiple companies selling interchangeable tissue products in large quantities** or extensive revenue streams from bio-fabricated tissues, which would mark Level 6 (growing customer demand, scaling production with cost decline). In short, the **trajectory is clearly upward** – substantial recent progress has elevated the score to 5 – but **evidence for Level 6 is still missing**: we need to see manufacturing scaling up with economies of scale and a competitive market of bio-fabricated products being adopted in industry/medicine.

**C) Sub-score breakdown** – This ART comprises several sub-technologies that are maturing at slightly different paces, so an average was used for the bundle score: - **Bioprinted therapeutic tissues (implants and grafts):** *Maturity ~5*. Achieved first human uses and regulatory clearances, indicating PoC and initial commercial viability. *Key evidence*: Dimension Inx's FDA-cleared bone graft used clinically[18][19], 3DBio's implanted ear cartilage in trials[15]. Multiple startups and large firms are in this space (competition forming), but products are just entering the market now, not yet widespread (hence not a 6). - **Automated biofabrication platforms (hardware & processes):** *Maturity ~4*. Demonstrated in pilot settings – e.g. ARMI's modular Tissue Foundry and academic automated bioprinters show that fully automated, closed-loop production is technically feasible[6]. Yet these are still prototypes or bespoke systems; they meet functionality requirements (solving contamination, scalability issues) but are not yet deployed in volume manufacturing or commercialized as turnkey products. Further engineering and cost optimization are ongoing before crossing to Level 5. - **Mass-produced living tissue models (organoids-on-demand for R&D):** *Maturity ~4–5*. Organoid and tissue model production is rapidly scaling with strong industry buy-in. Pharma companies are partnering or acquiring organoid tech (e.g. Merck's HUB acquisition) and new facilities can produce thousands of tissue units for testing[29][30]. This indicates a transition from lab research to **marketable services/products (early Level 5)**. Still, the market is emerging – standards and consistency are being established now, and significant expansion is expected in the next few years rather than already realized.

Taking these together, the **aggregate maturity is about mid-stage (Level 5)**. The more advanced segments (some specific products) pull it above Level 4, while the platform and infrastructure aspects still in development prevent claiming Level 6. In summary, bio-fabrication technologies are at the point where **key proofs have been delivered and first products are launching (score 5)**, with an anticipated jump to Level 6 once scaling and market competition further intensify in the coming years.

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## ART 06.042 4D Printed & Programmable Materials

1. **ART extraction**
2. **Primary capability** – Additively manufactured objects that can **change shape or material properties over time** in a programmable way. These “4D printed” structures respond to stimuli (heat, light, moisture, electric/magnetic fields, chemical signals) to alter form or function post-fabrication, essentially acting as “**physical software**” with **on-demand reconfiguration**.
3. **Key sub-components/variants** – (1) **Stimuli-responsive materials** (e.g. shape memory polymers, hydrogels, liquid crystal elastomers, magnetoactive composites) integrated into 3D prints to enable folding, bending, expansion, or stiffness change when triggered. (2) **Multi-material 3D printing techniques** (inkjet, FDM, DIW, vat polymerization) that embed different responsive regions or “memory” into one structure. (3) **Passive vs active control**: some designs rely on inherent material response (e.g. swelling when wet, thermal shape-memory), while others incorporate small embedded actuators or use external fields for coordinated actuation. (4) **Reconfigurable design libraries**: using geometric patterns (origami-inspired folds, lattices, etc.) to achieve complex sequences of shape changes, including one-shot deployments or multi-step transformations. (5) **Application-specific variants**: e.g. self-deploying aerospace components, biomedical implants that change shape in the body, adaptive metamaterials (tunable stiffness, variable porosity), smart textiles that respond to environment, and soft robotic systems without traditional hinges.
4. **Maturity indicators** – Evidence would include **lab prototypes demonstrating repeatable shape-change** and solving prior hurdles (e.g. multi-cycle durability, load-bearing actuation) in real conditions, **field trials or proof-of-concept deployments** (such as a 4D-printed part used in a space mission or in a clinical setting), the emergence of **dedicated equipment or materials** (commercial 4D printers, shape-shifting polymers on the market), **multiple funded programs or consortia** (indicating broad interest and investment), and early **commercial or industrial adoption** (e.g. startups or major manufacturers developing reconfigurable products, or standards efforts for programmable materials). Signs of competition (several companies racing to productize 4D materials) or **performance benchmarks** beating conventional static designs (e.g. significantly improved adaptability or lifecycle cost) would also signal higher maturity.
5. **Evidence (10–20 recent, reliable sources)**
6. **4D Printing Roadmap** – Mahdi Bodaghi et al., Smart Materials and Structures (roadmap review by 44 researchers), **2024**. *<br> A comprehensive 107-page roadmap assembled by experts worldwide highlights the rapid emergence of 4D printing as an “advanced manufacturing technology” distinguished by time-responsive behavior. It surveys recent advancements across biomedicine, aerospace, textiles, electronics, etc., and envisions creating intelligent adaptive objects that dynamically respond to external stimuli*<sup>[1][2]</sup>.



7. **4D Printing for Space Self-Deploying Structures** – Tim Richter & Christina Völlmecke, Applied Sciences (peer-reviewed paper), **12/2023**. <br> *Demonstrates PEEK shape-memory polymer hinges fabricated and “programmed” in a single 4D-printing process for space applications. The hinges achieved ~100% recovery of deformation (fully unfolding) and remained functional across a wide temperature range (including deep-cold), showing viability for self-deploying spacecraft components; however, a high activation temperature is required (~160 °C, a noted challenge for space use)*[\[3\]](#).
8. **4D-Printed Shape-Morphing Orbital Stent (Biomedical)** – Y. Deng et al., **Biomaterials 291**, 121886 (peer-reviewed journal), **2022**. <br> *Produced a CT-visible orbital implant via 4D printing of a shape-memory polyurethane composite to treat enophthalmos (sunken eye). The stent can be inserted in a compact shape and later expand in situ (triggered by body temperature) to fill the orbital cavity. This addresses current implants’ drawbacks – e.g. difficulty achieving precise fill, weak expansion, and large surgical incisions – by enabling a minimally invasive, self-adjusting solution*[\[4\]](#)[\[5\]](#).
9. **One-Piece 4D-Printed Flow Valve (Thermal Activation)** – L. Bottini & A. Boschetto, Progress in Additive Manufacturing (peer-reviewed), **05/2025**. <br> *Describes a rotary diverter valve 3D-printed in a single PLA piece that can open or close without any motor – the valve’s material is “programmed” to deform when heated, thus controlling flow via shape-change. The study optimized FFF printing parameters for maximal shape recovery and fixity. The result is a functional 4D valve that operates using only thermal stimulus (no sensors or electronics), illustrating how 4D printing can simplify mechanisms by embedding actuation in material geometry*[\[6\]](#)[\[7\]](#).
10. **Octopus-Inspired Smart Hydrogel Skin (Halftone-Encoded 4D Printing)** – Haoqing Yang et al. (Hongtao Sun’s group at Penn State), **Nature Communications 16**, 2025 (peer-reviewed; press release by Penn State 02/2026). <br> *Using a custom 4D printing technique, the team created a hydrogel-based “smart skin” that can change color/pattern, texture, and 3D shape on command. Digital instructions (binary halftone patterns) are embedded in the material during printing, allowing it to hide or reveal images and alter stiffness when exposed to triggers like temperature changes, liquids, or mechanical stretch. For example, a hidden image (the Mona Lisa) encoded in the flat hydrogel becomes visible only after specific triggers (cooling or heating)*[\[8\]](#)[\[9\]](#). *This single-material system achieves multiple coordinated responses (camouflage, information display, shape morphing) without layered devices, underscoring the versatility of programmable 4D prints.*
11. **Magnetically Tunable Stiffness Metamaterial (Direct Ink Writing)** – Yoonseok Park et al., Advanced Materials (peer-reviewed), **05/2025**. <br> *Developed a magneto-active mechanical metamaterial capable of a >390% change in stiffness between soft and rigid states*[\[10\]](#). *The team used 4D direct-ink-writing to print a composite of SIS elastomer and neodymium microparticles, creating a lattice that rapidly stiffens or softens under an external magnetic field. They demonstrated multilayer structures and even an adaptive soft robotic wheel that can quickly adjust its stiffness to terrain. This system achieves fast, precise, and reversible tunability of mechanical properties, pointing to applications in soft robotics and prosthetics where on-the-fly material property control is beneficial*[\[11\]](#).
12. **Cycle Durability of 4D-Printed Hinges (Shape Memory PLA)** – J. Huang et al., Materials & Design **260**, 114879 (peer-reviewed, open access), **12/2025**. <br> *Investigated the long-term performance of 4D-printed shape-memory hinges made of PLA via FDM. An optimized hinge design (0.8 mm thickness) showed 99.5% shape recovery on the first use, and an origami-inspired structure using these hinges could fully self-deploy in 8 seconds*[\[12\]](#). *However, under cyclic actuation the hinges’ performance degraded significantly – the shape recovery ratio fell*



to ~25% after 50 heating cycles at 65 °C[13]. This quantifies a key challenge for 4D materials (fatigue and repeatability), emphasizing ongoing needs in material improvements for durability.

13. **BIOMET4D Program – Shape-Shifting Metallic Implants – IMDEA Materials** (EU Horizon Europe Pathfinder project), **Launched 07/2022** – Project Abstract and Updates. <br> A European consortium is developing 4D-printed biodegradable metal implants that change shape in predesigned stages to assist tissue regeneration, then harmlessly degrade. The project targets “shape-morphing metamaterials” and multi-material metal additive manufacturing to create load-bearing implants that can be inserted minimally invasively and then gradually expand (actuate) in the body[14][15]. It aims for a 10× improvement over state-of-the-art, with proof-of-concept in complex applications like craniosynostosis correction (expanding a skull implant as a child grows) and skin tissue expansion. This large-scale R&D effort signals significant investment in bringing 4D materials into real medical use.
14. **Integrated 4D Printing & Programming System (Vendor Example)** – Orion AM “A150” 4D Printer, Orion Additive Mfg. GmbH (technical documentation via Appl. Sci. 2024 paper), **Accessed 2023**. <br> The Orion A150 is a commercial platform that not only 3D-prints shape-memory polymers but also “programs” the printed part’s memory in situ by thermal cycling – all in one machine[16][17]. Researchers used this system to produce and set shape-memory hinges in one go, eliminating the need for separate ovens or DMA equipment. The existence of such specialized 4D printing hardware in industry demonstrates progress toward practical fabrication workflows and supports more consistent, scalable production of programmable materials.
15. **Light-Fueled 4D-Printed Soft Actuators (No Wiring Needed)** – Sean J. D. Lugger et al., Advanced Materials Technologies 8(5), 2201472 (peer-reviewed), **03/2023**. <br> Reported a liquid crystal elastomer (LCE) actuator that is directly 4D-printed by DIW without any slow UV curing step. The printed supramolecular LCE devices show reversible shape-change under light illumination and can bend with enough force to lift a small load[18]. Using an azobenzene additive, the actuators respond to light via both photothermal heating and photochemical motion, and they work in air or under water. This is a clear proof-of-concept of wireless control of a 4D-printed material (using light as the trigger), illustrating feasibility of remotely-controlled shape-morphing components for soft robots or deployable structures.

#### 16. Maturity score (1–7) and reasoning

**A) Final score: 3 (out of 7) – Laboratory Prototype stage.**

**B) Justification:** The evidence shows **numerous lab-scale prototypes and experimental demonstrations**, which goes beyond mere theory or single experiments (ruling out Levels 1–2). Researchers have fabricated working 4D materials that solve specific technical challenges – for instance, multi-material prints that achieve complex shape changes and even functional devices like valves and stents, indicating key functionality is achieved (meets Level 3 criteria)[6][4]. These prototypes demonstrate clear *benefits* (e.g. a self-deploying stent that avoids invasive procedures, or a valve with no moving parts) and address prior bottlenecks in principle. **However, the technology is not yet at proof-of-concept for mass production or widespread deployment (Level 4).** There is little evidence that these 4D-printed devices fully meet real-world reliability or cost requirements – in fact, durability and materials limitations are still significant (e.g. 75% performance loss after 50 cycles in a lab hinge test[13]). We also do not see products in customers’ hands or competing commercial offerings; investment is mostly in R&D consortia and academic labs rather than in scaling up manufacturing, which rules out Levels 5–7. In short, 4D programmable materials are **scientifically proven and**

**actively prototyped** (many stimuli and use-cases have working demos), but **remain in the experimental/validation phase**, with substantial engineering work needed to reach commercial viability. Evidence of ongoing challenges (high actuation temperatures, material fatigue, regulatory hurdles for new materials, etc.) shows that a fully functional, market-ready product has not yet been realized – keeping the maturity at *TRL 3*.

**C) Sub-component breakdown:** Different application threads of 4D materials are at similar maturity, mostly in early prototype stage. For example, **4D-printed aerospace/robotic components** (shape-memory hinges, tunable metamaterials) are demonstrated in lab but not field-qualified ( $\approx$  Level 3)[3][10]. **Biomedical 4D implants** have shown feasibility in animals or bench tests (e.g. a self-expanding stent[4]), approaching proof-of-concept but still requiring clinical validation (Level 3 to 4). **Smart textiles and consumer uses** are largely conceptual or at prototype demos in labs (Level 2–3). Because these variants all share the core enabling technology (stimuli-programmable materials) and none have a sustained commercial rollout yet, the **overall maturity is best represented as Level 3** – multiple compelling prototypes exist, attracting broad research investment, but **no fully field-tested, commercially packaged product** has emerged to push it into the next stage.

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## ART 06.043 Volumetric Additive Manufacturing

### 1. ART extraction

**A) Primary capability** – The ART promises **3D printing entire objects “all at once” instead of layer-by-layer**. In a single step, shaped light/energy fields cure a photosensitive volume, forming a solid object throughout its interior. This yields **drastically shorter print times (seconds or minutes vs hours)** and produces **complex, smooth parts** (with internal channels, lattices, moving elements) without supports.

**B) Key sub-components/variants** – Volumetric 3D printing spans several approaches:

- **Tomographic projection (Computed Axial Lithography, CAL):** Project a series of 2D images around a rotating resin to reconstruct the 3D dose (essentially reversing a CT scan)[1][2]. Simpler hardware (just a projector, rotating vial) but requires careful dose calibration. Recent improvements include *holographic tomographic* methods using phase-modulating SLMs for higher light efficiency[3].
- **Holographic / multi-angle volumetric exposure:** Use beam-shaping optics or rotating mirrors to **project a 3D light intensity pattern** in the resin without rotating the sample[4][5]. E.g. the **DISH method** rapidly rotates a periscope to deliver 360° projections and achieve uniform high-resolution curing in one shot[5][6].
- **Dual-color photopolymerization (Xolography):** Two intersecting light sources (different wavelengths) with a special photoinitiator allow **volumetric curing in a stationary resin**. A moving light sheet “sensitizes” regions, and a second patterned beam solidifies them where they intersect[7]. This enables volumetric printing in continuous resin flow and can create **material property gradients** (by parallel curing of different chemistries)[8][9].
- **Specialized photopolymer materials: Photoswitchable or dual-wavelength resins** (for Xolography) and **“threshold” resins** that only polymerize upon receiving a cumulative dose (for CAL). Also, **biocompatible hydrogels and composite resins** are being formulated for volumetric use[10][11]. Resin chemistry is tuned for fast, controlled curing and minimal shrinkage.

- **Computation & control:** Inverse algorithms (tomographic reconstruction, hologram optimization) compute the projections needed for a given 3D model[12]. **Real-time monitoring and exposure control** loops are emerging to compensate for resin absorption and ensure uniform curing[13][14]. High-speed projectors or laser modulators (DMDs at kHz rates) synchronize with mechanical motion to “encode” the 3D shape in light[15][16].
- **System integration challenges:** *Optical hardware* (DLP projectors, lasers, rotating mirrors) must maintain alignment at high speed[17][16]. Removing uncured resin from internal cavities often requires *post-processing (solvent wash, centrifuge)*[18][19]. Designs must mitigate heat and polymerization shrinkage, and avoid turbulence in any flowing resin during exposure.

### C) Maturity indicators – Evidence of the ART’s progress would include:

- **Laboratory prototypes achieving key feats:** e.g. **printing cm-scale objects in seconds with fine resolution**, demonstrating parts unattainable by layering (intricate overhangs, embedded moving components). Peer-reviewed demos of stable, high-quality prints confirm scientific feasibility[20][21].
- **Expanding performance envelope:** Breakthrough results solving prior limits – for instance, **improving resolution–speed tradeoff** (maintaining tens-of-micron detail at high volume rates[20]), or **multi-material printing** (varying stiffness or composition within one print[22]).
- **Transition to practical use: Proof-of-concept use cases** in demanding environments (e.g. printing in microgravity[23][24], or bioprinting living cells with high viability[25][26]). **Early adoption by researchers or industry**, such as specialized volumetric bioprinters installed in labs, or prototypes used in field trials.
- **Commercial development activity:** Formation of **startups and industry groups** building volumetric printers, **VC funding rounds, product launches, or beta units shipped**. Competition among companies (across US/EU/Asia) and **collaborative projects (EU Horizon grants, national lab programs)** signal momentum. Availability of **compatible materials (resins, bio-inks) sold for volumetric printers** also indicates ecosystem growth[27][28].
- **Roadmaps and scaling plans:** Evidence that volumetric AM is **scaling beyond one-off demos** – e.g. plans for larger build volumes, automation (continuous resin feed, part handling), cost reduction, and integration into manufacturing lines. **Standardization efforts or benchmarks** comparing volumetric print quality/cost against conventional 3D printing would also reflect maturity.

### 2. Evidence (10–20 recent, reliable sources)

**Volumetric AM state-of-the-art review – Whyte et al. (Additive Manufacturing, Mar 2024):** *Peer-reviewed review.* Summarizes 30 recent VAM papers and notes **VAM can print entire objects in seconds/minutes** and overprint around existing parts. However, it finds **few commercial VAM printers available and a very limited materials palette**, with complex methods and specialized hardware requirements posing barriers to wider adoption[29]. (This underscores that the technique works in labs but is still early in commercialization.)

**“Sub-second volumetric 3D printing by holographic light fields” – Wang et al. (Nature, Feb 2026):** *Peer-reviewed journal article.* Demonstrates a new **DISH** method achieving **19 µm**

**feature resolution over a 1 cm volume**, printing millimeter-scale objects in **only 0.6 s**[30]. By rapidly rotating optics (no sample rotation) and optimizing projected holograms, they maintain high resolution and even integrated a flow of resin to **continuously mass-produce complex 3D parts** in a range of liquid acrylate materials[30]. *Significance*: Proves volumetric printing can combine **high precision and ultra-fast speed**, addressing a key previous trade-off and pointing toward scalable production throughput.

**“Holographic tomographic VAM” – Álvarez-Castaño et al. (Nat. Commun., Feb 2025):** *Peer-reviewed journal article (open access)*. Reports a tomographic VAM system using a **holographic phase modulator** for more efficient light delivery. Achieved a **20× improvement in light utilization** vs amplitude-only projection, enabling **millimetric objects with 31 μm details printed in <1 minute with only 40 mW LED power**[21]. Impressively, it printed structures in **scattering media (cell-laden hydrogels, 5×10<sup>5</sup> cells/mL)** with similar speed and resolution[21]. *Significance*: Shows progress in **energy efficiency and bioprinting capability** – volumetric prints can be done with modest light sources and even inside opaque, living materials, expanding practical applications.

**In-space volumetric printing demo – Waddell et al. (Acta Astronautica, Oct 2023):** *Peer-reviewed journal (open access, NASA/academia)*. Describes **“SpaceCAL” experiments on a microgravity flight (May 2022)** using Computed Axial Lithography. Demonstrated that CAL works in microgravity with **fewer distortions** (no sinking in low-viscosity resin) than on Earth[24]. They successfully **printed parts in under 20 s** using a 0.12 Pa·s (120 cP) liquid resin, including geometries **impossible to make on Earth (would deform under gravity)**[31][24]. *Significance*: Validates a functional volumetric printer prototype operating in an operational environment. It suggests **broader robustness** (potential for space-based manufacturing) and solved a major issue (gravity-induced distortion) via the technology’s unique approach.

**Volumetric overprinting around inserts – Bagheri et al. (Scientific Reports, Jan 2026):** *Peer-reviewed journal article (open access)*. Investigates printing **complex shapes around pre-existing solid inserts** using tomographic VAM. Identifies that naive volumetric printing fails with occluding inserts, and introduces an **orientation optimization algorithm** to maximize light exposure from all angles[32]. Using a commercial resin, they successfully **overprinted intricate structures onto complex inserts**, with micro-CT scans confirming improved fidelity and deep feature completion when using the optimized orientations[33]. *Significance*: Demonstrates VAM’s unique ability to **integrate/encapsulate objects in a single print**, and that software improvements can overcome optical challenges. This expands VAM’s applicability in manufacturing hybrid components not feasible by other AM methods.

**VAM for dental devices – Zhang et al. (Additive Manufacturing Frontiers, Jan 2026):** *Peer-reviewed review (open access, CMES China)*. Reviews how VAM could revolutionize dental appliance fabrication. Notes that VAM can **produce oral devices in seconds with superior isotropic strength** and smooth surface[34]. Early studies show **standard dental acrylic resins printed by VAM have far higher fabrication efficiency** than traditional methods, and with tailored photoinitiators plus nano-filler additives, the printed dentures achieved **high mechanical integrity, low shrinkage, and excellent biocompatibility**[35]. *Significance*: Indicates that **industry-specific R&D (dental)** is underway to optimize materials for VAM, aiming for real-world production. It highlights that even legacy materials (acrylics) can be



adapted for volumetric printing to yield **functional, durable parts**, supporting the plausibility of commercial deployment in medtech.

**Automated exposure control for VAM – NRC Canada & U. Victoria (arXiv preprint & news, May 2025):** *Research collaboration (preprint reported in Metrology News).* Developed a **closed-loop optical feedback system** for tomographic VAM[13]. In real time, sensors measure resin curing progress and the system adjusts projector intensity per angle to correct over/under exposure. The result was **feature resolution equal or better than commercial SLA/DLP printers, at up to 10× faster print speeds**[14]. *Significance:* Addresses a critical engineering hurdle – consistency and accuracy across a full 3D volume. This level of **precision and automation (“set-and-forget” printing)**[13] shows that volumetric printers can reach the reliability of today’s high-end 3D printers while preserving speed, paving the way for industrial-grade devices.

**BIO INX & Readily3D volumetric bio-resin (press release, May 2025):** *Vendor technical announcement (BIO INX, BE & Readily3D, CH).* Announced **READYPCL INX**, the first commercial **polyester-based resin optimized for volumetric bioprinting**[27]. Used with Readily3D’s Tomolite printer, it enables printing of **tough, load-bearing tissue constructs (cartilage, bone scaffolds) within seconds to minutes at ~100 µm resolution**[36]. The resin is biocompatible (ISO 10993-5) and fully biodegradable[11]. *Significance:* This shows **active industry ecosystem development** – companies are creating specialized materials for volumetric AM to unlock new applications. The availability of a **ready-to-use volumetric bio-ink** indicates that volumetric printing is moving toward real medical use (e.g. “printing replacement tissues during surgery” is cited as a goal) and that **feedstock limitations are being addressed**.

**Xolo (startup) funding and product development – (3DPrint.com news, Feb 2023):** *Industry news (funding report).* Berlin-based startup **Xolo GmbH** – developer of the “**xolography**” **volumetric printer (Xube)** – raised **€8 million in Series A funding in 2023** to accelerate commercialization[37]. This follows a €2.5 M seed round and the unveiling of their proprietary system that can “**print any design in seconds**” using dual-wavelength volumetric curing[37]. Investors include major tech VCs and a German government-backed deep-tech fund, aiming to help Xolo **bring its volumetric 3D printers from research labs to industrial markets**[38]. *Significance:* Clear evidence of **well-capitalized commercial effort**. Multiple investors are betting on volumetric AM’s potential, and Xolo is one of the first companies turning lab prototypes into a product line. This reflects a **competitive, fast-moving development race** beyond academia, an important marker on the path to widespread adoption.

**Dual-color volumetric printing for tailored mechanics – Bin Wang et al. (Nat. Commun., Jan 2022):** *Peer-reviewed journal article (open access).* Demonstrates **fully 3D control of material stiffness within a print** using dual-wavelength tomographic printing[8]. By mixing acrylate (radical cure) and epoxy (cationic cure) monomers with distinct photoinitiators, they used 455 nm and 365 nm light in one volumetric print to create internal **mechanical property gradients**. Achieved **~300 µm spatial resolution in stiffness tuning and a modulus range of 127–201 MPa** in one object[22]. *Significance:* Extends volumetric AM beyond just geometry – shows **multi-material or functionally graded printing is possible in one step**. This capability could outperform traditional 3D printing in creating parts with spatially optimized properties (for biomechanics, optics, etc.), thereby increasing the technology’s value proposition.



### 3. Maturity score (1–7) and reasoning

#### Overall Maturity Score: 5 (Early commercial prototype stage).

**A) Why not lower:** Volumetric 3D printing has **moved well past theory (Level 1)** – it’s not only experimentally proven[30] but has multiple working prototypes tackling prior roadblocks (e.g. sub-second high-res printing[30], multi-material control[22]). **Lab demos (Level 2–3)** have been plentiful since ~2019, and recent results show key functionality achieved: e.g. printing complex, support-free objects with competitive resolution and mechanics[21][35]. The technology has also **proven viable in new contexts** (bioprinting living cells, microgravity manufacturing), indicating robustness beyond a single lab setup[31][26]. These successes fulfill and exceed Level 3 criteria.

At **Level 4 (proof-of-concept for commercialization)**, we see that volumetric AM **clearly surpasses conventional methods in unique benefits** – it can produce shapes and internal features impossible by layering, and does so dramatically faster[31][26]. Indeed, researchers are citing volumetric printers’ speed and isotropy as game-changers for prototyping and small-batch production[34][26]. Evidence of meeting practical requirements is emerging: e.g. volumetric-printed parts with comparable accuracy to standard 3D prints[14] and improved material properties like higher isotropic strength and low shrinkage in dental resins[35]. These point to functional viability for real-world use, satisfying Level 4.

**B) Why score = 5:** Several independent actors are now pushing toward **productization of volumetric printers**, which is characteristic of Level 5. Notably, **multiple startups in different regions have working volumetric 3D printers** and have secured significant funding (e.g. **Xolo in Germany with €8M Series A**[37], Readily3D in Switzerland selling Tomolite bioprinters). They are effectively in competition to refine prototypes and enter niche markets (biomedical models, research tools). Additionally, **national-level programs and major grants** (e.g. EU’s ENLIGHT project with volumetric bioprinting[39], NASA-funded microgravity tests[24]) underscore that **well-resourced organizations see this as a viable near-term technology**. All this momentum goes beyond a single proof-of-concept – it shows an **ecosystem gearing up to deploy volumetric AM**. The **fast-paced progress** is evident: within the last 2–3 years, resolution improved tenfold, print speeds went from tens of seconds to sub-second[20][21], and the first **commercial materials and beta machines** have appeared[27][37]. These are strong indicators of Level 5 (early commercial prototype race).

**Missing evidence for Level 6:** To reach 6, we’d expect **actual products shipping in volume to customers and scaling of production**. As of now, volumetric printers are **mostly limited to research labs or pilot users** – e.g. Xolo’s and Readily3D’s systems are available but not yet broadly adopted in industry (they target R&D and medical research contexts first). There’s **no indication of dozens of units shipped or any cost reduction from scaling yet** – in fact, the 2024 review highlights that **commercial VAM printers remain scarce and specialized**[29]. Moreover, **materials constraints and process complexities persist**[40], which companies are only beginning to address (with new resins like READYPCl and automated calibration systems in development). This means volumetric AM is **still crossing the gap from lab innovation to reliable product**. Larger industry players (e.g. big 3D printer OEMs) have not yet released competing volumetric machines – competition is growing but not “wide” in the market sense.

**C) Sub-component variation:** All the variants aim at the same goal (rapid layerless printing) and improvements are cumulative, so we treat the **bundle's maturity as a whole**. The most advanced implementations (tomographic and bioprinting volumetric systems) are at ~Level 5, as argued. Some sub-threads:

- *Tomographic VAM (CAL and holographic) – Maturity ~5.* Key sub-systems exist as working prototypes trending toward products: e.g. **Xolo's Xube (tomographic dual-color)** is being marketed to advanced users[37], and volumetric printers are in use for specialized tasks (like microgravity CAL printing[31]). Ongoing improvements in software (exposure correction[14]) and hardware (fast optics[15]) are rapidly closing performance gaps.
- *Volumetric bioprinting – Maturity ~5.* Readily3D's commercial Tomolite printer indicates an available product (targeted to research) and partnerships for materials (BIO INX) show a proto-ecosystem[27][36]. This niche actually has paying customers (labs) and addresses urgent applications (tissue engineering), fueling investment.
- *Advanced research-only variants (e.g. DISH holography, multi-material xolography) – Maturity ~3–4.* These are cutting-edge lab demonstrations (Nature 2026) showing what might be possible next[30]. They solved specific barriers (like speed vs resolution), but are not yet in a deliverable product. However, their existence reinforces that the *core concept is robust and improving*, feeding into the more mature threads above.

Given that **the fundamental capability is shared** across these threads and the **leading groups have already transitioned to early commercial efforts**, the **overall ART is rated at Level 5**. In summary, volumetric additive manufacturing is **on the cusp of commercialization** – proven in principle and prototype, with active commercialization underway – but **not yet a widely adopted, scaled product** (hence not Level 6). The next few years should see it enter select markets, provided materials and engineering challenges continue to be addressed[40].

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## Group 7 - Advanced Materials & Nano-engineering

### ART 07.044 Metamaterials for Novel Optics & Connectivity

#### ART extraction

##### Primary capability claimed

- Thin, engineered “metamaterial/metasurface” structures that **shape electromagnetic waves (light and radio)** primarily via micro/nano-scale geometry rather than bulk chemistry, enabling steering, focusing, filtering, absorption, scattering, or polarisation control in compact form factors.
- **Reconfigurability (“programmable surfaces”)** in which the phase/amplitude/polarisation response can be adjusted electronically/software-defined in (near) real time, enabling adaptive beam steering, interference management, and multi-function operation.
- **System-level SWaP advantages** (size/weight/power), plus retrofit potential (tiles/coatings/inserts) that can displace bulk optics/antennas and improve link reliability in obstructed environments.

##### Key variants and sub-threads

- **Flat optics / meta-optics:** metalenses, metaholograms, beam shapers, structural colour, and multi-functional optical metasurfaces.
- **Scalable manufacturing:** wafer-scale / large-area patterning, nanoimprint lithography (NIL), photolithography, hybrid material stacks, and yield/defect tolerance.
- **Tunable optical metasurfaces:** electro-optic, MEMS, phase-change-material (PCM), or resonance-based tuning for dynamic focusing/beam control.
- **Metasurface antennas (RF/mmWave):** low-profile electronically steered antennas and related “wavefront-engineered” apertures.
- **Reconfigurable Intelligent Surfaces (RIS) for wireless:** passive/semi-passive surfaces that redirect signals around blockage, suppress interference, and enable smart radio environments; includes channel modelling, control architectures, and standardisation.
- **Environmental robustness:** thermal stability, outdoor exposure, vibration, and long-term reliability for deployed surfaces (especially RF infrastructure and space/defence contexts).

##### Maturity indicators needed for scoring

- **Peer-reviewed experimental demonstrations** showing high efficiency, large aperture, or broadband operation (optics), and validated beamforming/field trials (RF).
- **Scalable manufacturing proof** (wafer-scale, repeatable replication, high throughput) and evidence of defect tolerance/yield progress.
- **Field trials in realistic environments** (commercial or near-commercial wireless deployments) with measurable coverage/throughput/interference benefits.
- **Standardisation movement** (channel models, evaluation methodology, implementation considerations) from recognised bodies.

- **Commercial delivery evidence** (shipping products or very high-volume deployments), with measurable specifications and compliance/reliability details.

**Evidence (ten to twenty recent, reliable sources)**

**1) Scalable manufacturing of high-index atomic layer–polymer hybrid metasurfaces for metaphotonics in the visible**

**Lead author:** Joohoon Kim et al.

**Venue/type:** *Nature Materials* (peer-reviewed experimental paper)

**Date:** March 2023

**Link:** <https://www.nature.com/articles/s41563-023-01485-5>

**Why it matters:** Demonstrates an explicit **scalable manufacturing route** (hybrid meta-atoms) aimed at overcoming throughput/area barriers that historically blocked mass production of visible metasurfaces, directly addressing manufacturability constraints central to the ART. [1]

**2) 8" wafer-scale, centimetre-sized, high-efficiency metalenses in the ultraviolet**

**Lead author:** Joohoon Kim et al.

**Venue/type:** *Materials Today* (peer-reviewed experimental paper)

**Date:** 2024 (volume/issue date shown; month not stated on the preview page)

**Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S1369702124000105>

**Why it matters:** Reports a route to **centimetre-scale UV metalenses on 8-inch wafers** using reticle patterning + ArF lithography + NIL, with a reported **~80% conversion efficiency at 325 nm**—strong evidence that “flat optics” can move beyond small e-beam prototypes into scalable semiconductor-style flows. [2]

**3) Tantalum pentoxide: a new material platform for high-performance dielectric metasurface optics in the ultraviolet and visible region**

**Lead author:** Cheng Zhang et al.

**Venue/type:** *Light: Science & Applications* (peer-reviewed experimental paper; open via PMC)

**Date:** 2024 (month not clearly surfaced in the excerpted view)

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC10800353/>

**Why it matters:** Presents Ta<sub>2</sub>O<sub>5</sub> as a **fabrication-friendly wide-bandgap platform** (high refractive index, low loss, large-area deposition) and demonstrates multiple metasurface functions with **reported efficiencies up to ~80%**, supporting feasibility for robust UV/visible meta-optics. [3]

**4) Integrated metasurfaces for re-envisioning a near-future disruptive optical platform**

**Lead author:** Younghwan Yang et al.

**Venue/type:** *Light: Science & Applications* (peer-reviewed review article, but grounded in implementation/manufacturing considerations)

**Date:** June 2023

**Link:** <https://www.nature.com/articles/s41377-023-01169-4>

**Why it matters:** Synthesises the state of **integrated / system-level metasurface adoption**, explicitly linking meta-optics performance to packaging, integration, and manufacturability—helpful for judging practical plausibility and integration readiness beyond isolated device demos. [4]

### 5) 3D-printed multilayer structures for high-numerical aperture achromatic metalenses

**Lead author:** Cheng-Feng Pan et al.

**Venue/type:** *Science Advances* (peer-reviewed experimental paper; open via PMC)

**Date:** December 2023

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC10732525/>

**Why it matters:** Demonstrates a **fabricated multilayer achromatic metalens** approach (tackling bandwidth/aberration trade-offs) and reports **measured efficiencies up to ~42%** for visible-range devices—evidence of progress on the ART's bandwidth/optical-performance constraints. [5]

### 6) Three-dimensional, multi-wavelength beam formation with integrated metasurface optics for Sr laser cooling

**Organisation/lead:** National Institute of Standards and Technology[6] (with academic/industry co-authors)

**Venue/type:** *Optics Letters* (peer-reviewed experimental paper; PDF)

**Date:** October 2024 (published 17 Oct 2024; letter dated 1 Nov 2024)

**Link:** <https://tf.nist.gov/general/pdf/3273.pdf>

**Why it matters:** Shows metasurfaces integrated into a demanding precision-physics context, with **multi-wavelength beam pointing/divergence/polarisation control** across multiple mm-scale metasurfaces on a single substrate—strong evidence of system integration plausibility (alignment reduction, compactness). [7]

### 7) Roadmap for Optical Metasurfaces

**Lead author:** Arseniy I. Kuznetsov et al.

**Venue/type:** *ACS Photonics* (peer-reviewed roadmap/review)

**Date:** February 2024 (PubMed lists 27 Feb 2024; issue later in 2024)

**Link:** <https://pubmed.ncbi.nlm.nih.gov/38550347/>

**Why it matters:** A high-authority metasurface roadmap that explicitly outlines **remaining engineering bottlenecks** (e.g., scale, efficiency/bandwidth trade-offs, integration) and near-to-mid-term R&D directions, supporting maturity assessment across the full optical stack. [8]

### 8) Highly efficient, tunable, electro-optic metasurfaces based on quasi-bound states in the continuum (*preprint*)

**Lead author:** Christopher Damgaard-Carstensen et al.

**Venue/type:** arXiv (preprint with experimental metrics stated)

**Date:** December 2024

**Link:** <https://arxiv.org/abs/2412.01449>

**Why it matters:** Reports an electro-optic metasurface achieving **~95% modulation depth at telecom wavelengths** (with stated electrical bandwidth and voltage conditions), evidencing credible pathways to **software-defined/tunable optical surfaces**, while also signalling that this sub-thread is still pre-product. [9]

### 9) Continuous Varifocal Metalens Based on Phase-Change Material (*preprint*)

**Lead author:** Yilong Cui et al.

**Venue/type:** arXiv (preprint)

**Date:** December 2024

**Link:** <https://arxiv.org/abs/2412.07257>

**Why it matters:** Demonstrates a continuously tunable (PCM-based) metalens reporting **focal length tuning (tens of  $\mu\text{m}$ ) while maintaining >75% focusing efficiency**, directly relevant to



the ART's claim of dynamically reconfigurable flat optics (with remaining questions on cycling, packaging, and high-volume manufacturability). [10]

#### 10) STMicroelectronics and Metalenz sign a new licence agreement to accelerate metasurface optics adoption

**Organisations:** STMicroelectronics[11] and Metalenz[12]

**Venue/type:** Industry press release (shipment/manufacturing claim; treat as commercial evidence)

**Date:** July 2025

**Link:** <https://newsroom.st.com/media-center/press-item.html/t4717.html>

**Why it matters:** States that, **since 2022**, ST has shipped “**well over 140 million**” **metasurface optics and related modules** and is leveraging a **300 mm semiconductor + optics manufacturing platform**—strong evidence of real scaling, qualification, and high-volume delivery in at least one major application class (3D sensing modules). [13]

#### 11) HAWK u8 GEO / GEO-LTE product sheet (*vendor technical doc*)

**Vendor:** Kymeta[14]

**Venue/type:** Product datasheet (measurable RF performance and compliance)

**Date:** Specifications as of May 2022 (rev D)

**Link:** <https://www.idirect.net/wp-content/uploads/2023/01/ProductSheet-Kymeta-Hawk-u8.pdf>

**Why it matters:** Provides concrete commercially packaged performance for a low-profile electronically steered terminal (e.g., scan range, Ku-band RX/TX bands, **EIRP ~46 dBW, G/T up to ~12 dB/K**, IP rating, operating temperatures, regulatory compliance), indicating metamaterial/metasurface-derived apertures have reached deliverable hardware in connectivity markets. [15]

#### 12) EchoShield® technical spec sheet (*vendor technical doc*)

**Vendor:** Echodyne[16]

**Venue/type:** Product specification sheet

**Date:** 2025 (copyright shown on document)

**Link:** [https://www.echodyne.com/media/12tbkrho/ts-echoshield-echodyne\\_5jl1.pdf](https://www.echodyne.com/media/12tbkrho/ts-echoshield-echodyne_5jl1.pdf)

**Why it matters:** Documents a fielded “cognitive metamaterials ESA (MESA)” radar with measurable metrics (e.g., **Ku-band 15.4–16.6 GHz, <0.5° angular track accuracy, 10 Hz update rate, >1,000 tracks**, environmental specs), supporting maturity of metamaterial-based RF wave-control apertures in real products. [17]

#### 13) ETSI GR RIS 003 V1.1.1: Communication models, channel models, channel estimation and evaluation methodology

**Organisation:** European Telecommunications Standards Institute[18]

**Venue/type:** Standards-body technical report / methodology baseline

**Date:** June 2023

**Link:**

[https://www.etsi.org/deliver/etsi\\_gr/RIS/001\\_099/003/01.01.01\\_60/gr\\_RIS003v010101p.pdf](https://www.etsi.org/deliver/etsi_gr/RIS/001_099/003/01.01.01_60/gr_RIS003v010101p.pdf)

**Why it matters:** Establishes a recognised standardisation artefact for RIS evaluation, including scope covering **trade-offs between EM accuracy and simplicity**, channel modelling, and **channel estimation overhead challenges for large-element surfaces**—

critical maturity evidence for “programmable RF surfaces” moving toward interoperable ecosystem definitions. [19]

#### 14) ETSI GR RIS 004 V1.1.1: Implementation and practical considerations

**Organisation:** ETSI

**Venue/type:** Standards-body implementation report

**Date:** March 2025

**Link:**

[https://www.etsi.org/deliver/etsi\\_gr/RIS/001\\_099/004/01.01.01\\_60/gr\\_ris004v010101p.pdf](https://www.etsi.org/deliver/etsi_gr/RIS/001_099/004/01.01.01_60/gr_ris004v010101p.pdf)

**Why it matters:** Focuses explicitly on **implementation-level** considerations (hardware/control, deployment practicality), signalling movement from purely theoretical literature toward engineering constraints, test methods, and deployability requirements. [20]

#### 15) ETSI GR RIS 006 V1.1.1: Multi-functional RIS—modelling, optimisation, and operation

**Organisation:** ETSI

**Venue/type:** Standards-body report (multi-function operation, deployment)

**Date:** June 2025

**Link:**

[https://www.etsi.org/deliver/etsi\\_gr/RIS/001\\_099/006/01.01.01\\_60/gr\\_ris006v010101p.pdf](https://www.etsi.org/deliver/etsi_gr/RIS/001_099/006/01.01.01_60/gr_ris006v010101p.pdf)

**Why it matters:** Treats RIS as more than a reflector—covering **multi-functional surfaces** (e.g., transmission/reflection combinations and other functions), and suggests operational/deployment pathways, aligning with the ART’s “software-defined wave-control surface” vision while also evidencing that standards discussions are still consolidating. [21]

#### 16) A filtering reconfigurable intelligent surface for interference-free wireless communications

**Lead author:** Jing Cheng Liang et al.

**Venue/type:** *Nature Communications* (peer-reviewed experimental paper; open)

**Date:** May 2024

**Link:** <https://www.nature.com/articles/s41467-024-47865-6>

**Why it matters:** Demonstrates a RIS with **frequency-selective behaviour** plus **2-bit phase shifting**, directly supporting the ART’s claim that engineered surfaces can combine filtering + steering to mitigate interference in crowded spectral environments. [22]

#### 17) Field trial measurement and channel modeling for reconfigurable intelligent surface

**Lead author:** Peng Zheng et al.

**Venue/type:** *Digital Communications and Networks* (peer-reviewed experimental paper; open access)

**Date:** June 2023

**Link:** <https://www.sciencedirect.com/science/article/pii/S2352864822002103>

**Why it matters:** Explicitly reports **outdoor and indoor field trials** for a sub-6 GHz, 1-bit RIS and develops/validates pathloss and radiation-pattern modelling against measurements—key plausibility evidence that RIS effects persist outside lab chambers and can be modelled for network planning. [23]

#### 18) Design and validation of scalable reconfigurable intelligent surfaces

**Lead author:** Marco Rossanese et al.

**Venue/type:** *Computer Networks* (peer-reviewed paper with prototyping + data release)

**Date:** March 2024

**Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S1389128624000409>

**Why it matters:** Describes and empirically characterises an RF-switch/PCB-based RIS architecture designed for **scalability and reproducible experimentation**, including modular construction and public dataset release—useful maturity evidence for practical prototyping and benchmarking at scale. [24]

#### 19) **Prototyping and real-world field trials of RIS-aided wireless communications** *(preprint)*

**Lead author:** Xilong Pei et al.

**Venue/type:** arXiv (preprint; includes field measurements)

**Date:** August 2023

**Link:** <https://arxiv.org/abs/2308.03263>

**Why it matters:** Reports multiple experimental settings including outdoor tests (reporting **>35 dB received power gain**) and a commercial-network context where gains were smaller (**~4–7 dB**), giving grounded evidence of both upside and practical limits (antenna directivity, environment dependence). [25]

#### 20) **RIS-Aided mmWave O-RAN: coverage extension and user mobility handling** *(preprint)*

**Lead author:** Tawfik Osman et al.

**Venue/type:** arXiv (preprint; system testbed + field trials)

**Date:** October 2025

**Link:** <https://arxiv.org/abs/2510.20088>

**Why it matters:** Presents an implemented **1,024-element (32×32) 1-bit RIS at 28 GHz** integrated with an O-RAN control interface and reports **field-trial received-power gains** (reported ranges for indoor/outdoor trials), directly indicating progress toward practical control-plane integration for deployable RIS. [26]

#### **Maturity score and reasoning**

**Final maturity score: 6**

This ART is already beyond laboratory proof and early PoCs because there is clear evidence of **commercial delivery of metamaterial/metasurface-based wave-control hardware** at scale in at least one major market segment: STMicroelectronics[11] reports shipping **well over 140 million** metasurface optics and related modules since 2022 and highlights a 300 mm manufacturing/qualification platform for metasurface optics. [13] In RF connectivity and sensing, vendor technical specifications show delivered products with measurable performance and regulatory/environmental integration details—e.g., the Kymeta[14] flat-panel electronically steered terminal datasheet provides bands, EIRP/G/T, temperature range and compliance, consistent with a productised metasurface-style aperture. [15] Echodyne[16] similarly publishes a “cognitive metamaterials ESA” radar spec sheet with track accuracy, update rate, and environmental specs, indicating mature product packaging around metamaterial apertures. [17]

At the same time, parts of the ART—especially **network-integrated RIS as infrastructure** and **fast, high-efficiency tunable optical metasurfaces**—remain earlier-stage. Field trials and prototypes exist (including outdoor and commercial-network experiments and O-RAN-

integrated mmWave demonstrations), but these sources still read as **pre-standard / pre-mass-deployment engineering** rather than widely deployed infrastructure. [27] The presence of multiple recent standards-body reports from the European Telecommunications Standards Institute [18] illustrates momentum toward common evaluation and implementation frameworks, but also implies that large-scale interoperability and deployment norms are still being defined. [28]

### Evidence-to-rubric mapping

**What rules out levels 1–5 (why the ART is at least 6): - Delivered products with quantified specifications** exist for metamaterial/metasurface RF apertures (e.g., electronically steered terminals and metamaterials ESA radar), consistent with “products delivered to customers” rather than lab-only prototypes. [29]

- **Very high-volume shipments** are explicitly claimed for metasurface optics modules (hundreds of millions scale is not implied, but “well over 140 million” is explicitly stated), indicating mass manufacturing, qualification, and customer delivery at scale. [13]

- Multiple peer-reviewed papers demonstrate **manufacturing-scalable processes** and large-area/wafer-scale approaches, reinforcing that the underlying engineering is not confined to small, fragile demonstrations. [30]

**What is missing to justify level 7 (why the ART is not 7 overall):** - The evidence set does not cleanly establish that **multiple competing vendors** are delivering comparable metasurface-based products at high volume *across the full ART scope* (optics + connectivity infrastructure) with clearly rising demand; we have strong evidence for one large-scale optics channel and multiple niche-to-established RF products, but not broad cross-market competitive scaling data. [31]

- For RIS-as-network-infrastructure specifically, the evidence remains dominated by **field trials, prototypes, modelling reports, and standards groundwork** rather than ubiquitous deployments with sustained procurement signals. [32]

### Subcomponent breakdown and aggregation

- **Meta-optics in consumer-grade sensing modules** → 6–7 (delivered at very large volumes; manufacturing/qualification highlighted). Key evidence: shipment statement and manufacturing platform positioning. [13]
- **Scalable optical metasurface manufacturing (wafer/large-area)** → 5–6 (credible scalable processes in peer-reviewed work; supports manufacturability). Key evidence: scalable manufacturing in *Nature Materials* and wafer-scale UV metalenses. [33]
- **Tunable optical metasurfaces (electro-optic / PCM metalenses)** → 3–4 (prototype-level, largely preprint evidence; strong plausibility but not yet product scaling). Key evidence: tunable electro-optic modulation and PCM varifocal demonstrations. [34]
- **Metasurface/metamaterial RF apertures (satcom terminals, radars)** → 6 (vendor-published specs and productisation signals). Key evidence: product spec sheets. [35]
- **RIS for cellular / O-RAN integration and deployments** → 4–5 (field trials, measurement-based models, and standards body implementation reports; still not broadly deployed). Key evidence: field trial measurements and O-RAN RIS testbed field trials; ETSI implementation reports. [36]

**Aggregation logic:** Because the ART spans multiple application areas with meaningfully different maturity (mass-produced meta-optics and commercial RF apertures versus earlier-stage RIS infrastructure and tunable meta-optics), an average-based score is appropriate. The existence of high-volume delivered products and well-specified commercial hardware pulls the overall maturity into **level 6**, while the still-developing RIS infrastructure and tunable optical surfaces prevent a level 7 classification. [37]

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## ART 07.045 Room-Temperature Superconductors

### 1. ART extraction

#### A) Primary capability claimed (what “room-temperature superconductors” would do)

- Achieve *effectively zero electrical resistance* for bulk current flow at (or near) everyday temperatures, ideally also at *near-ambient pressure* and in *useful magnetic fields* (so it can replace copper/aluminium conductors without cryogenics).
- Provide *practical conductor form factors* (wire/tape/thin film/laminates) with robust encapsulation, joining, monitoring, and predictable behaviour under strain and field.

#### B) Key sub-components / variants implied by the ART description

- **Material families aiming at high  $T_c$ :** hydrogen-rich hydrides/superhydrides (currently high-pressure), “chemically precompressed” ternary hydrides, and other engineered compounds targeting ambient pressure stability.
- **Pressure/temperature stabilisation pathways:** chemical substitution (e.g., ternary alloying), metastable phase retention, and defect/stoichiometry control.
- **Conductor architectures:** superconducting layer + stabiliser metals + outer jacket; cable assemblies (stacked tapes, CORC®, CICC).
- **Joining & interfaces:** low-resistance splices/connectors that do not create weak points;



quality assurance along length.

- **Quench / instability sensing & protection:** monitoring electronics, current diversion strategies, and mechanical design to avoid degradation.
- **Manufacturing controls:** purity, grain alignment/texture, defect control, reproducible composition/phase, and scalable deposition or bulk synthesis.

### C) Maturity indicators that would constitute strong evidence (for this ART specifically)

- **Reproducible, independently verified superconductivity at  $\geq \sim 290\text{--}300\text{ K}$  with clear Meissner/flux exclusion and transport zero resistance, at  $\leq \sim 1\text{ bar}$  (or at least  $\leq \sim$  a few GPa as an interim step), plus meaningful critical current density  $J_c$  and upper critical field  $H_{c2}$ .**
- **Stability under realistic conditions:** survives thermal cycling, humidity/oxidation exposure, mechanical strain/bending, and magnetic-field cycling without catastrophic degradation.
- **Scalable materials processing:** repeatable synthesis and *process windows* demonstrated beyond single short samples (batch repeatability, yield statistics).
- **Conductor-length demonstrations:** continuous lengths (metres  $\rightarrow$  kilometres) with standardised connectors/joints, tested under load.
- **Field trials / system demos:** integration into power devices (cables, transformers, motors), magnets, or thermal-management-limited electronics without cryogenics.
- **Multiple well-capitalised actors and supply-chain evidence:** procurement specs, pilot lines, and a standardisation or qualification ecosystem.

## 2. Evidence (10–20 recent, reliable sources)

### 1) Retraction Note: Room-temperature superconductivity in a carbonaceous sulfur hydride

- **Authors/Org:** Elliot Snider[1] et al.
- **Venue/type:** Nature[2] (retraction note; peer-reviewed journal record)
- **Publication date:** Sept 2022 (published 26 Sept 2022)
- **Link:** <https://www.nature.com/articles/s41586-022-05294-9>
- **Why it matters:** A headline “room-temperature” superconductivity claim (2020) was formally retracted due to unresolved questions about data processing/analysis, underscoring that *extraordinary  $T_c$  claims remain fragile unless independently reproducible with transparent data.* [3]

### 2) RETRACTED ARTICLE: Evidence of near-ambient superconductivity in a N-doped lutetium hydride

- **Authors/Org:** Nathan Dasenbrock-Gammon[4] et al.
- **Venue/type:** Nature (peer-reviewed paper; later retracted)
- **Publication date:** Mar 2023 (published 08 Mar 2023; retracted 07 Nov 2023)
- **Link:** <https://www.nature.com/articles/s41586-023-05742-0>
- **Why it matters:** This paper claimed superconductivity around room temperature ( $\sim 294\text{ K}$ ) at “near-ambient” pressures ( $\sim 1\text{ GPa}$ -scale), but the article was later retracted—highlighting how *near-ambient/ambient RT superconductivity is not yet a stable, validated result.* [5]

### 3) Absence of near-ambient superconductivity in $\text{LuH}_{2\pm x}\text{Ny}$

- **Authors/Org:** Xue Ming[6] et al.
- **Venue/type:** Nature (peer-reviewed experimental replication)
- **Publication date:** May 2023 (published 11 May 2023)
- **Link:** <https://www.nature.com/articles/s41586-023-06162-w>

- **Why it matters:** Replication efforts synthesised nitrogen-doped lutetium hydride and reported *no superconductivity* (down to 2 K) across tested pressures up to ~40 GPa, weighing strongly against near-ambient validity and illustrating the field's *reproducibility gate* for maturity. [7]

#### 4) Observation of non-superconducting phase changes in nitrogen doped lutetium hydrides

- **Authors/Org:** Xiangzhuo Xing[8] et al.

- **Venue/type:** Nature Communications[9] (peer-reviewed experimental study)

- **Publication date:** Sept 2023 (published 26 Sept 2023)

- **Link:** <https://www.nature.com/articles/s41467-023-41777-7>

- **Why it matters:** Reports *no superconducting transition* from ~1.8–300 K and 0–38 GPa, and argues that observed resistance anomalies/colour changes can arise from non-superconducting electronic/structural effects—directly addressing a key failure mode in “RT superconductor” claims: misinterpreting anomalies as superconductivity. [10]

#### 5) Superconductivity above 200 K discovered in superhydrides of calcium

- **Authors/Org:** Zhiwen Li[11] et al.

- **Venue/type:** Nature Communications (peer-reviewed experimental paper)

- **Publication date:** May 2022 (published 23 May 2022)

- **Link:** <https://www.nature.com/articles/s41467-022-30454-w>

- **Why it matters:** Demonstrates *very high critical temperature* superconductivity (reported  $T_c$  ~210 K) in calcium superhydrides synthesised under extreme pressures (~160–190 GPa) and high-temperature laser heating, with reported high inferred field scales (e.g., very large  $H_c$  estimates). This supports *plausibility* for high- $T_c$  via hydrides, but also shows the *practicality bottleneck* (megabar pressures). [12]

#### 6) Enhancement of superconducting properties in the La–Ce–H system at moderate pressures

- **Authors/Org:** Wuhao Chen[13] et al.

- **Venue/type:** Nature Communications (peer-reviewed experimental paper)

- **Publication date:** May 2023 (published 09 May 2023)

- **Link:** <https://www.nature.com/articles/s41467-023-38254-6>

- **Why it matters:** Shows an experimental route to *engineer ternary hydrides* with lower stabilisation pressures than benchmark binary hydrides: synthesising hcp-(La,Ce)H<sub>9–10</sub> (~113 GPa) and reporting superconductivity at ~176 K around ~100 GPa plus very large extrapolated  $H_{c2}$  values. This supports the “chemical tuning” path while still far from ambient pressure. [14]

#### 7) Stoichiometric Ternary Superhydride LaBeH<sub>8</sub> as a New Template for High-Temperature Superconductivity at 110 K under 80 GPa

- **Authors/Org:** Yinggang Song[15] et al.

- **Venue/type:** Physical Review Letters (peer-reviewed experimental paper; indexed record)

- **Publication date:** Jun 2023 (PubMed: 30 Jun 2023)

- **Link:** <https://pubmed.ncbi.nlm.nih.gov/37450815/>

- **Why it matters:** Reports synthesis of a *stoichiometric ternary hydride with resolved structure* and superconductivity up to ~110 K at ~80 GPa, evidencing progress toward lower-pressure high- $T_c$  hydrides. Still, 80 GPa is orders of magnitude above device-relevant pressures. [16]

### 8) Mechanism of high-temperature superconductivity in compressed H<sub>2</sub>-molecular-type hydride CaH<sub>14</sub>

- **Authors/Org:** Zhao Liu[17] et al.
- **Venue/type:** Science Advances (peer-reviewed; open full text via PubMed Central)
- **Publication date:** Mar 2025 (PMC collection date 28 Mar 2025; accepted Feb 2025)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11952093/>
- **Why it matters:** Reports a hydride with an unusual electronic mechanism discussion and a reported  $T_c$  around ~204 K at very high pressure, while also discussing behaviour at reduced pressures (tens of GPa). It reinforces plausibility that new hydride structural motifs can sustain high  $T_c$ , but remains fundamentally constrained by extreme-pressure synthesis. [18]

### 9) X-ray-diffraction and electrical-transport imaging of superconducting superhydride (La,Y)H<sub>10</sub>

- **Authors/Org:** Abdul Haseeb Manayil Marathamkottil[19] et al.
- **Venue/type:** Nature Communications (peer-reviewed experimental paper)
- **Publication date:** Dec 2025 (published 18 Dec 2025)
- **Link:** <https://www.nature.com/articles/s41467-025-66262-1>
- **Why it matters:** Uses spatially resolved XRD imaging + transport to correlate *local structure domains* with distinct superconducting transitions (onsets reported near ~244 K and ~220 K) in (La,Y)H<sub>10</sub> at megabar pressures, illustrating increasing experimental sophistication and reproducibility work—important for plausibility, but still far from scalable ambient conditions. [20]

### 10) The maximum $T_c$ of conventional superconductors at ambient pressure

- **Authors/Org:** Kun Gao[21] et al.
- **Venue/type:** Nature Communications (peer-reviewed computational/meta-analysis)
- **Publication date:** Sept 2025 (published 10 Sept 2025)
- **Link:** <https://www.nature.com/articles/s41467-025-63702-w>
- **Why it matters:** Analyses large electron-phonon datasets and argues that *room-temperature conventional superconductivity at ambient pressure is extremely unlikely* due to trade-offs between phonon frequency scales and coupling/instability constraints; this is directly relevant to plausibility expectations for “ambient RT superconductors” in phonon-mediated regimes. [22]

### 11) Prediction of ambient pressure conventional superconductivity above 80 K in hydride compounds

- **Authors/Org:** Antonio Sanna[23] et al.
- **Venue/type:** npj Computational Materials (peer-reviewed computational prediction)
- **Publication date:** Feb 2024 (published 28 Feb 2024)
- **Link:** <https://www.nature.com/articles/s41524-024-01214-9>
- **Why it matters:** Uses ML-accelerated screening to propose Mg<sub>2</sub>XH<sub>6</sub> (X = Rh/Ir/Pd/Pt) hydrides with predicted  $T_c$  ranges ~45–80 K (and potentially >100 K with electron doping) at *room pressure*. This is a credible “design-for-ambient-pressure” direction, but remains at the *prediction stage*. [24]

### 12) Feasible route to high-temperature ambient-pressure hydride superconductivity

- **Authors/Org:** Kapildeb Dolui[25] et al.
- **Venue/type:** arXiv preprint (explicitly labelled); page notes a later journal reference in Physical Review Letters

- **Publication date:** Oct 2023 (submitted 11 Oct 2023; revised Apr 2024)
- **Link:** <https://arxiv.org/abs/2310.07562>
- **Why it matters:** Proposes a specific metastable hydride (e.g.,  $\text{Mg}_2\text{IrH}_6$ ) with very high predicted  $T_c$  at ambient pressure and discusses a plausible synthesis route via a related high-pressure-stable precursor phase. This informs plausibility pathways while still lacking experimental synthesis/validation at ambient pressure. [26]

### 13) Absence of Superconductivity in LK-99 at Ambient Conditions

- **Authors/Org:** K. Kumar[27] et al.
- **Venue/type:** ACS Omega (peer-reviewed experimental; open full text via PubMed Central)
- **Publication date:** Oct 2023 (ACS Omega issue: 25 Oct 2023)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC10633996/>
- **Why it matters:** Reports synthesised “LK-99” (Cu-doped lead apatite) samples that are highly resistive (insulator-like) in the measured temperature range and do not show superconductivity signatures, providing a peer-reviewed negative result for a widely publicised ambient-condition claim and emphasising the *gap between viral claims and validated maturity*. [28]

### 14) Technical Specification: REBCO Coated Conductor for the Muon Collider Solenoids Development

- **Authors/Org:** CERN[29] (technical specification / procurement-style requirements)
- **Venue/type:** Institutional technical specification (system/engineering evidence)
- **Publication date:** May 2023
- **Link:** <https://indico.cern.ch/event/1240046/contributions/5356502/attachments/2645865/4579815/HTS%20techspecs%20v3.pdf>
- **Why it matters:** While not room-temperature, it concretely documents how superconductors become “real conductors”: kilometre-scale quantities, defined tape geometry, minimum critical current targets (e.g., at 4.2 K and high fields), unit-length expectations, bend-radius constraints, and acceptance testing—all directly relevant to the ART’s claimed mature-state conductor packaging and QA needs once an ambient-temperature material exists. [30]

### 15) Twisting & Bending Performance of a Subscale CORC® Cable-in-Conduit-Conductor for Fusion and Detector Magnet Applications

- **Authors/Org:** Michael Naus[31] et al.
- **Venue/type:** IEEE Transactions on Applied Superconductivity (peer-reviewed engineering paper; PDF hosted by Advanced Conductor Technologies — treat as vendor-hosted copy of a journal paper)
- **Publication date:** Aug 2025 (journal issue shown as Aug 2025; paper metadata in PDF shows publication workflow in late 2024/early 2025)
- **Link:** <https://www.advancedconductor.com/wp-content/uploads/2025/11/Naus-M.-IEEE-Trans.-Appl.-Supercond.-35-4800805-2025.pdf>
- **Why it matters:** Demonstrates engineering-maturity elements the ART anticipates (mechanical deformation tolerance, manufacturability issues, measured performance degradation under twisting/bending) for high-temperature superconducting cable architectures—supporting the claim that *if* a room-temperature material existed, there is an

established pathway for conductor/cable qualification; but it also illustrates how sensitive superconducting performance can be to mechanical handling. [32]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 2

#### B) Justification mapped to the rubric

##### Why the evidence rules out level 1 (purely theoretical / early academic interest)

- Multiple peer-reviewed experimental works in the last four years demonstrate **very high- $T_c$**  superconductivity in hydrogen-rich hydrides/superhydrides (e.g.,  $T_c \sim 210$  K in calcium superhydrides under  $\sim 160$ – $190$  GPa; high- $T_c$  ternary hydride systems engineered by alloying; and additional hydride families explored experimentally). [33]
- The field is not just hypothesising “RT superconductivity”: it is repeatedly demonstrating *near-room-temperature class transition temperatures*—but under extreme pressures and specialised apparatus, indicating an established laboratory operating principle (rubric level 2). [34]

##### Why the ART does *not* reach level 3 (laboratory prototype solving a key blocking problem for deployment)

- The ART’s defining commercialisation blocker is **ambient (or device-compatible) pressure operation** plus usable fields/critical currents in scalable form factors. The strongest “near-ambient” claim in the period (Lu-N-H) was **retracted**, and independent experimental replication papers reported **no superconductivity** across wide conditions. [35]
- The best-validated high- $T_c$  hydrides still require **megabar-class pressures** (hundreds of GPa) achievable in diamond-anvil-cell experiments, which is fundamentally incompatible with wires/tapes/coatings operating in ordinary infrastructure—so the technology is not yet at a “prototype conductor” stage that could plausibly scale. [36]
- Computational work is progressing toward ambient-pressure candidates (ML/high-throughput predictions), but these remain **predictions without experimental synthesis/validation** at ambient pressure, which is insufficient for level 3. [37]

##### What is still missing to justify level 3 (and beyond)

- A **reproducible, independently replicated** demonstration of superconductivity at  $\sim 300$  K at  **$\sim 1$  bar** (or, as an interim, at dramatically reduced pressures that are realistically packageable), with robust Meissner screening and transport zero resistance, plus quantified  $J_c$ ,  $H_{c2}$ , and stability under strain. [38]
- Evidence of **materials/process scalability** (repeatable synthesis beyond small DAC samples; yield/variability statistics; degradation modes; joining methods), and **device-relevant prototypes** (even short, non-cryogenic conductor segments). The present evidence base does not show this for room-temperature materials. [34]

#### C) Sub-score breakdown (because the ART is effectively a bundle) and aggregation

- **High- $T_c$  superconductivity in hydrides under extreme pressure**  $\rightarrow \sim 2$ – $3$  (solid experimental demonstrations exist; however, not deployable)  $\rightarrow$  key sources: calcium superhydrides at  $> 200$  K (megabar pressures); ternary hydrides pushing pressure down but still tens to hundreds of GPa. [36]

- **Near-ambient / ambient-pressure “room-temperature” claims** → ~1 (claims retracted or not reproduced; no stable validated effect) → key sources: retractions and negative replications in Lu-N-H; negative results in LK-99. [39]
- **Ambient-pressure candidate design (computational/ML screening)** → ~1–2 (credible predictions and proposed synthesis routes, but limited experimental confirmation) → key sources:  $\text{Mg}_2\text{XH}_6$  predictions; arXiv high-throughput route paper; ambient-pressure limit analysis. [37]
- **Conductor engineering know-how (for existing cryogenic HTS, not RT materials)** → ~5–6 as a *supporting ecosystem* (procurement specs, cable tests), but **not** the bottleneck material capability → key sources: CERN REBCO tech specification; CORC/CICC deformation testing paper. [40]

**Aggregation to one ART score:** The ART’s core promise is **room-temperature superconductivity in practical form factors without cryogenics**, which is dominated by the *material feasibility at ambient conditions*. Given that verified high- $T_c$  superconductivity exists only under extreme pressures (supporting plausibility), while near-ambient “RT” claims have failed validation and ambient-pressure candidates remain largely predictive, the overall maturity most defensibly aligns with **rubric level 2**. [41]

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## ART 07.046 Self-Healing & Smart Polymers

### ART extraction

#### Primary capability the ART claims

- Autonomous repair of polymer parts (and polymer-matrix composites) such that microcracks, punctures, or abrasion damage can be sealed and meaningful mechanical/barrier function restored without disassembly (intrinsic dynamic bonds; extrinsic microcapsules or microvascular delivery).
- Adaptive (“smart”) behaviour in the same material platform, where the polymer network can shift properties such as stiffness/damping/permeability/adhesion/electrical conductivity in response to stimuli (temperature, strain, moisture, light, chemicals), potentially with low-power sensing and calibration.

#### Key sub-components or variants

- Intrinsic self-healing networks: dynamic covalent chemistries (e.g., Diels–Alder, exchangeable bonds/vitrimers) and reversible supramolecular interactions (e.g., hydrogen bonding, metal–ligand coordination, disulfide exchange) enabling repeatable healing.

- Extrinsic self-healing systems: encapsulated healing agents (microcapsules/nanocontainers) and/or microvascular channel networks that release or deliver repair chemistry when damaged.
- Vitrimer-based reprocessable thermosets and composites (including fibre-reinforced) that combine reparability with end-of-life reprocessing/recycling routes.
- Multifunctional self-healing conductors/ionogels/polymer electrolytes for soft electronics and energy devices (restore conductivity/electrochemical interfaces after mechanical damage).
- Smart coatings and films that combine self-healing with adaptive surface/optical/thermal properties (e.g., thermochromism, hydrophobicity) and/or corrosion-inhibitor release.

#### **Maturity indicators that would constitute evidence for this ART**

- Repeatable, quantified healing efficiencies (mechanical strength/toughness recovery; barrier/corrosion protection recovery; conductivity restoration) and multi-cycle performance under realistic damage modes.
- Device-level or component-level demonstrations (e.g., sensors, energy devices, structural composite joints) rather than only “materials coupons.”
- Standardised or pre-standard test methods for “healing efficiency” and durability/ageing (indicating readiness for qualification and procurement).
- Evidence of manufacturability (thermoforming/reprocessing, scalable synthesis, integration with fibres/fillers/conductive networks).
- Commercial shipments in at least some subdomains (e.g., coatings/films) with datasheets and warranty-backed performance claims, signalling real customer deployment.

#### **Evidence (10–20 recent, reliable sources)**

All sources below were published within the strict window **February 2022 to February 2026** (inclusive), and were prioritised toward peer-reviewed experimental papers, authoritative standards/consortia outputs, and vendor technical documentation with measurable properties.

#### **Evidence coverage map**

Collectively, the dossier spans (i) standardisation and test methodology for self-healing composites, (ii) intrinsic self-healing chemistries with quantified recovery, (iii) extrinsic capsule/vascular approaches for coatings and composites, (iv) multifunctional self-healing for electronics/energy devices, (v) commercialised self-healing polymer films/coatings, and (vi) sustainability/circularity constraints and lifecycle considerations. [\[1\]](#)

#### **Annotated sources**

**1) CWA 17896: Test method for determining adhesive properties in joints of continuous fibre-reinforced polymer composites using a Lap Strap specimen (applicable to repairable/self-healing composites)**

**Authors/organisation:** CEN[\[2\]](#) (workshop agreement; includes multiple industrial and research stakeholders)

**Venue/type:** Standards / pre-standard test methodology (CEN Workshop Agreement)

**Publication date:** June 2022

**Link:** [https://www.cenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896\\_2022.pdf](https://www.cenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896_2022.pdf)

**Why it matters:** Establishes a repeatable method to quantify “knockdown effect” and repair/healing efficiency in composite joints, explicitly covering capsule-based, vascular, intrinsic polymer, and vitrimer technologies—an indicator that the field is moving toward qualification-style evaluation rather than ad-hoc lab tests. [3]

## 2) 3M Paint Protection Film Series 100 Gloss Product Bulletin

**Authors/organisation:** 3M[4]

**Venue/type:** Vendor technical doc (product bulletin / datasheet-style)

**Publication date:** June 2022

**Link:** <https://multimedia.3m.com/mws/media/21497300/3m-paint-protection-film-series-100-gloss-product-bulletin-june-2022.pdf>

**Why it matters:** Demonstrates a commercial self-healing polyurethane film product with specified construction and thickness (e.g., ~7.5 mil / 0.19 mm construction) and a warranty, showing that at least “scratch-healing polymer films” are already beyond PoC and in real customer deployment. [5]

## 3) A self-healing polymerized-ionic-liquid-based polymer electrolyte enables long lifespan and dendrite-free solid-state Li metal batteries at room temperature

**Authors/organisation:** Xiuqing Lin[6] et al.

**Venue/type:** Peer-reviewed paper (journal: Materials Horizons[7])

**Publication date:** First published 19 Dec 2022 (journal issue 2023)

**Link:** <https://pubs.rsc.org/en/content/articlelanding/2023/mh/d2mh01289h>

**Why it matters:** Reports a self-healing polymer electrolyte that can reconstruct dendrite-induced defects at the Li/electrolyte interface; Li|LFP full cells show ~91.2% capacity retention after 206 cycles at room temperature—evidence that “self-healing + functional transport property (ion conduction)” can be integrated into working electrochemical devices. [8]

## 4) Vascular smooth muscle-inspired architecture enables soft yet tough self-healing materials for durable capacitive strain-sensor

**Authors/organisation:** FuYao Sun[9] et al.

**Venue/type:** Peer-reviewed paper (journal: Nature Communications[10])

**Publication date:** 10 Jan 2023

**Link:** <https://www.nature.com/articles/s41467-023-35810-y>

**Why it matters:** Demonstrates a route to overcome the common trade-off between softness/self-healing and fracture toughness, reporting fracture toughness up to ~111 kJ/m<sup>2</sup> and ultra-fast healing (~98% efficiency within ~1 minute under NIR-assisted conditions)—highly relevant to plausibility for durable, damage-tolerant “smart” polymer components. [11]

## 5) Fast self-healing at room temperature in Diels–Alder elastomers

**Authors/organisation:** Eva Roels[12] et al.

**Venue/type:** Peer-reviewed paper (open access journal article via PubMed Central[13])

**Publication date:** Collection date Sep 2023 (received Jul 2023; accepted Aug 2023)

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC10490179/>

**Why it matters:** Shows macroscopic damage healing at room temperature with complete restoration of mechanical properties within hours and partial recovery within minutes by

tuning stoichiometry—direct evidence that intrinsic reversible covalent networks can support autonomous/low-stimulus healing (a key feasibility claim for everyday polymer parts). [14]

#### 6) Scotchgard Paint Protection Film Pro Series 200 Gloss Product Bulletin

**Authors/organisation:** 3M

**Venue/type:** Vendor technical doc (product bulletin)

**Publication date:** September 2023

**Link:** <https://api-shop.spandex.com/medias/Data-Sheet-3M-Scotchgard-PPF-Pro-Series-200-Gloss-Sep-2023-US.pdf>

**Why it matters:** Reinforces market maturity for at least one self-healing polymer category (urethane films), including a 10-year warranty and performance-focused product positioning; this supports that self-healing is already commercial in surface-protection use cases. [15]

#### 7) Scotchgard Paint Protection Film Pro Series 200 Matte Product Bulletin

**Authors/organisation:** 3M

**Venue/type:** Vendor technical doc (product bulletin)

**Publication date:** November 2023

**Link:** <https://multimedia.3m.com/mws/media/23583950/scotchgard-paint-protection-film-pro-series-200-matte.pdf>

**Why it matters:** Provides another up-to-date commercial spec for self-healing polyurethane films (including film + adhesive thickness and stated “self-healing technology”), supporting that self-healing polymer functionality can survive real-world deployment constraints like installation, weathering, and long warranties. [16]

#### 8) A stable and self-healing thermochromic polymer coating for all-weather thermal regulation

**Authors/organisation:** Yuncong Liu[17] et al.

**Venue/type:** Peer-reviewed paper (journal article; thermochromic “smart coating” integrating adaptive response + self-healing)

**Publication date:** September 2023

**Link:**

[https://www.researchgate.net/publication/373687550\\_A\\_Stable\\_and\\_Self-Healing\\_Thermochromic\\_Polymer\\_Coating\\_for\\_All\\_Weather\\_Thermal\\_Regulation](https://www.researchgate.net/publication/373687550_A_Stable_and_Self-Healing_Thermochromic_Polymer_Coating_for_All_Weather_Thermal_Regulation)

**Why it matters:** Reports a smart coating concept where reversible phase behaviour (thermochromism) is tied to reversible interactions (ion–dipole) that also enable self-healing and environmental stability across harsh conditions—evidence for “adaptive behaviour” coexisting with self-repair in one platform (even if activation may be stimulus-dependent). [18]

#### 9) Dual rapid self-healing and easily recyclable carbon fiber reinforced vitrimer composites

**Authors/organisation:** Mingzhuan Li[19] et al.

**Venue/type:** Peer-reviewed paper (journal: Chemical Engineering Journal[20])

**Publication date:** 15 January 2024

**Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S1385894723068791>

**Why it matters:** Reports >95% scratch recovery in ~5 minutes for the vitrimer resin and ~77.4% interfacial healing retained after five cycles in carbon fibre/vitrimer composites, plus chemical recycling that recovers both resin and carbon fibre—strong evidence that self-

healing can be engineered into high-performance composites with multi-cycle capability and circularity pathways. [21]

#### 10) Sustainability of self-healing polymers: A holistic perspective towards circularity in polymer networks

**Authors/organisation:** Kenneth Cerdan[22] et al.

**Venue/type:** Peer-reviewed review/roadmap-style synthesis (journal: Progress in Polymer Science[23])

**Publication date:** Available online 26 March 2024 (issue dated May 2024)

**Link:**

[https://cris.vub.be/ws/portalfiles/portal/121165360/1\\_s2.0\\_S0079670024000339\\_main.pdf](https://cris.vub.be/ws/portalfiles/portal/121165360/1_s2.0_S0079670024000339_main.pdf)

**Why it matters:** Provides lifecycle-anchored analysis of intrinsic vs extrinsic self-healing chemistries, explicitly linking healing efficiency, number of healing cycles, processing, and end-of-life options (reprocessing/recycling/biodegradation) to overall sustainability—directly relevant to feasibility constraints and “scaling realism” for everyday parts. [24]

#### 11) Stretchable and biodegradable self-healing conductors for multifunctional electronics

**Authors/organisation:** Tae Min Jang[25] et al.

**Venue/type:** Peer-reviewed paper (journal: Science Advances[26]; open access via PubMed Central)

**Publication date:** September 2024

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11373598/>

**Why it matters:** Reports rapid/complete recovery of electrical conductivity (~1000 S/cm) and stretchability (~500%) after repeated damage using dynamic bonding; demonstrates system-level self-healing electronics (including sensing) in a biomedical context—evidence for “smart polymer” integration with functional electronics and practical form factors. [27]

#### 12) Preparation and properties of double-layer phenolic/polyurethane coated isophorone diisocyanate self-healing microcapsules

**Authors/organisation:** Liye Yuan[28] et al.

**Venue/type:** Peer-reviewed paper (journal: Scientific Reports[29])

**Publication date:** 09 September 2024

**Link:** <https://www.nature.com/articles/s41598-024-68917-3>

**Why it matters:** Demonstrates improved capsule robustness (thermal/ageing/environmental stability) and coating-level performance: with 10 wt.% capsules in an epoxy coating, scratch corrosion testing shows successful repair and no corrosion after 7 days in 10 wt.% NaCl; reported self-healing efficiency in tensile terms is ~57.9%—useful, quantitative evidence for extrinsic healing in protective coatings. [30]

#### 13) Self-healable, recyclable, and mechanically robust vitrimer composite for high-performance triboelectric nanogenerators and self-powered wireless electronics

**Authors/organisation:** Araz Rajabi-Abhari[31] et al.

**Venue/type:** Peer-reviewed paper (journal: Nano Energy[32])

**Publication date:** 01 December 2024

**Link:** <https://www.sciencedirect.com/science/article/pii/S2211285524010589>

**Why it matters:** Shows a vitrimer composite enabling both self-healing/recyclability and strong functional output in a device: power density ~2571 mW/m<sup>2</sup> (15 N, 6 Hz) and output

voltage ~1325 V, with demonstration use cases (e.g., watchband, wireless transmission)—evidence that self-healing polymers can be embedded into functional “smart” energy-harvesting hardware rather than isolated material samples. [33]

**14) Enhanced method in the design of microvascular self-healing system in a composite structure based on a Newtonian healing agent**

**Authors/organisation:** Ameer S. Zirjawi[34] et al.

**Venue/type:** Peer-reviewed paper (Journal of Materials Research and Technology; open access via ScienceDirect)

**Publication date:** March–April 2025

**Link:** <https://www.sciencedirect.com/science/article/pii/S2238785425000924>

**Why it matters:** Provides engineering-level design guidance for microvascular self-healing architectures (e.g., identifying ~0.5 mm channel diameter as meeting design criteria) and ties it to impact-loading scenarios (e.g., ~31.55 J impact leading to ~10.79 kN maximum contact force), supporting plausibility for vascular delivery approaches in structural composites. [35]

**15) Preparation and properties study of self-healing anticorrosive coating based on MCM-41 nanocontainer and triazinyl corrosion inhibitor**

**Authors/organisation:** Guangqun Cao[36] et al.

**Venue/type:** Peer-reviewed paper (Scientific Reports)

**Publication date:** 01 July 2025

**Link:** <https://www.nature.com/articles/s41598-025-06528-2>

**Why it matters:** Demonstrates a “smart + self-healing” anticorrosive coating concept (pH-responsive inhibitor release) with quantitative electrochemical performance: after 30 days immersion, impedance magnitude  $|Z|$  at 0.01 Hz is reported as ~3 orders of magnitude higher than pure epoxy—evidence for adaptive, environment-responsive protection rather than purely passive barrier coatings. [37]

**16) Eco-friendly thermally activated vitrimer resin composites with self-healing mechanical and electrically conducting functional capabilities**

**Authors/organisation:** L. Amorim[38] et al.

**Venue/type:** Peer-reviewed paper (journal: Next Materials; open access via ScienceDirect)

**Publication date:** January 2026

**Link:** <https://www.sciencedirect.com/science/article/pii/S2949822825009992>

**Why it matters:** Reports a bio-based epoxy/vitrimer system (58% renewable carbon) and MWCNT composites with >80% repair efficiency upon heating, adhesive stress ~4 MPa, and “functional conductivity recovery,” including Joule-heating-enabled repair—direct evidence toward the ART claim that polymers can self-heal and also adapt/restore functional properties (electrical) with low-power triggering. [39]

**Maturity score (1–7) and reasoning**

**Final maturity score:** 5

**Rationale (mapping evidence to rubric):**

This ART is best treated as a **bundle** with uneven maturity: certain self-healing polymer products (notably surface-protection films/coatings) are already commercially delivered, while more structurally ambitious “self-healing + smart multifunctional” polymer platforms for load-bearing composites and embedded electronics remain largely in prototype/PoC stages. [40]



- **What rules out levels 1–3:**
- Multiple peer-reviewed papers demonstrate **quantified, device-relevant performance** (e.g., rapid strength recovery and multi-cycle healing in fibre/vitrimer composites; functional electronics that regain high conductivity and stretchability after cutting; device-level energy-harvesting outputs with self-healing materials). [\[41\]](#)
- There is evidence of **real commercial delivery** in at least one self-healing polymer segment (urethane paint-protection films with stated self-healing function and long warranties). [\[42\]](#)
- **Why the score is not higher (what is missing for level 6):**
- For the **broader** “everyday parts that fail by microcracks/wear” vision (especially structurally loaded components and multifunctional composites), the dossier is still dominated by **laboratory and early engineering demonstrations**, not large-scale field qualification (multi-year service) and not clear evidence of ramping manufacturing volumes for structural self-healing polymers. [\[43\]](#)
- Although standardisation is emerging (a sign of maturation), widespread adoption of standard test methods, procurement specifications, and long-term reliability datasets for diverse environments (hot/wet/UV/chemical exposure, cyclic fatigue, repeated healing over many cycles) remains a major gating item for “scale to mainstream structural parts.” [\[44\]](#)

In short: the **operating principles and prototypes** are clearly demonstrated and in some niches **already commercial**, but the **full two-capability platform** (autonomous repair + adaptive multifunctionality across broad part categories) is not yet broadly deployed at industrial scale—consistent with a **level 5** “post-PoC / early commercial + multiple actors preparing production-scale pathways” position. [\[45\]](#)

#### Subcomponent maturity breakdown and aggregation

- **Commercial self-healing polymer films/coatings (scratch-healing polyurethane films): maturity ~6**  
Evidence: vendor product bulletins describing self-healing function, material construction, and long warranties indicate customer delivery (commercial products), even if the use case is primarily surface damage rather than structural crack healing. [\[42\]](#)
- **Self-healing structural polymer networks and composites (intrinsic vitrimer networks; high-toughness self-healing architectures; microvascular design): maturity ~4**  
Evidence: strong lab and engineering demonstrations (e.g., rapid >95% recovery in minutes for vitrimer resin; multi-cycle interface healing; design methodologies for vascular delivery), but limited evidence here of certified field trials or scaled manufacturing of structural parts. [\[46\]](#)
- **Self-healing + functional “smart” electronics/energy devices (conductors, polymer electrolytes, TENGs): maturity ~4**  
Evidence: device-level prototypes with quantified recovery (conductivity recovery and stretchability; battery cycling retention; energy-harvesting outputs) demonstrate plausibility, but these remain mainly research/early prototype demonstrations rather than widely shipped product classes. [\[47\]](#)
- **Responsive / adaptive coatings (thermochromic self-healing; pH-responsive anticorrosion): maturity ~4**  
Evidence: papers show combined self-healing with adaptive behaviours (thermal response;

pH-triggered inhibitor release) and quantitative corrosion-resistance metrics, but scaling and qualification across application sectors remains largely unproven in the dossier. [48]

- **Testing and sustainability/scale-enabling infrastructure (standard methods; lifecycle/circularity analysis): maturity ~5**

Evidence: a recent CEN Workshop Agreement explicitly addressing how to test repairable/self-healing composites signals movement toward comparability and qualification; the sustainability/circularity review frames design constraints for scalable adoption. [49]

### Aggregation to one score:

Given the ART's breadth and the clear split between (i) some commercially deployed self-healing polymer surface products (~6) and (ii) broader structural/multifunctional platforms mostly in PoC/prototype stages (~4), an average-based assessment centres on ~5 as the most defensible single maturity score. [50]

[1] [3] [4] [9] [12] [13] [19] [44] [45] [49] [https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896\\_2022.pdf](https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896_2022.pdf)

[https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896\\_2022.pdf](https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17896_2022.pdf)

[2] [5] [32] [34] [38] [40] [42] [50] <https://multimedia.3m.com/mws/media/2149730O/3m-paint-protection-film-series-100-gloss-product-bulletin-june-2022.pdf>

<https://multimedia.3m.com/mws/media/2149730O/3m-paint-protection-film-series-100-gloss-product-bulletin-june-2022.pdf>

[6] [15] <https://api-shop.spandex.com/medias/Data-Sheet-3M-Scotchgard-PPF-Pro-Series-200-Gloss-Sep-2023-US.pdf?context=bWFzdGVyfHMzZG9jdW1lbnRzfDYyMTc5MnxhcHBsaWNhdGlvbI9wZGZ8YURjNUwyZzRPUzh4TWpNMk16WXlOemM1TURNMk5pOUVZWFFJoWDFOb1pXVjBYek5OWDFOamlzUmphR2RoY21SZlVGQkdYMUJ5YjE5VFpYSnBaWE5mTWpBd1gwZHNiM056WDFObGNGOHlNREl6WDFWVExuQmtaZ3w2NWUxMGM2YTdiZDIzYmE2OWJiZGI1ZjAxOWMyMTc5ODRkMTNiZTUyZmMxOGNlY2YyMjlmYTc0ZjEwNW11MDQw>

<https://api-shop.spandex.com/medias/Data-Sheet-3M-Scotchgard-PPF-Pro-Series-200-Gloss-Sep-2023-US.pdf?context=bWFzdGVyfHMzZG9jdW1lbnRzfDYyMTc5MnxhcHBsaWNhdGlvbI9wZGZ8YURjNUwyZzRPUzh4TWpNMk16WXlOemM1TURNMk5pOUVZWFFJoWDFOb1pXVjBYek5OWDFOamlzUmphR2RoY21SZlVGQkdYMUJ5YjE5VFpYSnBaWE5mTWpBd1gwZHNiM056WDFObGNGOHlNREl6WDFWVExuQmtaZ3w2NWUxMGM2YTdiZDIzYmE2OWJiZGI1ZjAxOWMyMTc5ODRkMTNiZTUyZmMxOGNlY2YyMjlmYTc0ZjEwNW11MDQw>

[7] [8] <https://pubs.rsc.org/en/content/articlelanding/2023/mh/d2mh01289h>

<https://pubs.rsc.org/en/content/articlelanding/2023/mh/d2mh01289h>

[10] [33] <https://www.sciencedirect.com/science/article/pii/S2211285524010589>

<https://www.sciencedirect.com/science/article/pii/S2211285524010589>

[11] [25] [29] <https://www.nature.com/articles/s41467-023-35810-y>

<https://www.nature.com/articles/s41467-023-35810-y>

[14] <https://pmc.ncbi.nlm.nih.gov/articles/PMC10490179/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC10490179/>

[16] <https://multimedia.3m.com/mws/media/2358395O/scotchgard-paint-protection-film-pro-series-200-matte.pdf>

<https://multimedia.3m.com/mws/media/2358395O/scotchgard-paint-protection-film-pro-series-200-matte.pdf>

[17] [18] [26] [48] [https://www.researchgate.net/publication/373687550\\_A\\_Stable\\_and\\_Self-Healing\\_Thermochromic\\_Polymer\\_Coating\\_for\\_All\\_Weather\\_Thermal\\_Regulation](https://www.researchgate.net/publication/373687550_A_Stable_and_Self-Healing_Thermochromic_Polymer_Coating_for_All_Weather_Thermal_Regulation)

[https://www.researchgate.net/publication/373687550\\_A\\_Stable\\_and\\_Self-Healing\\_Thermochromic\\_Polymer\\_Coating\\_for\\_All\\_Weather\\_Thermal\\_Regulation](https://www.researchgate.net/publication/373687550_A_Stable_and_Self-Healing_Thermochromic_Polymer_Coating_for_All_Weather_Thermal_Regulation)

[20] [23] [27] [47] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11373598/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11373598/>

[21] [31] [36] [41] [43] [46]

<https://www.sciencedirect.com/science/article/abs/pii/S1385894723068791>

<https://www.sciencedirect.com/science/article/abs/pii/S1385894723068791>

[22] [37] <https://www.nature.com/articles/s41598-025-06528-2>

<https://www.nature.com/articles/s41598-025-06528-2>

[24]

[https://cris.vub.be/ws/portalfiles/portal/121165360/1\\_s2.0\\_S0079670024000339\\_main.pdf](https://cris.vub.be/ws/portalfiles/portal/121165360/1_s2.0_S0079670024000339_main.pdf)

[https://cris.vub.be/ws/portalfiles/portal/121165360/1\\_s2.0\\_S0079670024000339\\_main.pdf](https://cris.vub.be/ws/portalfiles/portal/121165360/1_s2.0_S0079670024000339_main.pdf)

[28] [39] <https://www.sciencedirect.com/science/article/pii/S2949822825009992>

<https://www.sciencedirect.com/science/article/pii/S2949822825009992>

[30] <https://www.nature.com/articles/s41598-024-68917-3>

<https://www.nature.com/articles/s41598-024-68917-3>

[35] <https://www.sciencedirect.com/science/article/pii/S2238785425000924>

<https://www.sciencedirect.com/science/article/pii/S2238785425000924>

## ART 07.047 Nano-Catalysts & Advanced Coatings

### ART extraction

**A) Primary capability claimed (core “what it does”)** - Engineer surface/interface behaviour at the **nanometre scale** to increase catalytic activity per gram, improve selectivity (fewer by-products), and add designed surface functions (e.g., corrosion resistance, low friction,

controlled wetting) without redesigning whole systems.

- Deploy as **retrofittable form factors**: catalyst cartridges/structured catalyst inserts, thin films, or spray/dip/ALD/PVD layers compatible with existing pipes, vessels, filters, radomes, components.
- Incorporate “smart” elements: **durability against deactivation/wear**, and (in more advanced versions) **self-indicating/self-reporting** coatings plus data-driven recipes/quality metrics updated over time.

**B) Key sub-components / variants (technology bundle threads) - Nano-catalysts with maximised active-site efficiency** (e.g., single-atom / single-site catalysts; defect/interface-engineered supports; high-entropy oxides; nanostructured electrocatalysts). [1]

- **Structured catalysts & washcoats** (monolith/honeycomb supports; slurry rheology → coating quality control; anti-shedding and anti-clogging coatings; scale-up fabrication). [2]
- **Advanced protective coatings** (corrosion-resistant multilayers; hybrid PVD/ALD sealing; conformal barrier films; thermal-spray wear coatings). [3]
- **Large-area functional wetting/anti-fouling coatings** (durable sprayable superhydrophobic and related surfaces). [4]
- **Smart / self-reporting & self-healing coatings** (microcapsules, fluorophores, mechanochromic indicators; visual/fluorescent wear or corrosion cues; “early warning”). [5]
- **Digital optimisation and repeatability** (use of ML/automation for recipe screening; modelling degradation vs signal; scale-up workflows). [6]

**C) Maturity indicators that would count as “good evidence” for this ART - Relevant-environment durability**: multi-hundred to multi-thousand-hour stability under heat, contaminants, salinity, pressure, abrasion or cyclic conditions (not just short lab runs). [7]

- **Scale-up proof**: kilogram-scale catalyst synthesis with preserved structure/performance; large-area or high-volume coating runs; repeatable QC metrics. [8]
- **System integration**: catalysts validated in device-relevant configurations (e.g., membrane electrode assemblies / electrolyzers) and coatings validated in real use cases. [9]
- **Deployability evidence**: field trials in operational industrial settings; documented maintenance/inspection advantages (e.g., self-reporting signals), and credible pathways to manufacturing/qualification. [10]

**Evidence (10–20 recent, reliable sources)**

#### 1) **Cost-efficient and stable electrolysis of reverse osmosis water using a Co–RuO<sub>2</sub>-enabled PEM electrolyser**

- Authors/organisation: Hao Liu[11] et al.
- Venue/type: peer-reviewed paper (Nature Catalysis[12])
- Publication date: **Jan 2026** (Published 07 Jan 2026)
- Link (URL): <https://www.nature.com/articles/s41929-025-01456-w>
- Why it matters: Demonstrates a **device-level prototype** where a standard PEM water electrolyser runs **2,000 h at 1.0 A cm<sup>-2</sup>** on RO-grade impure water with a reported **10.2 μV h<sup>-1</sup> degradation rate**, directly supporting plausibility of impurity-tolerant, nano-engineered catalyst interfaces and their durability constraints. [13]

#### 2) **Universal scalable production of single-atom catalysts for antibiotic wastewater treatment**

- Authors/organisation: Xunheng Jiang[14] et al.

- Venue/type: peer-reviewed paper (Nature Water[15])
- Publication date: **Jan 2026** (Published 09 Jan 2026)
- Link (URL): <https://www.nature.com/articles/s44221-025-00561-1>
- Why it matters: Reports **kilogram-scale** production of single-/dual-atom catalysts with **up to 14 wt% metal loading** and validates stability/efficacy in a **near-industrial continuous-flow reactor** with limited Fe leaching—direct evidence for scalability and real-reactor maturity. [16]

### 3) Intrinsic metal-support interactions break the activity–stability dilemma in electrocatalysis

- Authors/organisation: Lingxi Zhou[17] et al.
- Venue/type: peer-reviewed paper (Nature Communications[18])
- Publication date: **Oct 2025** (Published 01 Oct 2025)
- Link (URL): <https://www.nature.com/articles/s41467-025-63397-z>
- Why it matters: Presents an integrated Ru/TiMnO<sub>x</sub> electrode with reported **multi-fold mass activity gains** and **up to 3,000 h** stable operation, illustrating that nanoscale interface design can materially shift the activity–durability trade-off (a core constraint in the ART description). [19]

### 4) A corrosion-resistant RuMoNi catalyst for efficient and long-lasting seawater oxidation and anion exchange membrane electrolyzer

- Authors/organisation: Xin Kang[20] et al.
- Venue/type: peer-reviewed paper (Nature Communications)
- Publication date: **Jun 2023** (Published 17 Jun 2023)
- Link (URL): <https://www.nature.com/articles/s41467-023-39386-5>
- Why it matters: Shows a nanostructured electrocatalyst sustaining **>3,000 h at 500 mA cm<sup>-2</sup>** in alkaline seawater conditions and demonstrates an AEM electrolyser reaching **1,000 mA cm<sup>-2</sup> at 1.72 V**, supporting plausibility of corrosion-resistant nano-catalysts and device-level integration. [21]

### 5) A single site ruthenium catalyst for robust soot oxidation without platinum or palladium

- Authors/organisation: Yuanfeng Li[22] et al.
- Venue/type: peer-reviewed paper (Nature Communications)
- Publication date: **Nov 2023** (Published 06 Nov 2023)
- Link (URL): <https://www.nature.com/articles/s41467-023-42935-7>
- Why it matters: Single-atom Ru on ceria is reported to deliver **~9× higher TOF** than Ru nanoparticles and to rival commercial Pt-based soot oxidation performance while addressing volatility/stability—evidence for “more activity per gram” and stability engineering at the surface lattice level. [23]

### 6) Single Ru(II) ions on ceria as a highly active catalyst for abatement of NO

- Authors/organisation: Konstantin Khivantsev[24] et al.
- Venue/type: peer-reviewed paper (Journal of the American Chemical Society[25])
- Publication date: **Feb 2023** (Published 22 Feb 2023)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/36812067/>
- Why it matters: Reports that **only 0.1–0.5 wt% Ru** (atomically dispersed) can achieve high NO reduction activity by CO at low temperatures, supporting feasibility of ultra-low-loading nano-catalysts that reduce precious-metal dependence. [26]

### 7) **Highly Efficient Fabrication of Kilogram-Scale Palladium Single-Atom Catalysts for the Suzuki–Miyaura Cross-Coupling Reaction**

- Authors/organisation: Hao Zhang[27] et al.
- Venue/type: peer-reviewed paper (2entity[2] ["organization", "ACS Applied Materials & Interfaces", "materials journal"] [2])
- Publication date: **Nov 2022** (Epub 21 Nov 2022; in issue Dec 2022)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/36410052/>
- Why it matters: Describes a **direct ball-milling** method with reported **~100% productivity** and **kilogram-scale** Pd single-atom catalyst synthesis, plus concrete activity metrics (TOF reported in the abstract), directly addressing the ART's "consistent nanostructures at scale" constraint. [28]

### 8) **Water-retaining slurry washcoat for high-loading and robust CuMnO<sub>x</sub> structured catalyst toward durable monoxide oxide purification from real flue gas**

- Authors/organisation: Xuan Zhang[29] et al.
- Venue/type: peer-reviewed paper (Separation and Purification Technology[30])
- Publication date: **Mar 2025** (1 March 2025 issue)
- Link (URL): <https://www.sciencedirect.com/science/article/abs/pii/S1383586624033240>
- Why it matters: Explicit **industrialisation evidence**: reports structured catalyst washcoats with **high loading (>160 kg/m<sup>3</sup>)**, **powder shedding <1 wt%**, and a **2 m<sup>3</sup> scale-up** validated in a **steel plant** achieving **>90% CO removal for >1,440 h**—strong maturity signal for retrofittable catalyst-coated structures. [31]

### 9) **Durable superhydrophobic coatings for prevention of rain attenuation of 5G/weather radomes**

- Authors/organisation: Jinfei Wei[32] et al.
- Venue/type: peer-reviewed paper (Nature Communications)
- Publication date: **May 2023** (Published 19 May 2023)
- Link (URL): <https://www.nature.com/articles/s41467-023-38678-0>
- Why it matters: Demonstrates a spray-applied coating design that targets **mechanical robustness + weather resistance** simultaneously and reports **large-scale preparation and practical application** on 5G/weather radomes, directly matching the ART's "sprayable retrofit functional coating" form factor. [33]

### 10) **Dense Al<sub>2</sub>O<sub>3</sub> sealing inhibited high hydrostatic pressure corrosion of Cr/GLC coating**

- Authors/organisation: Shuyu Li[34] et al.
- Venue/type: peer-reviewed paper (npj Materials Degradation[35])
- Publication date: **May 2024** (Published 04 May 2024)
- Link (URL): <https://www.nature.com/articles/s41529-024-00469-3>
- Why it matters: Shows ALD as a scalable "engineered interface" approach: adding an **ALD Al<sub>2</sub>O<sub>3</sub> sealing layer** to a multilayer coating reduces corrosion current density by **>2 orders of magnitude** across **0.1–15 MPa** pressure range—direct durability evidence under harsh conditions (deep-sea relevant). [36]

### 11) **Al<sub>2</sub>O<sub>3</sub>–ZnO atomic layer deposited nanolaminates for improving mechanical and corrosion properties of sputtered CrN coatings**

- Authors/organisation: Elias Kaady[37] et al.
- Venue/type: peer-reviewed paper (Thin Solid Films[38])
- Publication date: **Oct 2022** (1 October 2022 issue)



- Link (URL): <https://www.sciencedirect.com/science/article/abs/pii/S0040609022003881>
- Why it matters: Demonstrates hybrid **PVD/ALD architectures** where ALD nanolaminates act as sealing/interlayers to improve corrosion and mechanical performance (measured via electrochemistry and nanoindentation), supporting plausibility of scalable thin-film “retrofit” protective stacks. [39]

#### 12) Tribological Performance of Thin HVOF-Sprayed WC–CoCr Coatings Fabricated Employing Fine Powder Feedstock

- Authors/organisation: Kaveh Torkashvand[40] et al.
- Venue/type: peer-reviewed paper (Journal of Thermal Spray Technology[41])
- Publication date: **Dec 2022** (Published 08 Dec 2022; issue date 2023)
- Link (URL): <https://link.springer.com/article/10.1007/s11666-022-01506-w>
- Why it matters: Provides quantified wear results for an industrially relevant, scalable coating method (HVOF), with reported **specific wear rates on the order of  $10^{-8} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$** —direct evidence for the ART’s durability/value proposition around friction and wear losses. [42]

#### 13) A novel self-healing coating with mechanically-triggered self-reporting properties: Color and fluorescence dual damage indications

- Authors/organisation: Yue Wang[43] et al.
- Venue/type: peer-reviewed paper (Progress in Organic Coatings[44])
- Publication date: **Feb 2024**
- Link (URL): <https://www.sciencedirect.com/science/article/abs/pii/S0300944023007439>
- Why it matters: Demonstrates “embedded markers that indicate wear/loss of function”: microcapsules release a dye (DCF) upon damage to yield **visible colour change and fluorescence**, and links this to self-healing via shape-memory epoxy—credible lab evidence for self-reporting coatings. [45]

#### 14) Real-time and visual monitoring coating damage and metal corrosion ... quantified via a Python program integrated into smartphones

- Authors/organisation: Tianfei Qi[46] et al.
- Venue/type: peer-reviewed paper (Sensors and Actuators B: Chemical[47])
- Publication date: **Sep 2024** (15 September 2024)
- Link (URL): <https://www.sciencedirect.com/science/article/abs/pii/S0925400524007330>
- Why it matters: Implements a **self-reporting** corrosion/damage monitoring concept with quantitative readout (Python/smartphone workflow) and indicator chemistry, directly supporting the ART’s “monitoring via embedded markers” and the bridge to digital lifecycle tracking. [48]

#### 15) COAT4LIFE periodic reporting: Eco-friendly corrosion protective coatings based on smart nanotechnology platforms for a circular economy

- Authors/organisation: European Commission[49] / CORDIS[50] project reporting page
- Venue/type: authoritative government programme report (H2020 project periodic reporting)
- Publication date: **Nov 2025** (Last update 11 Nov 2025; reporting period 2023–2025)
- Link (URL): <https://cordis.europa.eu/project/id/101007430/reporting>
- Why it matters: Explicitly frames a combined pathway of **corrosion sensing + anticorrosion nanoadditives**, including stated integration of sensing **TRL 3–4** with protective systems **TRL >5** and subsequent **scale-up and demonstration**, aligning with the ART bundle’s mixed-maturity reality. [51]

#### 16) Atomic Layer Deposition solutions and wafer-scale ALD technology (MEMS Sensors & Actuators Webinar)

- Authors/organisation: Beneq[52] technical webinar slide deck
- Venue/type: vendor technical presentation (equipment/process characteristics and scale approaches)
- Publication date: **Jun 2023** (8 Jun 2023)
- Link (URL): <https://www.semi.org/sites/semi.org/files/2023-06/Beneq%20-%20SEMI%20MEMS%20%26%20SENSOR%20Webinar%20Final.pdf>
- Why it matters: Documents ALD as an industrially supported deposition route emphasising **pinhole-free conformal films**, process windows, and throughput scaling via **batch processing** (and references to roll-to-roll/spatial concepts), relevant to the ART's "scalable application methods" and maturity of enabling equipment ecosystems. [53]

#### 17) Coatings Made by Atomic Layer Deposition for the Protection of Materials from Atomic Oxygen in Space

- Authors/organisation: Leo Nyman[54] et al.
- Venue/type: peer-reviewed conference paper (IOP Conf. Series: Materials Science and Engineering; open-access via Aalto University[55] repository)
- Publication date: **2023**
- Link (URL): <https://aaltodoc.aalto.fi/items/9fa4670c-d562-4271-a4f2-f3fb1e83dcb9>
- Why it matters: Reports **20 nm** ALD metal-oxide films deposited at **125 °C** on polymers/PCBs and then exposed to atomic oxygen at an European Space Agency[56] ESTEC facility; the coated samples show improved survivability versus uncoated substrates—direct evidence of thin-film coatings as engineered interfaces for extreme environments. [57]

#### Maturity score (1–7) and reasoning

##### Final maturity score

##### Final maturity score for the ART (bundle): 5

This ART is best interpreted as a **technology family** where some threads (structured catalyst washcoats; industrial thin-film deposition methods) are already near- or in industrial practice, while other threads (field-tunable catalysts; self-reporting/self-healing coatings with validated long-term reliability) remain at lab-to-PoC stages. [58]

#### Evidence-to-rubric mapping

##### Why the evidence rules out scores 1–3 (i.e., it is beyond “just theory” or early lab verification)

- Multiple sources show **device-relevant prototypes** and **long-duration operation**, not only short lab demonstrations. Examples include a PEM electrolyser operating **2,000 h at 1.0 A cm<sup>-2</sup>** on RO-grade impure water (catalyst/interface engineering in a practical configuration) and multiple **~3,000 h** durability demonstrations in electrocatalysis contexts. [59]
  - There is also direct **field-scale validation** of structured catalysts (2 m<sup>3</sup> scale) in an operational industrial setting (steel plant flue gas), aligned with the ART's “retrofit, cartridge/insert/washcoat” deployment model. [2]
- These collectively exceed “lab prototype exists” (score 3) by including **system integration + durability + scale/field trial** evidence.

### Why the evidence supports score 5 rather than 4

- Score 4 (PoC) is strongly supported in several subthreads, but the dossier also includes **clear post-PoC scale-up signals**: kilogram-scale catalyst synthesis with preserved performance, near-industrial continuous-flow reactor validation for water treatment, and an actual large-volume structured catalyst deployment/validation for real flue gas. [8]
- The EU COAT4LIFE programme explicitly describes moving from sensing elements around **TRL 3–4** into **scale-up and demonstration**, consistent with active development and multiple actors bridging R&D to deployment (a hallmark of score 5 in a bundled field). [51]

### What is still missing to justify score 6 (and therefore also 7)

- The rubric for 6 requires strong, recent evidence that **products are being delivered to customers in increasing amounts**, with expansion of production financed, and that application areas are broadening with economies of scale. Across this ART bundle, the dossier shows **compelling prototypes, long tests, and selective field deployments**, but it does not, as a whole, document **broad multi-customer shipment volumes** or sustained market-scale roll-out for the newest nano-engineered catalyst/coating formulations (especially smart/self-reporting variants). [60]
- Durability remains a recognised barrier in several subthreads (abrasion, harsh chemicals, inhibitor/sensor longevity). While individual studies show impressive durability (thousands of hours; high-pressure corrosion improvements), translating that into **standardised qualification + widespread procurement** is not demonstrated consistently across the whole family in the last-4-years evidence set. [61]

### Sub-component maturity breakdown and aggregation approach

(Estimates are mapped to the rubric and then averaged, because applications and value capture differ materially across subthreads.)

- **Structured catalysts / washcoats for industrial gas purification → 6**  
Evidence: scale-up to **2 m<sup>3</sup>** and steel-plant flue-gas validation with **>90% efficiency for >1,440 h** indicates delivery-like maturity for that slice. [2]
- **Nano-catalysts in electrolyzers / harsh electrochemical environments → 4–5**  
Evidence: thousands-of-hours stability and device-level demonstrations are strong PoC / advanced prototype signals, but customer shipment scaling is not evidenced here. [62]
- **Scalable synthesis of high-loading single-atom catalysts for water treatment → 5**  
Evidence: kilogram-scale synthesis plus validation in a near-industrial continuous-flow reactor suggests post-PoC scale-up, but not yet broad market delivery evidence. [63]
- **Advanced protective coatings via scalable deposition (ALD/PVD/thermal spray) → 6**  
(enabling toolchains are mature; specific formulations vary)  
Evidence: quantified corrosion/wear improvements and mature deposition routes, with vendor documentation indicating industrial scale equipment ecosystems; still formulation-dependent for end-use qualification. [64]
- **Smart/self-reporting coatings and digital/visual monitoring methods → 3–4**  
Evidence: convincing laboratory demonstrations of colour/fluorescence reporting and smartphone/Python quantification, but limited long-term field reliability/standards qualification evidence. [65]

**Aggregation:** Averaging these (with the bundle's "frontier" elements pulling down the mature deposition and structured-catalyst slices) produces an overall **ART maturity  $\approx 5$** , reflecting a field with **validated prototypes and selective real-world deployments**, but without comprehensive evidence of **broad, increasing customer deliveries across the full technology family** in the last four years. [66]

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[1] [6] [19] Intrinsic metal-support interactions break the activity-stability dilemma in electrocatalysis | Nature Communications

<https://www.nature.com/articles/s41467-025-63397-z>

[2] [10] [22] [25] [30] [31] [46] [47] [49] [58] [60] [66] Water-retaining slurry washcoat for high-loading and robust CuMnOx structured catalyst toward durable monoxide oxide purification from real flue gas - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S1383586624033240>

[3] [36] [37] [40] [55] [61] [64] Dense Al<sub>2</sub>O<sub>3</sub> sealing inhibited high hydrostatic pressure corrosion of Cr/GLC coating | npj Materials Degradation

<https://www.nature.com/articles/s41529-024-00469-3>

[4] [27] [33] [44] Durable superhydrophobic coatings for prevention of rain attenuation of 5G/weather radomes | Nature Communications

<https://www.nature.com/articles/s41467-023-38678-0>

[5] [32] [45] [52] [65] A novel self-healing coating with mechanically-triggered self-reporting properties: Color and fluorescence dual damage indications - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0300944023007439>

[7] [9] [13] [24] [29] [34] [59] [62] Cost-efficient and stable electrolysis of reverse osmosis water using a Co-RuO<sub>2</sub>-enabled PEM electrolyser | Nature Catalysis

<https://www.nature.com/articles/s41929-025-01456-w>

[8] [11] [15] [16] [17] [18] [43] [56] [63] Universal scalable production of single-atom catalysts for antibiotic wastewater treatment | Nature Water

<https://www.nature.com/articles/s44221-025-00561-1>

[12] [20] [28] Highly Efficient Fabrication of Kilogram-Scale Palladium ...

[https://pubmed.ncbi.nlm.nih.gov/36410052/?utm\\_source=chatgpt.com](https://pubmed.ncbi.nlm.nih.gov/36410052/?utm_source=chatgpt.com)

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[21] A corrosion-resistant RuMoNi catalyst for efficient and long-lasting seawater oxidation and anion exchange membrane electrolyzer | Nature Communications

<https://www.nature.com/articles/s41467-023-39386-5>

[23] [50] A single site ruthenium catalyst for robust soot oxidation without platinum or palladium | Nature Communications

<https://www.nature.com/articles/s41467-023-42935-7>

[26] [38] Single Ru(II) Ions on Ceria as a Highly Active Catalyst for ...

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[35] [51] Eco-friendly corrosion protective coatings based on smart nanotechnology platforms for a circular economy | H2020 | CORDIS | European Commission

<https://cordis.europa.eu/project/id/101007430/reporting>

[39] Al<sub>2</sub>O<sub>3</sub>-ZnO atomic layer deposited nanolaminates for improving mechanical and corrosion properties of sputtered CrN coatings - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0040609022003881>

[41] [48] Real-time and visual monitoring coating damage and metal corrosion based on the multiple chromatic transition of TMB triggered by highly active N-CDs/Fe<sub>3</sub>O<sub>4</sub> peroxidase mimics and Fe<sup>3+</sup> - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0925400524007330>

[42] Tribological Performance of Thin HVOF-Sprayed WC-CoCr Coatings Fabricated Employing Fine Powder Feedstock | Journal of Thermal Spray Technology | Springer Nature Link

<https://link.springer.com/article/10.1007/s11666-022-01506-w>

[54] [57] Coatings Made by Atomic Layer Deposition for the Protection of Materials from Atomic Oxygen in Space

<https://aaltodoc.aalto.fi/items/9fa4670c-d562-4271-a4f2-f3fb1e83dcb9>

## ART 07.048 High-Entropy Alloys & Advanced Metals

### ART extraction

#### Primary capability

- Engineer **advanced metallic materials** (high-entropy alloys and related compositionally complex alloys) that can **shift or escape conventional strength-ductility-temperature trade-offs**, especially for harsh environments (high temperature, oxidation/corrosion, irradiation). [1]
- Deliver **selectable “recipes”** (composition + processing + heat treatment) that remain compatible with **industrial routes** such as powder metallurgy, coatings, and metal additive manufacturing (AM), enabling near-net-shape parts and/or protective surfaces. [2]

- Couple alloy design to **data/computation + high-throughput experimentation** (materials acceleration platforms, ML/CALPHAD/DFT screening, automated testing/characterisation) to speed up discovery and down-selection. [3]

#### Key sub-components or variants

- **Refractory HEAs (RHEAs)** for  $>\sim 1000$  °C structural use (mechanical stability, creep strength, oxidation resistance). [4]
- **Precipitation-strengthened / dual-phase HEAs** (e.g., A2/B2, FCC/BCC/B2) targeting strength-ductility synergy and thermal stability. [5]
- **AM-processable HEAs/MEAs** (LPBF/L-PBF, DED/L-DED, laser cladding) with strategies for crack mitigation and defect control. [6]
- **HEA coatings** for corrosion/steam oxidation and nuclear “accident tolerant fuel” (ATF) coating concepts, including irradiation-coupled degradation mechanisms. [7]
- **Powder feedstock & processing windows** (atomised / PREP powders, particle-size effects, flowability, defect formation). [8]
- **Oxidation-resistant “bond coat” compositions** (Ni-Co-Cr-Al-Fe HEAs) designed via ML and validated experimentally versus incumbent MCrAlY. [9]
- **Materials acceleration platforms** integrating AI + high-throughput manufacturing and automated characterisation for metallic HEAs. [10]

#### Maturity indicators that would constitute strong evidence

- **Repeatable processing windows** for dense/crack-free builds (e.g., quantified porosity/defect fractions; demonstrated across multiple builds and geometries). [11]
- **Service-relevant property datasets**, including high-temperature creep/oxidation, fatigue, corrosion/steam exposure, irradiation effects, and long-duration stability (100s–1000s of hours). [12]
- **Manufacturing and qualification pathways**: powder specifications, joining/heat treatment standards development, and documented qualification concerns (especially irradiation/corrosion). [13]
- **Industrial involvement beyond lab scale**: consortia programmes, funded scale-up, prototype components, and clear evidence of pre-commercial prototypes. [14]
- **Comparative benchmarks** vs incumbent alloys/coatings (e.g., oxidation resistance vs MCrAlY; corrosion vs AFA/AFA-like alloys; creep vs conventional high-T alloys). [15]

#### Evidence (10–20 recent, reliable sources)

##### Peer-reviewed experimental papers and open-access technical literature

##### 1) Additive manufacturing of defect-free TiZrNbTa refractory high-entropy alloy with enhanced elastic isotropy via in-situ alloying of elemental powders

- **Author(s)/org**: Shahryar Mooraj[16] et al.
- **Type**: Peer-reviewed paper (open access)
- **Date**: Feb 2024 (published 16/02/2024)
- **Link**: <https://www.nature.com/articles/s43246-024-00452-0>
- **Why it matters**: Demonstrates a **nearly defect-free** RHEA made by L-PBF using **in-situ alloying of elemental powders**, with an identified processing window and reported



comparability to as-cast properties plus improved elastic isotropy—direct plausibility evidence for AM-compatible RHEA platforms and process-window engineering. [17]

## 2) Intrinsic factors responsible for brittle versus ductile nature of refractory high-entropy alloys

- **Author(s)/org:** Tomohito Tsuru[18] et al.
- **Type:** Peer-reviewed paper (open access)
- **Date:** Feb 2024 (published 24/02/2024)
- **Link:** <https://www.nature.com/articles/s41467-024-45639-8>
- **Why it matters:** Provides combined experimental/theoretical insight into why prototypical RHEAs can be **ductile to cryogenic temperatures (77 K) or brittle at room temperature**, clarifying feasibility constraints and guiding composition/process choices—key to making RHEAs “engineerable” rather than one-off curiosities. [19]

## 3) Crack mitigation in additively manufactured AlCrFe<sub>2</sub>Ni<sub>2</sub> high-entropy alloys through engineering phase transformation pathway

- **Author(s)/org:** Xizhen Dong[20] et al.
- **Type:** Peer-reviewed paper (open access)
- **Date:** Jun 2024 (published 18/06/2024)
- **Link:** <https://www.nature.com/articles/s43246-024-00542-z>
- **Why it matters:** Shows a concrete route to suppress **solid-state cracking** in an AM HEA by controlling cooling rate and phase evolution: high cooling rates yield crack-susceptible BCC/B2, whereas lower cooling rates promote FCC precipitation and ~10% ductility, improving crack resistance—direct evidence that “narrow manufacturing windows” are tractable with physics-guided process control. [21]

## 4) Creep behavior of a precipitation-strengthened A2-B2 refractory high entropy alloy

- **Author(s)/org:** Liu Yang[22] et al.
- **Type:** Peer-reviewed paper (open access)
- **Date:** Apr 2025 (15/04/2025 issue date)
- **Link:** <https://www.sciencedirect.com/science/article/pii/S1359645425001193>
- **Why it matters:** Measures high-temperature creep on a Ta-Mo-Ti-Cr-Al **A2+B2** two-phase microstructure, explicitly positioning “refractory HEA superalloy” analogues as credible high-T structural candidates rather than purely strength-at-room-temperature materials. [23]

## 5) Ultra-high temperature oxidation resistant refractory high entropy alloys fabricated by laser melting deposition: Al concentration regulation and oxidation mechanism

- **Author(s)/org:** Ziyi Zhou[24] et al.
- **Type:** Peer-reviewed paper
- **Date:** 2023 (journal article; DOI page indicates 2023)
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0010938X23005796>
- **Why it matters:** Reports a laser-deposited Al<sub>x</sub>(CrMoTaTi)<sub>1-x</sub> RHEA where higher Al (x=0.15) can form an **external Al<sub>2</sub>O<sub>3</sub> scale during oxidation in air at 1300 °C**, directly supporting plausibility for oxidation-resistant high-T RHEAs. [25]

## 6) Enhancing high-temperature corrosion and cracking resistance of a dual-phase high entropy alloy through surface grinding

- **Author(s)/org:** Kai Chen[26] et al.

- **Type:** Peer-reviewed paper
- **Date:** 2025 (DOI page indicates 2025)
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S0010938X25005542>
- **Why it matters:** Evaluates an Al-enriched dual-phase HEA under **600 °C steam**, reporting corrosion/cracking resistance benefits linked to phase-specific Al content (BCC phase reaching ~16.63 wt% Al) and surface state—evidence for “workhorse” HEAs/coatings aimed at aggressive steam/corrosion environments. [27]

**7) High temperature steam oxidation behavior of AlCrNbTiZr high entropy alloy coating modified by irradiation-induced atomic diffusion**

- **Author(s)/org:** Zhaoming Yang[28] et al.
- **Type:** Peer-reviewed paper
- **Date:** Sep 2025 (01/09/2025 issue date)
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S0257897225005778>
- **Why it matters:** Directly targets a nuclear-relevant constraint—**irradiation effects on subsequent steam oxidation**—by Au-ion irradiating AlCrNbTiZr HEA coatings and testing at 1000–1200 °C; this is maturity-relevant because qualification for harsh environments depends on understanding coupled degradation mechanisms. [29]

**8) A precipitation strengthened high entropy alloy with high (Al+Ti) content for laser powder bed fusion: Synergizing intrinsic hot cracking resistance and ultrahigh strength**

- **Author(s)/org:** Shiwei Wu[30] et al.
- **Type:** Peer-reviewed paper
- **Date:** Oct 2023 (01/10/2023 issue date)
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S1359645423005232>
- **Why it matters:** Demonstrates an HEA designed to be **crack-free in LPBF without preheating** despite high (Al+Ti) content (~7.4 wt%), directly addressing AM manufacturability bottlenecks (cracking/printability) that block scaling. [31]

**9) Effect of heat treatment on mechanical and corrosion properties of an Al<sub>0.8</sub>CrFe<sub>2</sub>Ni<sub>2</sub> alloy processed by laser powder bed fusion**

- **Author(s)/org:** Dimitrios Vogiatzief[32] et al.
- **Type:** Peer-reviewed paper
- **Date:** Aug 2023 (25/08/2023 issue date)
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S0925838823011192>
- **Why it matters:** Reports **crack-free, high-density (>99.9%)** LPBF coupons from prealloyed powder with microstructure and property tuning via heat treatments (FCC → FCC+BCC-B2 precipitates) and corrosion testing in 3.5% NaCl—evidence of post-processing routinisation (heat treatment) and realistic property trade-offs. [33]

**10) Effect of annealing on microstructure and mechanical properties of AlCrFe<sub>2</sub>Ni<sub>2</sub> medium entropy alloy fabricated by laser powder bed fusion additive manufacturing**

- **Author(s)/org:** Tianyi Han[34] et al.
- **Type:** Peer-reviewed paper
- **Date:** Apr 2022 (06/04/2022 issue date)

- **Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S0921509322002763>

- **Why it matters:** Systematically studies annealing (750–1050 °C) to obtain **strength–ductility synergy** in LPBF AlCrFe<sub>2</sub>Ni<sub>2</sub>, supporting the ART claim that these materials become practical through “recipe-like” combinations of composition + processing + heat treatment. [35]

11) **Additive manufacturing of a functionally graded high entropy alloy using a hybrid powder-bed wire-based direct energy deposition approach**

- **Author(s)/org:** Yao Lu[36] et al.

- **Type:** Peer-reviewed paper (open access)

- **Date:** Feb 2023 (05/02/2023 issue date)

- **Link:** <https://www.sciencedirect.com/science/article/pii/S2214860423000374>

- **Why it matters:** Demonstrates **functionally graded HEA** manufacture (Al content gradient) by hybrid DED, achieving continuous FCC → BCC(+FCC) transitions and quantifying strengthening contributions—evidence for HEAs as configurable “families” rather than single compositions. [37]

12) **High entropy alloys amenable for laser powder bed fusion: A thermodynamics guided machine learning search**

- **Author(s)/org:** Ran Duan[38] et al.

- **Type:** Peer-reviewed paper

- **Date:** Apr 2024 (25/04/2024 issue date)

- **Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S2214860424002410>

- **Why it matters:** Presents a thermodynamics-informed ML strategy to predict LPBF printability using parameters like liquid temperature range and viscosity—directly supporting the feasibility of a design stack linking **computational screening → manufacturable HEAs**. [39]

13) **Microstructure and mechanical properties of Co<sub>31.5</sub>Cr<sub>7</sub>Fe<sub>30</sub>Ni<sub>31.5</sub> high-entropy alloy powder produced by plasma rotating electrode process and its applications in additive manufacturing**

- **Author(s)/org:** Xiaping Fan[40] et al.

- **Type:** Peer-reviewed paper (open access)

- **Date:** Jul–Aug 2024

- **Link:** <https://www.sciencedirect.com/science/article/pii/S223878542401528X>

- **Why it matters:** Links **powder production quality** (PREP powders; particle size 20–106 μm) to AM outcomes, reporting tensile properties for laser cladding AM bulk (UTS ~481 MPa, elongation ~35.9%) and identifying defects (pores/prior particle boundaries) driving brittle fracture in cold spray—evidence for manufacturability and scale-up constraints residing in feedstock and consolidation routes. [41]

**Authoritative lab / metrology / consortium reports and programmes**

14) **Advanced Manufacturing Techniques and Compositions of High Entropy Alloys for Nuclear Applications**

- **Author(s)/org:** Pacific Northwest National Laboratory[42] (prepared for US DOE)

- **Type:** National lab technical report

- **Date:** Aug 2024

- **Link:**

[https://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-36488.pdf](https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-36488.pdf)

- **Why it matters:** A programme-level survey plus experimental work that explicitly evaluates **AM routes (DED/SLM) and solid-phase processing (e.g., friction surface layer deposition)** and builds a decision matrix for nuclear-relevant HEA candidates; it also highlights performance claims (e.g., for NASA GRX-810) and frames where qualification gaps remain. [43]

#### 15) **Summary Report of the High Entropy Alloys for Nuclear Applications Workshop**

- **Author(s)/org:** OECD Nuclear Energy Agency[44]

- **Type:** Authoritative international workshop report (EGISM/NEA)

- **Date:** Mar 2024 (document dated March 2024; issued 12/03/2024)

- **Link:** [https://www.oecd-neo.org/upload/docs/application/pdf/2024-03/nea\\_nsc\\_r\\_2023\\_9.pdf](https://www.oecd-neo.org/upload/docs/application/pdf/2024-03/nea_nsc_r_2023_9.pdf)

- **Why it matters:** Provides a conservative, deployment-focused view: HEAs likely need **reliable manufacturing processes**, are expected (given probable high costs) to be used **mostly as coatings**, and face qualification challenges (notably irradiation-property data)—direct maturity evidence about barriers to market adoption. [45]

#### 16) **Complex Precipitation Behavior in a Co-free High Entropy Alloy during Aging**

- **Author(s)/org:** National Institute of Standards and Technology[46]

- **Type:** Government lab publication record (journal paper with detailed abstract)

- **Date:** Sep 2024 (published 11/09/2024)

- **Link:** <https://www.nist.gov/publications/complex-precipitation-behavior-co-free-high-entropy-alloy-during-aging>

- **Why it matters:** Gives highly specific, time-resolved precipitation kinetics ( $L_{1/2}/B_2/\chi$ ) at 650 °C and quantifies microstructure evolution (e.g., >50% precipitate volume fraction after 120 h) in a Co-free HEA—critical for moving from “interesting composition” to **certifiable heat-treatment schedules and microstructural stability**. [47]

#### 17) **SOLID-MAP: Development of a Materials Acceleration Platform for High-Entropy Alloys**

- **Author(s)/org:** VTT Technical Research Centre of Finland[48]

- **Type:** Peer-reviewed paper (publisher final version; CC BY)

- **Date:** Dec 2025 (published 01/12/2025)

- **Link:** <https://cris.vtt.fi/ws/portalfiles/portal/118860004/s11665-025-11504-y.pdf>

- **Why it matters:** Describes an end-to-end HEA materials acceleration platform combining active-learning surrogate modelling + CALPHAD/DFT screening with **high-throughput DED of elemental powders** and automated XRD/electron microscopy + AI analysis, reporting a “significant speed-up” in development—direct evidence for the ART’s “database + high-throughput testing” pillar. [10]

#### 18) **Machine learning and high-throughput computational guided development of high temperature oxidation-resisting Ni-Co-Cr-Al-Fe based high-entropy alloys**

- **Author(s)/org:** Xiaobo Tan[49] et al.

- **Type:** Peer-reviewed paper (open access)

- **Date:** Apr 2025 (published 04/04/2025)
- **Link:** <https://www.nature.com/articles/s41524-025-01568-8>
- **Why it matters:** Uses ML + high-throughput computation with experimental validation to identify non-equiatomic Ni-Co-Cr-Al-Fe HEAs with oxidation resistance **surpassing the state-of-the-art bond coat MCrAlY**, illustrating the emerging “design-select-validate” loop needed for near-market adoption in turbines. [9]

#### 19) **SUSustainable production of High Entropy Alloys from Secondary metals (SUSHEAS)**

- **Author(s)/org:** CORDIS[50] (European Commission project fact sheet)
- **Type:** EU programme / consortium project record
- **Date:** Aug 2025 (EC signature date 06/08/2025; start 01/11/2025)
- **Link:** <https://cordis.europa.eu/project/id/101236968>
- **Why it matters:** Signals funded, multi-party work on a specific bottleneck—**sustainable HEA production from secondary metals**, with explicit mention of AI optimisation, manufacturing/characterisation, and prototype demonstration—evidence that actors are actively tackling material supply/cost and process scale-up constraints. [51]

#### **Maturity score (1–7) and reasoning**

**Final maturity score: 4**

#### **Why this is at least level 4 (rules out levels 1–3):**

- The ART is far beyond theory or basic lab principle: multiple peer-reviewed studies demonstrate **repeatable, parameterised manufacturing pathways** (e.g., defined processing windows for near-defect-free L-PBF RHEAs; crack-mitigation via phase-transformation pathway engineering) that directly address known blockers like cracking and porosity. [52]
- There is strong evidence of **application-relevant performance testing** (creep at elevated temperatures for A2/B2 RHEAs; oxidation in air at 1300 °C with protective Al<sub>2</sub>O<sub>3</sub> scale formation; steam corrosion and cracking resistance at 600 °C; irradiation-coupled steam oxidation of HEA coatings). [53]
- The ecosystem is not only academic: national-lab programmes and metrology organisations are publishing design/qualification-relevant work (e.g., PNNL’s AM methods and candidate down-selection; NIST’s time-resolved precipitation evolution). [54]

These collectively indicate **Proof-of-Concept functionality**: the materials can be made via relevant industrial processes (AM, coatings) with controlled microstructures and measured properties that credibly target commercial requirements for harsh environments. [55]

#### **Why it is not level 5 (what is missing):**

- Level 5 would require clear evidence that **multiple well-capitalised market actors are competing to launch production prototypes** (pilot lines, qualification campaigns, production tooling, customer trials with timelines). The recent record is dominated by high-quality R&D and funded programmes, but even authoritative assessments stress that deployment will require **reliable manufacturing processes** and that qualification—especially post-irradiation behaviour—is hard and still developing. [56]
- The evidence base here shows **promising prototypes and design frameworks**, but not yet broad proof of scaled supply (standardised bar stock/sheet/wire powders at industrial volumes), certified joining/surface treatment standards, or long-duration service qualification datasets across many compositions. [57]

### Sub-score breakdown and aggregation

Because “High-Entropy Alloys & Advanced Metals” is a **family** spanning bulk alloys, AM-tailored grades, coatings, and discovery platforms, maturity varies by sub-thread:

- **AM-processable bulk HEAs / MEAs (LPBF/L-PBF/DED): ~4** — Crack mitigation and high-density builds with post-heat-treatment tunability are demonstrated, indicating PoC manufacturability (but not yet widespread product qualification). [58]
- **High-temperature structural RHEAs (creep + oxidation): ~3–4** — Strong experimental progress (creep studies; oxidation-protective scales at 1300 °C), but still largely pre-certification and composition-specific. [59]
- **HEA coatings for harsh/water/steam/irradiation environments: ~3–4** — Clear lab demonstrations including irradiation-coupled oxidation behaviour, but authoritative reports emphasise qualification challenges and a likely early role as coatings. [7]
- **Accelerated discovery / materials acceleration platforms for HEAs: ~3–4** — Integrated computational + high-throughput experimental pipelines are demonstrated, and oxidation-resistant candidates outperform incumbents in targeted comparisons, but this is still early in terms of standard industrial adoption as a routine “platform”. [60]

**Aggregation to one score:** The dominant value proposition across variants is **the same functional claim** (tailored, manufacturable advanced alloys for harsh environments), but maturity is uneven; taking an **evidence-weighted average** across the most application-proximate sub-threads (AM-processable alloys and coatings), the dossier supports **overall level 4** today. [61]

[1] [4] [19] [48] Intrinsic factors responsible for brittle versus ductile nature of refractory high-entropy alloys | Nature Communications

<https://www.nature.com/articles/s41467-024-45639-8>

[2] [6] [11] [16] [17] [22] [32] [52] [58] Additive manufacturing of defect-free TiZrNbTa refractory high-entropy alloy with enhanced elastic isotropy via in-situ alloying of elemental powders | Communications Materials

<https://www.nature.com/articles/s43246-024-00452-0>

[3] [9] [15] [26] [42] [46] Machine learning and high-throughput computational guided development of high temperature oxidation-resisting Ni-Co-Cr-Al-Fe based high-entropy alloys | npj Computational Materials

<https://www.nature.com/articles/s41524-025-01568-8>

[5] [12] [20] [23] [30] [53] [59] Creep behavior of a precipitation-strengthened A2-B2 refractory high entropy alloy - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S1359645425001193>

[7] [29] High temperature steam oxidation behavior of AlCrNbTiZr high entropy alloy coating modified by irradiation-induced atomic diffusion - ScienceDirect



<https://www.sciencedirect.com/science/article/abs/pii/S0257897225005778>

[8] [18] [41] Microstructure and mechanical properties of Co<sub>31.5</sub>Cr<sub>7</sub>Fe<sub>30</sub>Ni<sub>31.5</sub> high-entropy alloy powder produced by plasma rotating electrode process and its applications in additive manufacturing - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S223878542401528X>

[10] [40] [50] [60] cris.vtt.fi

<https://cris.vtt.fi/ws/portalfiles/portal/118860004/s11665-025-11504-y.pdf>

[13] [24] [45] [56] [57] [61] Summary Report of the High Entropy Alloys for Nuclear Applications Workshop

[https://www.oecd-nea.org/upload/docs/application/pdf/2024-03/nea\\_nsc\\_r\\_2023\\_9.pdf](https://www.oecd-nea.org/upload/docs/application/pdf/2024-03/nea_nsc_r_2023_9.pdf)

[14] [43] [54] Title

[https://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-36488.pdf](https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-36488.pdf)

[21] Crack mitigation in additively manufactured AlCrFe<sub>2</sub>Ni<sub>2</sub> high-entropy alloys through engineering phase transformation pathway | Communications Materials

<https://www.nature.com/articles/s43246-024-00542-z>

[25] [36] [44] Ultra-high temperature oxidation resistant refractory high entropy alloys fabricated by laser melting deposition: Al concentration regulation and oxidation mechanism - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0010938X23005796>

[27] Enhancing high-temperature corrosion and cracking resistance of a dual-phase high entropy alloy through surface grinding - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0010938X25005542>

[28] [33] [55] Effect of heat treatment on mechanical and corrosion properties of an Al<sub>0.8</sub>CrFe<sub>2</sub>Ni<sub>2</sub> alloy processed by laser powder bed fusion - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S0925838823011192>

[31] A precipitation strengthened high entropy alloy with high (Al+Ti) content for laser powder bed fusion: Synergizing in intrinsic hot cracking resistance and ultrahigh strength - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S1359645423005232>

[34] [37] [49] Additive manufacturing of a functionally graded high entropy alloy using a hybrid powder-bed wire-based direct energy deposition approach - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S2214860423000374>

[35] Effect of annealing on microstructure and mechanical ...

[https://www.sciencedirect.com/science/article/abs/pii/S0921509322002763?utm\\_source=chatgpt.com](https://www.sciencedirect.com/science/article/abs/pii/S0921509322002763?utm_source=chatgpt.com)

[38] [47] Complex Precipitation Behavior in a Co-free High Entropy Alloy during Aging | NIST

<https://www.nist.gov/publications/complex-precipitation-behavior-co-free-high-entropy-alloy-during-aging>

[39] High entropy alloys amenable for laser powder bed fusion: A thermodynamics guided machine learning search - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S2214860424002410>

[51] SUSustainable production of High Entropy Alloys from Secondary metals | SUSHEAS | Project | Fact Sheet | HORIZON | CORDIS | European Commission

<https://cordis.europa.eu/project/id/101236968>

## ART 07.049 Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

### 1. ART extraction

**A) Primary capability claimed (core “what it does”)** - Engineer CO<sub>2</sub>-selective capture media based on metal–organic frameworks (MOFs), leveraging tuneable pore chemistry/geometry to preferentially bind CO<sub>2</sub> in complex gas streams (varying CO<sub>2</sub> %, humidity, and contaminants). - Package these materials into practical, modular contactor formats (e.g., coated structures, pellets/monoliths/laminates, fibres, cartridges) compatible with conventional ducting, blowers, and control systems. - Enable relatively low-intensity regeneration (temperature swing, vacuum/pressure swing, humidity swing, and potentially electro-assisted/rapid heating) to deliver a concentrated CO<sub>2</sub> stream for downstream handling.

**B) Key sub-components / variants (technology sub-threads) - MOF chemistries optimised for specific separations:** post-combustion (CO<sub>2</sub>/N<sub>2</sub>), direct air capture (DAC; ~400 ppm), and higher-concentration industrial streams. - **Moisture/impurity tolerance:** stability to H<sub>2</sub>O, O<sub>2</sub>, NO<sub>x</sub>/SO<sub>x</sub>, and other trace contaminants; mitigation of sorbent degradation pathways. - **Shaping and contactor engineering:** structured beds (laminates, monoliths, extrudates, membranes), hollow fibres and composite architectures to reduce pressure drop and improve kinetics/heat transfer. - **Regeneration approaches:** VSA/PSA/TSA and rapid/electrified heating (e.g., Joule heating) to reduce heat-transfer bottlenecks and energy penalties. - **Manufacturing scale-up:** synthesis routes that reduce solvent use, shorten cycle times, increase yields, and support tonnage-scale output with consistent performance. - **Operational monitoring and service model:** modular replacement/tuning (cartridge swaps, operating “recipes”) rather than wholesale equipment replacement.

**C) Maturity indicators that constitute evidence** - Demonstrated **humid/flue-gas-relevant performance** (breakthrough, purity/recovery/productivity) in structured formats, not just powder isotherms. - **Cycle durability evidence** (hundreds to thousands of cycles; minimal capacity loss) and at least some **realistic impurity exposure** studies (O<sub>2</sub>, SO<sub>2</sub>, etc.). - **Pilot or field trials** in industrial environments (e.g., cement, hydrogen/SMR, refineries), with time-on-stream and post-mortem sorbent analysis. - Credible signs of **manufacturing feasibility** (high-yield/low-solvent synthesis routes; mechanochemical or microwave acceleration; documented scale-up). - Evidence of **industrial or government-backed programmes**

moving from PoC to engineering design/FEED and techno-economic analysis (TEA), plus multiple well-capitalised actors.

## 2. Evidence (10–20 recent, reliable sources)

### 1) Experimental demonstration of humid post-combustion CO<sub>2</sub> capture by vacuum swing adsorption using CALF-20

Organisation(s): University of Alberta[1]; University of Calgary[2]

Venue/type: Peer-reviewed journal article (Adsorption, Springer Nature)

Publication date: **February 2025** (published 09 Feb 2025)

Link: <https://link.springer.com/article/10.1007/s10450-025-00600-z>

Annotation: Reports VSA experiments on *structured* CALF-20 across humidity (13–70% RH), showing minimal performance difference vs dry operation at 13–45% RH and reporting multi-day runs (hundreds of cycles) with **minimal CO<sub>2</sub>-capacity loss after ~10,000 cycles**—directly addressing moisture tolerance and cyclic durability in a process-relevant configuration. [3]

### 2) Gas adsorption and framework flexibility of CALF-20 explored via experiments and simulations

Organisation(s): Collaborative work including Svante[4] (industry collaboration mentioned)

Venue/type: Peer-reviewed, open-access article (Nature Communications)

Publication date: **May 2024** (published 09 May 2024)

Link: <https://www.nature.com/articles/s41467-024-48136-0>

Annotation: Combines experiments and modelling to explain CALF-20's CO<sub>2</sub> and H<sub>2</sub>O adsorption behaviour and the role of water-framework interactions/hydrogen-bond networks in its hydrophobic response—evidence for scientific plausibility of performance under humid conditions and a basis for rational “family” tuning across operating regimes. [5]

### 3) CALF-20 obtained by mechanochemical synthesis for temperature swing adsorption CO<sub>2</sub> capture: a thermodynamic and kinetic study

Organisation(s): Italian research institutes (CNR/ENEA listed on the article page)

Venue/type: Peer-reviewed, open-access article (Chemical Engineering Journal)

Publication date: **2025** (journal year 2025)

Link: <https://www.sciencedirect.com/science/article/pii/S138589472500765X>

Annotation: Demonstrates CALF-20 made via reduced-solvent mechanochemical synthesis and tested dynamically in a lab fixed-bed TSA reactor across 28–130 °C and 3–20% CO<sub>2</sub>, reporting **up to ~2.55 mmol g<sup>-1</sup> capacity** and stable multi-cycle regeneration—direct evidence that greener synthesis routes can preserve cyclic, process-relevant performance. [6]

### 4) MOF-carbon fibre composites for electrically driven CO<sub>2</sub> regeneration under direct air capture conditions

Organisation(s): (Authors listed on article page; academic team)

Venue/type: Peer-reviewed article (Chemical Engineering Journal)

Publication date: **2025** (journal year 2025)

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S1385894725111534>

Annotation: Develops a MOF/carbon-fibre composite enabling **Joule-heating (ETSA) regeneration**; reports DAC-relevant CO<sub>2</sub> capacities (e.g., **~2.32 mmol g<sup>-1</sup> at 400 ppm, 25 °C**

for one formulation) and **complete desorption in ~4 minutes** with >95% retention and **~66% higher regeneration efficiency** vs conventional TSA—concrete evidence for electro-assisted regeneration pathways and structured formats. [7]

#### 5) **Efficient solvent-free mechanochemical synthesis of CALF-20 for carbon dioxide capture**

Organisation(s): (Authors; paper in CrystEngComm)

Venue/type: Peer-reviewed research article (CrystEngComm, RSC)

Publication date: **2025** (received June 2025; accepted August 2025 per the manuscript metadata)

Link: <https://www.rsc.org/suppdata/d5/ce/d5ce00632e/d5ce00632e1.pdf>

Annotation: Provides an experimentally detailed, **solvent-free mechanochemical route** to CALF-20 (supporting information with procedural detail and stability testing), supporting the plausibility of manufacturing routes that reduce solvent dependence while maintaining capture-relevant properties. [8]

#### 6) **Enhancing CO<sub>2</sub> capture via fast microwave-assisted synthesis of the CALF-20 metal-organic framework**

Organisation(s): (Authors; peer-reviewed article hosted on PMC)

Venue/type: Peer-reviewed article (Inorganic Chemistry; open full text via PMC)

Publication date: **2025**

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11863388/>

Annotation: Reports microwave synthesis cutting time drastically (e.g., “92% reduction” vs solvothermal) and improving yields (e.g., **~97%**), with characterisation showing comparable structure and improved adsorption/selectivity; also notes an industrial-relevance context including a **1 tonne/day** cement-plant demonstration claim and explicitly frames CALF-20 as advanced TRL—useful (but interpret cautiously) for maturity signals plus concrete manufacturing acceleration metrics. [9]

#### 7) **Mechanistic studies of oxidative degradation in diamine-appended MOFs exhibiting cooperative CO<sub>2</sub> capture**

Organisation(s): Lawrence Berkeley National Laboratory[10]; University of California, Berkeley[11] (authors’ affiliations indicated via associated records)

Venue/type: Peer-reviewed article (Journal of the American Chemical Society; bibliographic record) + detailed experimental manuscript

Publication date: **July 2025**

Link: <https://www.osti.gov/biblio/2574016>

Annotation: Provides mechanistic evidence that O<sub>2</sub> exposure can degrade diamine functionalities (impacting chemisorption) while parent frameworks remain largely intact, identifying degradation products and proposing radical-mediated pathways—directly addressing a key “lifetime under real-world impurities” constraint and guiding more robust formulations. [12]

#### 8) **Impact of SO<sub>2</sub> on the stability and CO<sub>2</sub> capture performance of a diamine-appended MOF**

Organisation(s): University of California, Berkeley[11] (author manuscript hosted)

Venue/type: Peer-reviewed article (JACS; author manuscript)

Publication date: **2022** (Epub Oct 2022 per indexing)

Link: <https://escholarship.org/content/qt3p36h4c4/qt3p36h4c4.pdf>

Annotation: Experimental study focused on SO<sub>2</sub> effects on a leading diamine-appended MOF system, directly targeting contaminant robustness—an essential plausibility/maturity gate for deploying MOF sorbents in “dirty” industrial flue gas. [13]

#### 9) Scalable formation of diamine-appended MOF hollow fibre sorbents for post-combustion CO<sub>2</sub> capture

Organisation(s): Georgia Institute of Technology[14]; ExxonMobil[15]

Venue/type: Peer-reviewed article (JACS Au; open full text via PMC)

Publication date: **June 2022** (collection date 27 Jun 2022; accepted Apr 2022)

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC9241006/>

Annotation: Demonstrates a *manufacturable contactor format* (MOF/polymer composite **hollow fibres spun via a conventional dry-jet wet-quench method**), explicitly aimed at diluted streams such as NGCC flue gas—evidence for compatibility with scalable processing and real contactor geometries beyond powders. [16]

#### 10) CO<sub>2</sub> capture from wet flue gas using a water-stable and cost-effective MOF (MIL-120)

Organisation(s): Oregon State University (correspondence indicated); U.S. Department of Energy[17] (hosted via OSTI)

Venue/type: Peer-reviewed, open-access article (Cell Reports Physical Science; PDF via OSTI)

Publication date: **July 2023** (19 Jul 2023)

Link: <https://www.osti.gov/servlets/purl/2000685>

Annotation: Reports breakthrough capture from **dry and wet flue gas** with measured capacities (**~1.215 vs 1.118 mmol g<sup>-1</sup>** dry vs wet) and a reported CO<sub>2</sub> affinity (**~44 kJ mol<sup>-1</sup>**), providing concrete evidence that water-stable, lower-cost MOF chemistries can work under humid flue gas conditions. [18]

#### 11) Rapid Cycle Temperature Swing Adsorption using CALF-20 MOF structured adsorbent for cement carbon capture

Organisation(s): Svante[4]; TotalEnergies[19]; Lafarge Canada (listed on the preprint page)

Venue/type: Conference-linked technical paper hosted as SSRN preprint (labelled as such)

Publication date: **February 2023** (posted 06 Feb 2023)

Link: <https://ssrn.com/abstract=4349347>

Annotation: Reports **~900 hours of field-testing** of a CALF-20 structured sorbent in a **real cement kiln flue gas** context—materially stronger maturity evidence than lab-only studies, while also highlighting contaminant/lifetime evaluation in situ. [20]

#### 12) Engineering study of a solid-sorbent (MOF) CO<sub>2</sub> capture technology at a steam methane reforming (H<sub>2</sub>) plant

Organisation(s): Linde[21]; BASF[22]; Svante[4]; National Energy Technology Laboratory[23] (host)

Venue/type: Authoritative programme/engineering presentation (DOE/NETL project material)

Publication date: **September 2023** (document dated 09/01/2023)

Link: [https://netl.doe.gov/sites/default/files/netl-file/23CM\\_PSCC1\\_Shah.pdf](https://netl.doe.gov/sites/default/files/netl-file/23CM_PSCC1_Shah.pdf)

Annotation: Documents a DOE-supported, site-specific engineering design/TEA effort for integrating a MOF-based solid sorbent capture system at an SMR H<sub>2</sub> plant, including project objectives and deployment planning—evidence that MOF sorbents are being engineered into full-plant designs rather than remaining lab concepts. [24]

### 13) **Field/pilot performance and TEA signals from structured sorbent bed development (CALF-20)**

Organisation(s): (NETL-hosted carbon management project material; includes “1 TPD” pilot references)

Venue/type: Technical programme presentation (DOE/NETL carbon management review material)

Publication date: **2023** (embedded in file path and meeting context; slide deck includes operational-hour reporting)

Link: [https://netl.doe.gov/sites/default/files/netl-file/23CM\\_PSCC30\\_Fagundo.pdf](https://netl.doe.gov/sites/default/files/netl-file/23CM_PSCC30_Fagundo.pdf)

Annotation: Reports pilot/durability indicators such as **500 hours** post-mortem analysis (noting negligible loss for the MOF section vs contaminant sensitivity for amine sections) and **accumulated operating hours** plus TEA assumptions—useful maturity evidence around lifetime and cost-relevant operation (noting the presentation context). [25]

### 14) **Sorbents for Carbon Capture (programme overview and R&D framing)**

Organisation(s): National Energy Technology Laboratory[23]

Venue/type: Authoritative government lab factsheet / programme material

Publication date: **August 2023**

Link: <https://netl.doe.gov/sites/default/files/2023-08/NETL-sorbents-2023.pdf>

Annotation: Summarises the DOE/NETL R&D framing for sorbent-based capture (including goals, constraints, and pathways), supporting maturity evaluation by showing sustained, structured public-sector investment and a pipeline of projects beyond single-lab efforts. [26]

### 15) **A holistic platform for accelerating sorbent-based carbon capture**

Organisation(s): Multi-institution academic team (paper focus: platform)

Venue/type: Peer-reviewed article (Nature)

Publication date: **2024** (published 2024)

Link: <https://www.nature.com/articles/s41586-024-07933-6>

Annotation: Presents an integrated platform approach to accelerate identification/validation of carbon-capture sorbents—relevant to the ART’s “configurable capture family” claim by supporting faster iteration from material discovery to process-relevant screening. [27]

### 16) **Compendium of Carbon Capture Technology (DOE/NETL)**

Organisation(s): National Energy Technology Laboratory[23]

Venue/type: Government programme repository/compendium (technical summaries of projects)

Publication date: **2024 update**

Link: <https://netl.doe.gov/carbon-management/carbon-capture/compendium>

Annotation: Indicates a large active portfolio (e.g., “technology sheets for 145 active and recent R&D projects”), supporting maturity assessment by evidencing breadth of ongoing capture R&D and multiple parallel development tracks (including sorbents and point-source capture). [28]

### 17) **Direct Air Capture 2022 (IEA analysis)**

Organisation(s): International Energy Agency[29]

Venue/type: Authoritative international agency report/analysis

Publication date: **April 2022** (published 01 Apr 2022)



Link: <https://www.iea.org/reports/direct-air-capture-2022>

Annotation: Establishes DAC as an emerging but scaling-critical climate technology and summarises the early deployment landscape (e.g., counts of operating facilities and the scale-up implied by net-zero pathways), providing market/scale context for why higher-performance solid sorbents (including MOF-based) matter and what “maturity” must ultimately achieve at system level. [30]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 5

#### B) Why this score fits the rubric (evidence-to-rubric mapping)

##### What rules out levels 1–3 (the “it’s not just theory or a lab trick” bar):

Multiple sources demonstrate process-relevant prototypes and performance evidence beyond single-material equilibrium testing. A peer-reviewed study reports humid VSA operation with structured MOF sorbent and documents multi-day cycling with minimal capacity loss after ~10,000 cycles. [3] Government/industry-linked materials document site-specific engineering and techno-economic work for integrating MOF solid sorbents into an H<sub>2</sub> plant context (an “engineering design” maturity indicator rather than lab-only work). [24] Field testing in an industrial cement flue gas environment (~900 hours) further rules out a purely laboratory-prototype stage. [20]

##### What justifies level 5 (vs stopping at level 4):

Level 5 requires either (i) several well-capitalised actors competing to develop production prototypes post-PoC or (ii) clear evidence that production prototypes are in a finishing phase with investments made to launch production. The evidence shows:

- **Industrial ecosystem + engineering progression:** DOE/NETL-hosted work involves major industrial participants (e.g., Linde, BASF, and a MOF-sorbent capture developer) conducting site-specific engineering design and TEA for a real industrial plant. [24]
- **Pilot/field validation signals:** field-testing in cement and programme materials referencing pilot-scale configurations and durability/post-mortem results that distinguish sorbent sensitivity to contaminants. [31]
- **Manufacturing acceleration evidence:** multiple recent synthesis papers show clear progress toward scalable, faster, higher-yield routes (microwave-assisted yields ~90–99% for some conditions and reduced synthesis time; mechanochemical approaches aimed at reducing solvents while preserving performance), strengthening the plausibility of tonnage-scale manufacturing pathways. [32]

Together, this is more consistent with a post-PoC push toward production prototypes than with a single isolated PoC. [33]

##### What is still missing to justify level 6 (products delivered to customers in increasing amounts):

The dossier shows strong pilot/field and engineering evidence, but it does not provide robust, independently verifiable indicators that MOF-based capture *products* (standardised modules/cartridges) are being delivered broadly to multiple customers “in increasing amounts,” nor the kind of market-wide shipment/scale expansion data expected at level 6. Current evidence is strongest for advanced pilots, field testing, and engineering design/TEA rather than documented, ramping commercial deliveries. [34]

### C) Sub-component maturity breakdown (bundle logic) and aggregation to one score

- **MOF sorbent chemistry and durability under O<sub>2</sub>/SO<sub>2</sub>/H<sub>2</sub>O:** maturity ~4 (PoC-level durability mechanisms and mitigation strategies are increasingly well-characterised, but broadly generalisable, “drop-in” robustness across contaminants remains an active research frontier). Key sources: oxidative degradation mechanisms in diamine-appended systems (2025) and SO<sub>2</sub> stability studies (2022), plus humid cyclic operation results (2025). [35]
- **Shaped/structured contactor formats (fibres/structured adsorbents):** maturity ~4–5 (demonstrated scalable fabrication routes such as hollow-fibre composite sorbents; deployment-relevant structured beds in VSA studies). Key sources: scalable MOF hollow fibre fabrication (2022) and structured-bed humid VSA operation (2025). [36]
- **Regeneration approaches (TSA/VSA and electrified rapid heating):** maturity ~4–5 (credible prototype demonstrations exist, including ETSA/Joule heating composites under DAC-relevant concentrations, but industrial standardisation and scaling remain uneven). Key source: ETSA MOF/carbon-fibre composite with rapid desorption and quantified efficiency gains (2025). [7]
- **Manufacturing scale-up pathways:** maturity ~4–5 (multiple credible routes—microwave, mechanochemical—show clear process intensification and yield improvements; still, supply-chain resilience and consistent megaton-scale production are not yet evidenced as “routine”). Key sources: microwave-assisted synthesis with high yields (2025) and mechanochemical synthesis + process testing (2025). [32]
- **System integration and industrial pilots/engineering:** maturity ~5 (engineering studies + field testing indicate serious commercialisation work with major industrial actors). Key sources: DOE/NETL engineering design study (2023) and cement field testing (2023). [37]

**Aggregation rationale:** Because the ART’s end-user functionality is largely consistent across variants (modular MOF-based capture media in engineered contactor formats, regenerated by swing processes), it is reasonable to score near the leading edge of demonstrated system integration while acknowledging that not all MOF chemistries are equally mature. The combined evidence supports a **level-5** overall assessment (production-prototype push with well-capitalised actors and advanced pilots), rather than averaging down to level 4 (which would underweight the field/engineering evidence). [34]

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[4] [10] [16] [36] <https://pmc.ncbi.nlm.nih.gov/articles/PMC9241006/>

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## ART 07.050 Graphene and Nanotube Composites for Lightweight Strength

### ART extraction

- **Primary capability (claimed)**
- **Structural composites with higher specific performance:** graphene- and/or carbon-nanotube–reinforced polymers/laminates that meaningfully improve

**strength-to-weight, fatigue/delamination resistance, and crack tolerance** over baseline fibre-reinforced polymers (FRPs). [1]

- **Multifunctionality via conductivity:** engineered electrical/thermal conduction in otherwise insulating laminates enabling **embedded sensing** (strain, delamination, impact damage) through resistance/impedance measurements and simple electronics. [2]
- **Partial manufacturing compatibility:** nanomaterials added via **masterbatches, sprays/coatings, interleaves, or resin mixing**, keeping some alignment with established composite manufacturing routes. [3]
- **Key sub-components / variants (sub-threads)**
- **CNT/graphene in resin (“nano-filled matrix”):** direct mixing into epoxies/thermosets; properties sensitive to dispersion state, CNT geometry, and mixing protocol. [4]
- **Interlaminar toughening interleaves:** CNT- or graphene-based veils/films/interleaves placed between plies to target delamination and mode-I/II fracture toughness. [5]
- **Surface modification / coated fibres:** CNT-coated glass/carbon fibres and graphene oxide surface treatments to improve interfacial adhesion and/or create conductive sensing layers. [6]
- **Self-sensing architectures:** grids, embedded sensing layers, electrotopography, or resistance mapping to localise impact damage/delamination. [7]
- **Process control and inspection:** metrics+automation (e.g., computer vision) to quantify dispersion quality for repeatable performance at scale. [8]
- **Standards, purity, and safety envelope:** standardised characterisation methods (graphene structure; CNT impurity quantification) and occupational exposure sampling guidance that shape scalable industrial handling. [9]
- **CNT fibres/yarns as “engineered fabrics”:** CNT fibre tows/yarns as conductive, lightweight structural textile candidates usable in composites and sensing. [10]
- **Maturity indicators that would count as strong evidence**
- **Repeatable mechanical delamination/fatigue gains** (mode-I/II fracture toughness, CAI, lap-shear/joint durability) demonstrated on **multi-ply laminates**, not just neat resin coupons, using industrially relevant processes. [11]
- **Embedded sensing validated against ground truth** (e.g., DIC, tomography) with quantified localisation error, sensitivity, and minimal mechanical penalty. [12]
- **Scale-up enablers:** industrial masterbatches, roll-to-roll/continuous processing demonstrations, and in-line QC methods that reduce batch-to-batch variance. [13]
- **Standardisation / metrology readiness:** clear, adopted standards (or late-stage drafts) for graphene structure, CNT purity/impurities, and workplace sampling protocols. [9]
- **Market proximity:** evidence of qualified parts, field trials, or shipped products specifically for structural composite applications (not only lab prototypes). (This type of evidence is comparatively weaker in the sources found below.) [14]

## 2. Evidence (10–20 recent, reliable sources)

### 1) Effects of carbon nanotube (CNT) geometries on the dispersion characterizations and adhesion properties of CNT reinforced epoxy composites

- Authors/organisation: Dawei Zhang[15] et al.
- Venue/type: Peer-reviewed paper in Composite Structures[16]
- Publication date: 15 Sep 2022
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S0263822322007000>
- What it shows and why it matters: Demonstrates that **CNT diameter and length materially affect dispersion and adhesive performance**, with larger-diameter CNTs dispersing more uniformly and “normal-length” CNTs giving higher lap-shear strength/toughness than shorter CNTs—evidence that **process/material reproducibility is a real maturity bottleneck** (geometry → dispersion → joint reliability). [17]

### 2) Technical Report: Occupational Exposure Sampling for Engineered Nanomaterials

- Authors/organisation: NIOSH[18] (by Hodson & Eastlake)
- Venue/type: Authoritative government technical report
- Publication date: Jul 2022 (NIOSH Publication No. 2022-153)
- Link: <https://www.cdc.gov/niosh/docs/2022-153/default.html>
- What it shows and why it matters: Provides consolidated workplace sampling guidance for engineered nanomaterials including **carbon nanotubes/nanofibres**, reflecting that **EHS sampling/controls are necessary for scale-up** and can influence cost and regulatory acceptance of CNT handling in composite manufacturing. [19]

### 3) Comprehensive Data via Spectroscopy and Molecular Dynamics of Chemically Treated Graphene Nanoplatelets

- Authors/organisation: NIST[20] (paper by Olasunbo Farinre[21] et al.)
- Venue/type: Government-hosted peer-reviewed journal publication page (paper in *Data*)
- Publication date: 30 Mar 2022 (page updated Nov 2022)
- Link: <https://www.nist.gov/publications/comprehensive-data-spectroscopy-and-molecular-dynamics-chemically-treated-graphene>
- What it shows and why it matters: Provides **measurement datasets and characterisation** for chemically treated graphene nanoplatelets—relevant to the ART’s practical constraints around **impurities, repeatability, and quality control** of graphene feedstocks before they can reliably reinforce composites. [22]

### 4) ISO/AWI 21356-1 — Nanotechnologies: Structural characterization of graphene — Part 1: Graphene from powders and dispersions

- Authors/organisation: ISO[23]
- Venue/type: Standards work item (authoritative; under development)
- Publication date: New project approved 09 Aug 2023
- Link: <https://www.iso.org/standard/87572.html>
- What it shows and why it matters: Specifies a **sequence of methods** and protocols to characterise graphene (layer number/thickness, lateral size, disorder, alignment, specific surface area) from powders/dispersions—evidence that **metrology/standardisation infrastructure is catching up**, which is a prerequisite for vendor qualification and scalable composites. [24]

### 5) ISO/DTS 23690:2023 — Nanotechnologies: Multiwall carbon nanotubes — Determination of carbon impurity content by thermogravimetric analysis

- Authors/organisation: ISO technical specification preview (source shows ISO copyright

marking)

- Venue/type: Standards document (technical specification / draft technical specification; treat cautiously as “preview”)

- Publication date: 2023 (document header indicates ISO/DTS 23690:2023)

- Link:

<https://cdn.standards.iteh.ai/samples/76660/4aee3524509f4419928f475a1ca86e06/ISO-DTS-23690.pdf>

- What it shows and why it matters: Defines a method (TGA under CO<sub>2</sub>) to quantify **carbon impurities in MWCNT samples**, explicitly noting that impurities affect nanomaterial properties—directly aligned to the ART’s constraint about **impurity control and repeatable quality** for structural reliability. [25]

#### 6) Multiscale nano-integration in the scarf-bonded patches for enhancing the performance of the repaired secondary load-bearing aircraft composite structures

- Authors/organisation: Serra Topal[26] et al.

- Venue/type: Peer-reviewed paper in Carbon[27]

- Publication date: Feb 2023

- Link: <https://www.sciencedirect.com/science/article/abs/pii/S0008622322010983>

- What it shows and why it matters: Demonstrates **upscaled integration** of thermally exfoliated graphene oxide and a CNT epoxy masterbatch (Epocyl 128-06) into scarf repair patches; reports stiffness recoveries of **~109.9%, 99.7%, and 99.3%** (depending on nano-integration strategy), supporting plausibility for **interfaces/joints/repairs**—a known weak point for composites. [28]

#### 7) Computer vision and machine learning for assessing dispersion quality in carbon nanotube / resin systems

- Authors/organisation: Henry P. Diehl[29] et al.

- Venue/type: Peer-reviewed paper in Carbon (same journal as above; not repeated as entity)

- Publication date: Sep 2023

- Link: <https://www.sciencedirect.com/science/article/abs/pii/S000862232300475X>

- What it shows and why it matters: Trains a computer-vision model on segmented microscopy images to rapidly, quantitatively assess **dispersion quality** in CNT-loaded commercial resins, claiming accuracy/repeatability comparable to current methods—direct evidence for **process control/inspection** needed for scaling. [8]

#### 8) Hierarchical toughening and self-diagnostic interleave for composite laminates manufactured from industrial carbon nanotube masterbatch

- Authors/organisation: Biltu Mahato[30] et al.

- Venue/type: Peer-reviewed paper in Composites Science and Technology[31]

- Publication date: 20 Oct 2023

- Link: <https://www.sciencedirect.com/science/article/abs/pii/S0266353823003354>

- What it shows and why it matters: Uses an **industrially available CNT masterbatch** painted onto prepregs to create conductive interleaves for **damage self-diagnostics** during double-cantilever-beam tests; also shows a key maturity caveat: a **0.6 wt%** interleave *reduced* Mode-I toughness (~80% detrimental), whereas **7.5 wt%** improved initiation (~27%)—highlighting that scalable formulations exist but robustness/process windows remain immature. [32]



### 9) Improved interlaminar property of carbon fiber/epoxy composites with polyurethane/RGO core-shell structure fibrous mat

- Authors/organisation: Nan Zheng[33] et al.
- Venue/type: Peer-reviewed paper in Composites Communications[34]
- Publication date: Dec 2023
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S2452213923002565>
- What it shows and why it matters: Reports interlaminar gains from an electrospun PU veil decorated with reduced graphene oxide: **Mode-I toughness +170%, Mode-II toughness +21%, and interlaminar shear strength +14%**, supporting the ART's claim that nano-reinforcements can bridge/deflect cracks and raise delamination resistance using laminate-compatible interleaves. [35]

### 10) In-situ monitoring of crack growth and fracture behavior in composite laminates using embedded sensors of rGO coated fabrics and GnP paper

- Authors/organisation: Mohamed Salman Sikandar Bathusha[36] et al.
- Venue/type: Peer-reviewed paper (bibliographic record in institutional repository)
- Publication date: 2024 (repository record lists "01.01.2024"; journal volume 365)
- Link: <https://khazna.ku.ac.ae/en/publications/in-situ-monitoring-of-crack-growth-and-fracture-behavior-in-compo/>
- What it shows and why it matters: Reports use of **rGO-coated fabric** and **graphene nanoplatelet paper** as embedded sensors for in-situ crack/fracture monitoring in laminates—directly aligned to the ART's embedded-sensing pathway (conductive reinforcement as a sensing network). [37]

### 11) Monitoring of static and vibration responses of laminated composite materials using integrated carbon nanotube fibers

- Authors/organisation: Jandro L. Abot[38] et al.
- Venue/type: Peer-reviewed paper (Composites Science and Technology; journal entity already introduced)
- Publication date: 26 Jul 2024
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S0266353824002641>
- What it shows and why it matters: Demonstrates CNT yarn/fibre sensors integrated into glass-fibre/epoxy laminates; sensors track deformation **instantaneously** via electrical resistance under four-point bending and capture sinusoidal vibration cycles, supporting feasibility of **continuous condition monitoring** without heavyweight instrumentation. [39]

### 12) Structural Health Monitoring of GFRP laminates with CNT-coated glass fiber sensing layer after low-velocity impact using Electrical Resistance Tomography

- Authors/organisation: Zijie Zhao[40] et al.
- Venue/type: Peer-reviewed open-access paper in Nanomaterials[41]
- Publication date: Published 09 Sep 2024
- Link: <https://www.mdpi.com/2079-4991/14/17/1462>
- What it shows and why it matters: Embeds an MWCNT-coated glass-fibre sensing layer and uses ERT to localise impact damage; reports **~4.5% error** in detected damage area and notes the sensing layer does not adversely affect impact response (with a nuance: energy absorption behaviour occurs ~10% earlier), evidencing progress toward usable SHM-enabled composites. [42]

### 13) Damage monitoring on inter-lamination of GFRP via the resistance change of the MWCNT@GF sensor

- Authors/organisation: Changfu Tang[43] et al.
- Venue/type: Peer-reviewed paper (Composites Communications; journal entity already introduced)
- Publication date: Dec 2024
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S2452213924003280>
- What it shows and why it matters: Embeds a PVD-manufactured MWCNT-coated glass-fibre sensor within laminates and correlates resistance changes with interlaminar shear damage, including monotonic and cyclic tests; claims a quantitative relation between shear damage and relative resistance—supporting the ART’s “self-reporting delamination/damage” potential. [44]

### 14) Versatile fabrication of CNT yarn composites by in-situ interfacial polymerization of polyetherimide

- Authors/organisation: Michael N. Durso[45] et al.
- Venue/type: Peer-reviewed paper in Composites Part B: Engineering[46]
- Publication date: Dec 2024
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S1359836824005821>
- What it shows and why it matters: Addresses a core scale-up issue (infiltrating nanoporous CNT networks) using in-situ interfacial polymerization; reports specific stiffness up to **142 N/tex** and tenacity **2.2 N/tex**, and demonstrates a **prototype roll-to-roll** apparatus for continuous processing—strong evidence for manufacturability beyond benchtop. [47]

### 15) Effective interlaminar toughening of CFRP laminate by extremely low loadings of monolayer graphene oxide

- Authors/organisation: Chongyang Gao[48] et al.
- Venue/type: Peer-reviewed paper (publisher preview via ResearchGate; paper in Polymer Composites[49])
- Publication date: Accepted 10 Oct 2024; journal issue year shown as 2025
- Link: [https://www.researchgate.net/publication/385425990\\_Effective\\_interlaminar\\_toughening\\_of\\_carbon\\_fiberepoxy\\_composite\\_laminates\\_by\\_extremely\\_low\\_loadings\\_of\\_monolayer\\_graphene\\_oxide](https://www.researchgate.net/publication/385425990_Effective_interlaminar_toughening_of_carbon_fiberepoxy_composite_laminates_by_extremely_low_loadings_of_monolayer_graphene_oxide)
- What it shows and why it matters: Uses an “ultrafine spraying” interlaminar method to distribute monolayer GO between CFRP plies; reports **Mode-I fracture toughness +140%** at extremely low GO loadings and frames this as a low-cost path with industrial scale-up potential—directly supporting the ART’s “large gains using familiar laminates/coatings” claim. [50]

### 16) Efficacy of carbon nanotube bucky paper for interlaminar damage sensing in composites and fibre-metal laminates

- Authors/organisation: Vinay Kumar[51] and Prabhat Agnihotri[52] et al.
- Venue/type: Peer-reviewed paper (publisher preview via ResearchGate; Polymer Composites)
- Publication date: Dec 2024 (ResearchGate metadata)
- Link: [https://www.researchgate.net/publication/386580108\\_Efficacy\\_of\\_carbon\\_nanotube\\_bucky](https://www.researchgate.net/publication/386580108_Efficacy_of_carbon_nanotube_bucky)

\_paper\_for\_interlaminar\_damage\_sensing\_in\_composites\_and\_fiber-metal\_laminates

- What it shows and why it matters: Demonstrates CNT bucky-paper interleaves for strain/damage sensing; reports sensor strain accuracy comparable to a commercial **120  $\Omega$  strain gauge** and shows delamination detection as a steep resistance rise across multiple laminate types including GLARE, supporting multi-material applicability. [53]

### 17) Self-sensing composites with damage mapping using 3D carbon fibre grid

- Authors/organisation: G. Jovarauskaite[54] et al.

- Venue/type: Peer-reviewed paper (Composites Part B: Engineering; journal entity already introduced)

- Publication date: 15 Apr 2025

- Link: <https://www.sciencedirect.com/science/article/abs/pii/S1359836825000721>

- What it shows and why it matters: Develops sandwich composites combining 3D carbon-fibre grids and CNT-modified conductive layers; maps damage area/size via **local electrical resistance deviation**, comparing sensitivity across **0.1–0.5 wt% CNT**—a concrete prototype of “electrically readable damage maps” for aerospace and wind blades. [55]

### 18) Galvorn Data Sheet

- Authors/organisation: DexMat[56]

- Venue/type: Vendor technical doc (data sheet)

- Publication date: Aug 2025

- Link: [https://dexmat.com/wp-content/uploads/Galvorn-Data-Sheet\\_20AUG2025.pdf](https://dexmat.com/wp-content/uploads/Galvorn-Data-Sheet_20AUG2025.pdf)

- What it shows and why it matters: Provides quantified properties for CNT fibre/yarn forms (e.g., conductivity, tensile strength, modulus, available lengths) and explicitly notes customers use CNT fibre tows for “electrodes, sensors, composites”; a sign that **CNT-based “engineered fabric” reinforcements** are already in product form factors, even if structural qualification remains application-specific. [57]

## 3. Maturity score (1–7) and reasoning

### A) Final maturity score: 4

### B) Evidence-to-rubric mapping

- **What evidence rules out levels 1–3 (the “lab principle only” region)**
- Multiple peer-reviewed studies demonstrate **functional laminate-level prototypes** that simultaneously deliver (i) mechanical delamination/toughening benefits and/or (ii) electrically enabled sensing/damage monitoring in representative composite architectures. Examples include PU/RGO interleaves with **Mode-I +170%** and shear strength gains in carbon/epoxy laminates, and monolayer GO interlaminar modification with **Mode-I +140%** improvements. [58]
- Embedded sensing is demonstrated with quantified localisation performance, e.g., ERT-based impact damage mapping with **~4.5% area error** in CNT-coated fibre sensing layers. [59]
- Industrially oriented integration paths are explicitly tested, such as using an **industrial CNT masterbatch** for interleaves and performing in-situ resistance measurements during fracture tests—moving beyond “principle shown” into “prototype in a manufacturing-relevant form factor”. [32]
- **Why the evidence supports level 4 (PoC) rather than level 5+**

- Level 4 requires a functional PoC that plausibly meets commercial requirements (functionality and viability for production). The dossier contains repeated PoCs for key claims:
  - **Structural repair/joint interface performance** with nano-integration demonstrated in a repair-relevant geometry (scarf patches) showing near-complete stiffness recovery. [28]
  - **Self-diagnostic / self-sensing** laminate concepts demonstrated under indentation/impact/delamination tests and correlated with DIC/tomography or resistance mapping. [60]
  - **Scale-up enablers** like dispersion QC via ML for CNT-resin systems and prototype continuous (roll-to-roll) processing for CNT yarn composites. [61]
- However, the sources do **not** provide strong, direct evidence that multiple well-capitalised actors are already competing with near-finished **production prototypes for structural aerospace/automotive primary parts**, nor do they show **increasing customer deliveries** of structural components at scale (levels 5–7). Instead, the evidence is dominated by lab-to-pilot demonstrations, methods papers, and enabling standards work. [62]
- A key “missing maturity” signal is that performance can be **highly formulation-dependent** and even negative in some conditions (e.g., the CNT masterbatch interleave at 0.6 wt% showing ~80% detrimental effect on Mode-I toughness). This kind of sensitivity indicates that robust process windows, qualification datasets, and production consistency are still being stabilised—more consistent with PoC than near-market production. [32]
- **What is still missing to justify the next higher level (5)**
- Public evidence of **production-prototype programmes** (e.g., automotive/aerospace supplier qualification campaigns, standardised test allowables, certified manufacturing routes) plus clear investment activity specific to **structural CNT/graphene-reinforced composite parts**, not only sensing concepts. [63]
- Demonstrated **field trials / service exposure** showing durability under environment (moisture, thermal cycling, fatigue spectrum loading) with quantified maintenance/inspection reductions enabled by embedded sensing. Current sources focus mostly on lab tests (DCB, impacts, cyclic bending rigs). [64]
- Clear evidence of **repeatable quality at scale** (batch-to-batch control, supplier specs, inline inspection deployment). There are strong “enablers” (ML dispersion QC; ISO characterisation/purity standards), but not yet a mature ecosystem of widely adopted industrial standards and audited supply chains for structural composites. [65]

### C) Sub-component maturity breakdown and aggregation

- **Interlaminar toughening with CNT/graphene interleaves (delamination resistance)**  
→ 4
- Evidence: large improvements in interlaminar fracture properties are demonstrated in laminate architectures (PU/RGO interleaves; GO ultrafine spraying) and a scalable industrial masterbatch route is tested, but results remain process-sensitive. [66]
- **Self-sensing / damage localisation via electrical resistance mapping** → 4

- Evidence: ERT-based impact damage localisation with quantified error; resistance-based shear damage evaluation; damage mapping in sandwich composites across CNT loadings. [67]
- **Scale-up enablers: dispersion QC + continuous processing → 4–5 (leaning 4)**
- Evidence: ML-based dispersion assessment suitable for in-line QC; roll-to-roll prototype processing for CNT yarn composites suggests manufacturability, but widespread industrial adoption isn't demonstrated in these sources. [61]
- **Standards / metrology / safety envelope (graphene/CNT characterisation and handling) → 3–4**
- Evidence: new ISO graphene characterisation work item and CNT impurity quantification methods; NIOSH sampling guidance. These are necessary underpinnings but don't alone demonstrate market readiness. [9]

**Aggregation to one score:** The ART's core functionality (lightweight structural reinforcement + self-sensing) is largely shared across variants; most critical elements cluster around mature PoC demonstrations with incomplete evidence of production scaling and field deployment. Therefore, the overall single score is set to **4**. [68]

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## ART 07.051 Smart Thermal Materials for Energy-Efficient Heating & Cooling

### ART extraction

#### A) Primary capability the ART claims

- Retrofittable materials that **dynamically manage heat flow** (block, spread, store/release, or radiate heat) to reduce heating/cooling energy demand and improve thermal safety/comfort. [1]
- A **portfolio/suite approach**: layered insulations + coatings + thermal interface layers + embedded structures, increasingly coordinated with sensing/control (semi-passive to actively switchable). [2]
- **Peak load and temperature stabilisation** via latent thermal storage (phase-change cycling) and dynamic envelope behaviour (switchable insulation / “thermal valve” behaviour). [3]

#### B) Key sub-components / variants (sub-threads)

- **Switchable thermal resistance / “thermal valves”** (electrically or thermally triggered thermal conductivity switching; electrochemical thermal switches). [4]
- **Phase change materials (PCMs)** for load shifting/peak shaving in buildings and HVAC add-ons (ceiling tiles, wallboards, heat exchangers). [5]
- **Superinsulation**: vacuum insulation panels (VIPs) and their ageing/declared performance; thin high-R retrofits. [6]
- **Aerogel-based insulations** (blankets/composites) targeting thin, hydrophobic, high-temperature, mechanically robust insulation. [7]
- **Radiative cooling coatings/films** (passive daytime radiative cooling; durable, scalable paints/coatings; building field tests; appliance integration). [8]
- **Thermal interface materials (TIMs)** including phase-change TIMs for robust heat transfer at interfaces (electronics/modules; transferable concept to industrial thermal interface pads). [9]
- **Variable-emissivity (“smart radiative”) surfaces** (electrochromic IR modulation at large area form factors). [10]

#### C) Maturity indicators that would count as evidence

- **Measured performance vs baselines**: thermal conductivity switching ratios/widths, emissivity modulation ( $\Delta\epsilon$ ), sub-ambient cooling ( $\Delta T$ ), building energy savings (%), R-values/ $\lambda$ -values, cycle life, ageing drift. [11]
- **Durability and compliance evidence**: repeatable cycling, outdoor exposure stability, ageing/edge effects for VIPs, fire class ratings, standards-referenced testing. [12]
- **Field deployments / operational trials** (occupied building retrofits; long-term roof tests; appliance integration). [13]

- **Commercial product signals:** dated datasheets/brochures, “shipping option” features (e.g., factory-applied TIM), multiple vendors with comparable offerings. [14]
- **Roadmaps / programs / multi-country consortia** (evidence of sustained funded effort and standardisation pathways). [15]

## 2. Evidence (10–20 recent, reliable sources)

### 1) **Techno-Economic Analysis of Dynamic Building Envelopes Comprising Phase Change Materials and Switchable Insulations (Preprint)**

- Authors/Org: National Renewable Energy Laboratory[16]
- Venue/type: Government lab conference paper / preprint
- Publication date: **January 2023**
- Link: <https://docs.nrel.gov/docs/fy23osti/82623.pdf>
- Reports a techno-economic framing for **dynamic envelopes combining PCMs and “switchable” insulation** to better exploit ambient/free heating-cooling and improve load shifting, directly supporting the ART’s “thermal valve + thermal storage” plausibility at building scale. [17]

### 2) **Retrofittable Thermal Switches for Dynamic Building Envelopes Integrated with Thermal Energy Storage: Preprint**

- Authors/Org: U.S. Department of Energy Building Technologies Office[18] + National Renewable Energy Laboratory[16]
- Venue/type: Government lab conference paper / preprint
- Publication date: **October 2024** (presented Aug 2024)
- Link: <https://docs.nrel.gov/docs/fy25osti/89100.pdf>
- Directly targets **retrofittable “thermal switch” concepts** integrated with latent storage (PCMs), which is a close match to the ART’s suite idea (insulation ↔ heat flow switching + storage). [19]

### 3) **Technology Strategy Assessment – Thermal Energy Storage**

- Authors/Org: U.S. Department of Energy[20]
- Venue/type: Authoritative government strategy/report
- Publication date: **July 2023**
- Link: <https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Thermal%20Energy%20Storage.pdf>
- Positions TES (including **latent storage**) as a pathway to reduce peak demand and enable flexibility in buildings, supporting the ART’s value proposition and signalling sustained programme interest. [21]

### 4) **Energy Storage TCP Annual Report 2023** (Task 40: Compact Thermal Energy Storage)

- Authors/Org: International Energy Agency[22] (Energy Storage TCP)
- Venue/type: Authoritative international programme report
- Publication date: **June 2024** (report release shown)
- Link: [https://iea-es.org/wp-content/uploads/public/ES\\_TCP\\_Annual\\_Report\\_2023.pdf](https://iea-es.org/wp-content/uploads/public/ES_TCP_Annual_Report_2023.pdf)
- Documents a multi-country collaboration focused on **characterisation, degradation, and state-of-charge determination** for compact TES (PCM/TCM), mapping strongly to the ART’s constraints around cycling drift and monitoring/control. [23]

**5) A phase change material (PCM) based novel retrofitting approach in the air conditioning system to reduce building energy demand**

- Authors/Org: Rahul Kumar Sharma[24] et al.
- Venue/type: Peer-reviewed paper (Applied Thermal Engineering)
- Publication date: **1 February 2024**
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S1359431123019014>
- Demonstrates an HVAC retrofit using a **PCM heat-exchanger** approach and reports a **peak energy saving of ~12%** in the studied configuration—evidence that “heat storage without bulky tanks” can work in conventional systems. [25]

**6) Energy performance of an operational government building retrofitted with ceiling phase change material tiles in a mixed-humid climate**

- Authors/Org: Sajith Wijesuriya[26] et al.
- Venue/type: Peer-reviewed paper (Energy and Buildings)
- Publication date: **1 March 2025**
- Link: <https://www.sciencedirect.com/science/article/abs/pii/S037877882500043X>
- Provides rare **operational-building retrofit evidence** for PCM ceiling tiles, addressing maturity indicators beyond lab tests (real schedules/loads, practical retrofit constraints). [27]

**7) From lab to building: Real-world integration of phase change materials for comfort, energy, and flexibility**

- Authors/Org: Shady Attia[28] et al.
- Venue/type: Peer-reviewed paper (Energy and Buildings)
- Publication date: **1 February 2026**
- Link: <https://orbi.uliege.be/handle/2268/338044>
- Synthesises evidence from **eight full-scale monitored buildings** (explicitly framed at **TRL 6–9**), supporting that PCM retrofits are beyond theory and increasingly evaluated in real deployments. [29]

**8) High-performance solid-state electrochemical thermal switches with earth-abundant cerium oxide**

- Authors/Org: Ahnong Jeong[30] et al. (Hokkaido University[31]; The University of Tokyo[32])
- Venue/type: Peer-reviewed paper (Science Advances)
- Publication date: **January 2025**
- Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11691636/>
- Demonstrates an electrically switched thermal device with  **$\kappa$  changing from ~2.2 to ~12.5 W/m·K** (on/off ratio **5.8**) over **100 cycles**, supporting feasibility of “thermal valves” albeit currently in specialised device form factors. [33]

**9) Observation of solid-state bidirectional thermal conductivity switching in antiferroelectric lead zirconate (PbZrO<sub>3</sub>)**

- Authors/Org: Kiumars Aryana[34] et al.
- Venue/type: Peer-reviewed paper (Nature Communications)
- Publication date: **23 March 2022**
- Link: <https://www.nature.com/articles/s41467-022-29023-y>
- Reports solid-state thermal conductivity modulation including an **~10% decrease under electrical bias** and **~25% increase under heating**, reinforcing plausibility of stimulus-

responsive “thermal switching” materials while highlighting early-stage integration challenges. [35]

#### 10) Flexible and large-area electrochromic infrared devices with superior modulation functionality

- Authors/Org: Zongtao Zhang[36] et al.

- Venue/type: Peer-reviewed paper (Chemical Engineering Journal)

- Publication date: **15 January 2025**

- Link:

<https://www.sciencedirect.com/science/article/abs/pii/S1385894724104445>

- Shows large-area-compatible IR electrochromic devices with emissivity tuning ( $\Delta\epsilon \sim 0.56$  in **8–14  $\mu\text{m}$** ) and a reported **radiative temperature modulation of  $\sim 10.9^\circ\text{C}$** , supporting the ART’s “tunable radiative loss” pathway (still prototype maturity). [10]

#### 11) Analysis of the thermal and energy saving performance of the concrete roof with radiative cooling coating

- Authors/Org: Qingdong Xuan[37] et al.

- Venue/type: Peer-reviewed paper (Journal of Building Engineering)

- Publication date: **15 July 2025**

- Link:

<https://www.sciencedirect.com/science/article/abs/pii/S2352710225008150>

- Long-term **field tests on an in-service office building** report up to **20% electricity reduction** under identical A/C settings and large roof surface temperature reduction, directly supporting maturity via real-world building evidence. [38]

#### 12) Daytime radiative cooling coating for cooling energy efficiency of conventional air conditioners

- Authors/Org: Zheng Yang[39] et al.

- Venue/type: Peer-reviewed paper (Applied Thermal Engineering)

- Publication date: **15 February 2025**

- Link:

<https://www.sciencedirect.com/science/article/abs/pii/S1359431124027285>

- Integrates a passive sub-ambient radiative cooling coating into **real A/C external units** and reports improved cooling energy efficiencies (e.g.,  **$\sim 12\text{--}13\%$**  depending on system type), evidencing “retrofit coating” viability in conventional equipment. [40]

#### 13) Water-Based Hydrophobic Paints for Daytime Radiative Cooling

- Authors/Org: Abdulrahman K. Aljwirah[41] et al.

- Venue/type: Peer-reviewed paper (ACS Applied Materials & Interfaces)

- Publication date: **21 May 2025**

- Link:

[https://engineering.purdue.edu/NANOENERGY/publications/Aljwirah\\_ACS%20AMI\\_2025.pdf](https://engineering.purdue.edu/NANOENERGY/publications/Aljwirah_ACS%20AMI_2025.pdf)

- Demonstrates **water-based, low-VOC** radiative-cooling paint formulations with reported **daytime sub-ambient cooling ( $\sim 2.7^\circ\text{C}$ )**, addressing manufacturability/safety barriers that often block scaling for coatings. [42]

#### 14) Vacuum Insulation Panel: Evaluation of Declared Thermal Conductivity Value and Implications for Building Energy

- Authors/Org: Fred Edmond Bofo[43] et al.
- Venue/type: Peer-reviewed paper (Energies, open access)
- Publication date: **7 August 2023**
- Link: <https://www.mdpi.com/1996-1073/16/15/5841>
- Quantifies VIP ageing/declared performance: reports mean centre-of-panel  $\lambda$  around **0.0042 W/(m·K)** and shows how different declared/aged  $\lambda$  metrics materially affect energy modelling outcomes—key for long-term reliability claims. [44]

#### 15) **va-Q-vip – Technical Data Sheet**

- Authors/Org: va-Q-tec[45]
- Venue/type: Vendor technical doc (dated datasheet)
- Publication date: **7 February 2023**
- Link: [https://www.va-q-tec.com/wp-content/uploads/pimcore-2/230207\\_va-Q-vip\\_English.pdf](https://www.va-q-tec.com/wp-content/uploads/pimcore-2/230207_va-Q-vip_English.pdf)
- Provides productised VIP metrics (e.g., initial thermal conductivity at delivery  $\leq$  **0.0050 W/(m·K)** at 10 °C; stated lifetime “up to 60 years” depending on usage), supporting that VIPs are already market-delivered superinsulation components. [46]

#### 16) **Panasonic ADVANC-R® Vacuum Insulation Panel (VIP) – Product Brochure**

- Authors/Org: Panasonic[47]
- Venue/type: Vendor technical doc (product brochure with standards references)
- Publication date: **August 2023**
- Link: <https://www.holcimelevate.com/content/dam/elevateamericas/migrated-document/us/en/60/605976.pdf>
- Describes a building-focused VIP product with centre-of-panel **R-value 66** (reported) and **Class A** flame/smoke rating, indicating commercial offerings exist that fit retrofit constraints (thin, high-R). [48]

#### 17) **Spaceloft® Subsea insulation system – Product data sheet (Rev 5.2)**

- Authors/Org: Aspen Aerogels[49]
- Venue/type: Vendor technical doc (dated revision/year)
- Publication date: **2024** (©2024; Rev 5.2)
- Link: [https://www.aerogel.com/wp-content/uploads/2025/01/Spaceloft-Subsea-datasheet-updated-V2\\_2024\\_v5.2.pdf](https://www.aerogel.com/wp-content/uploads/2025/01/Spaceloft-Subsea-datasheet-updated-V2_2024_v5.2.pdf)
- Shows mature, field-deployed aerogel insulation with thermal conductivity values on the order of **~13–19 mW/(m·K)** across temperatures and claims **>1 million km of pipelines insulated**, indicating substantial real-world deployment (albeit in industrial subsea contexts). [50]

#### 18) **ArmaGel HT – Technical Datasheet**

- Authors/Org: Armacell[51]
- Venue/type: Vendor technical doc (dated datasheet)
- Publication date: **9 January 2026**
- Link: <https://www.armacell.com/sites/default/files/2026/01/09/ArmaGel%20HT%20-%20Technical%20Datasheet%20-%20en-US.pdf>
- Documents a commercial aerogel blanket rated for **up to 650 °C** and compliance to an insulation material standard (ASTM C1728), aligning with the ART’s “thin superinsulation within existing workflows” and durability/fire constraints. [52]

### 19) Fabrication of flexible silica aerogel composite blankets from an aqueous fumed silica-based slurry

- Authors/Org: Shunyao Zhang[53] et al.
- Venue/type: Peer-reviewed paper (Science China Materials)
- Publication date: **5 March 2024**
- Link: <https://link.springer.com/article/10.1007/s40843-023-2787-5>
- Demonstrates a lower-complexity route (ambient drying + slurry impregnation/roller pressing) to flexible aerogel blankets and reports **thermal conductivity ~0.046 W/m·K** (monolith) and **~0.054 W/m·K at 800 °C** (optimised blanket), supporting manufacturability improvements. [54]

### 20) Hydrophobic phenolic/silica aerogel composites with high fire safety and strength for efficient thermal insulation

- Authors/Org: Yonghua Wang[55] et al.
- Venue/type: Peer-reviewed paper (RSC Advances; open via PMC)
- Publication date: **5 November 2025**
- Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12587478/>
- Reports an aerogel composite targeting key constraints (moisture + mechanical + high-temperature stability), including **very low reported thermal conductivity (~0.021 W/m·K)** and strong hydrophobicity, addressing durability/fire-performance bottlenecks relevant to building-scale materials. [56]

## 3. Maturity score (1–7) and reasoning

### A) Final maturity score: 5

### B) Why this rules out lower levels, and what blocks a higher level

A score below **4** is ruled out because multiple elements of the ART are already **beyond lab prototype**: there are **operational-building retrofits** using PCMs (not just test cells), and there are **long-term field tests** of radiative cooling coatings on real buildings and conventional A/C equipment with quantified energy/performance impacts. [13]

A score below **5** is also difficult to justify because several sub-threads already have **market-delivered, dated technical documentation** (VIPs and aerogel blanket products with standardised properties and installation/ratings), and multiple well-capitalised industrial actors exist in these categories—indicating the space is already in production-prototype or product phases for parts of the suite. [57]

A score of **6** for the ART *as a whole* is not supported yet because the “smart thermal materials” concept in the prompt is explicitly a **coordinated suite** including **dynamic switching (“thermal valves”)** and sensor/control-aware operation at scale; the strongest thermal-switch evidence remains in specialised device demonstrations (e.g., electrochemical  $\kappa$ -switching with defined cycling limits) rather than widely deployed building/appliance-grade products with standardised durability + cost/performance-at-scale validation. [4]

A score of **7** would require evidence that competing *integrated* solutions are being delivered broadly with rising demand and largely internally financed growth across the whole suite; the evidence base here shows a mixed landscape: **superinsulation and aerogel blankets are**



**strongly commercial**, but **dynamic thermal switching and large-area variable-emissivity control** remain closer to R&D/prototype stages. [58]

### C) Sub-scores (bundle components) and aggregation approach

Because the ART bundles materially different mechanisms and markets (envelope superinsulation vs latent storage vs dynamic switching vs radiative coatings), an **average-based** assessment is most defensible.

- **Superinsulation (VIPs) → 6**
- Evidence: commercial VIP datasheets with quantified  $\lambda/R$  and building-target packaging/fire ratings. [59]
- **Aerogel insulation blankets → 6**
- Evidence: vendor datasheets showing high-temperature aerogel blanket products; also a vendor-documented large deployment footprint in industrial contexts. [60]
- **PCM-based thermal storage in building retrofits → 5–6**
- Evidence: operational building retrofit studies and synthesis of full-scale monitored buildings at TRLs 6–9; still not uniformly mainstream. [61]
- **Radiative cooling coatings/films → 4–5**
- Evidence: long-term in-service building roof field tests and appliance integration with quantified energy-efficiency improvements; still limited proof of mass-market standardisation/durability across many climates and suppliers. [8]
- **Dynamic “thermal valves” / thermal conductivity switching materials → 3–4**
- Evidence: peer-reviewed demonstrations of  $\kappa$ -switching (electrochemical and ferroic systems) with cycling evidence, but not yet broadly packaged for commodity building/HVAC retrofits. [62]
- **Large-area variable-emissivity IR control (electrochromic IR devices) → 4**
- Evidence: large-area-compatible prototypes with strong  $\Delta\epsilon$  and durability claims in a peer-reviewed venue, but not yet established as a scaled building product category. [10]

**Aggregation:** Averaging the above sub-scores yields an overall maturity around the **mid-5 range**, and the bundle’s “smart coordinated suite” character (dynamic switching + monitoring + scalable durability) is not yet consistently at product-delivery scale, so the consolidated score is set to **5**. [63]

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<https://docs.nrel.gov/docs/fy25osti/89100.pdf>

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## ART 07.052 Rare-Earth-Free Magnets for Sustainable Motors

### . ART extraction

- **Primary capability (what the ART claims)**
- Rare-earth-free **permanent magnets** that can be used in efficient electric motors (and related rotating machines) while reducing dependence on Nd-Fe-B supply chains and associated price/availability volatility. [1]
- A **practical family** of magnet materials spanning performance tiers (e.g., “good-enough” torque density via motor/topology optimisation; higher-temperature stability; lower cost; improved corrosion resistance), with industrially interpretable specifications. [2]
- **Manufacturability via familiar routes** (powders → sintered blocks, bonded shapes, additively manufactured parts) to minimise retooling and accelerate adoption. [3]
- **Key sub-threads / variants**
- **Ferrite** (Sr/Ba hexaferrite) magnets + motor topologies that compensate for lower remanence (e.g., spoke rotors, PM-assisted SynRM). [4]

- **MnBi** magnets (notable for coercivity increasing with temperature) in bonded and bulk/warm-sintered forms; microstructure/grain-boundary engineering to reduce coercivity loss upon densification. [5]
- **MnAl ( $L1_0$  /  $\tau$ -MnAl, often Mn–Al–C)** magnets; twin suppression, grain/particle size control, texture development; emerging manufacturing (e.g., LPBF). [6]
- **Iron nitride ( $\alpha$ "-Fe<sub>16</sub>N<sub>2</sub>)** magnets; low-temperature consolidation and alignment/bonding strategies to address metastable phase decomposition. [7]
- **FeNi (tetrataenite  $L1_0$ -FeNi)** and FeNi-inspired microstructures; thin-film synthesis routes; contested bulk-casting claims and subsequent corrections/retractions. [8]
- **System-level “compensation”**: geometry, thermal management, demagnetisation-robust designs, and control strategies that allow lower-Br magnets to meet application specs. [9]
- **Maturity indicators that would count as strong evidence**
- **Materials performance**: measured coercivity ( $H_c/H_{cj}$ ), remanence ( $Br/M_r$ ), and/or energy product ( $(BH)_{max}$ ) at relevant temperatures; evidence of stability against demagnetisation and cycling. [10]
- **Process viability at scale**: demonstrable densification/texture routes (SPS, high-pressure compaction, bonded magnets, AM) that preserve critical phases and reduce defect rates. [11]
- **Prototype rotating machine results**: traction/industrial motor prototypes hitting meaningful output/efficiency and showing demagnetisation robustness. [12]
- **Field trials & reliability**: fatigue/endurance testing, operation in real industrial equipment, and repeatable quality profiles. [13]
- **Scaling signals**: participation of major magnet/motor manufacturers, funded multi-partner programmes, patents with concrete engineering detail, and movement toward mass production. [14]

## 2. Evidence (10–20 recent, reliable sources)

### 1) Production and characterization of compacted Fe<sub>16</sub>N<sub>2</sub> permanent magnets

- **Authors/Org**: Nilay Gunduz Akdogan[15] et al.
- **Type/Venue**: Peer-reviewed paper, *Acta Materialia*
- **Date**: Aug 2022
- **Link**: <https://doi.org/10.1016/j.actamat.2022.118064>
- **Why it matters (concise)**: Demonstrates rare-earth-free Fe<sub>16</sub>N<sub>2</sub> compacts made by **cold compaction (~1 GPa) plus annealing under higher pressure** to reach ~80% density while preserving Fe<sub>16</sub>N<sub>2</sub>, directly addressing manufacturability of metastable iron-nitride magnets. [16]

### 2) Production of Rare-Earth-Free Iron Nitride Magnets ( $\alpha$ "-Fe<sub>16</sub>N<sub>2</sub>)

- **Authors/Org**: Tetsuji Saito[17] et al.
- **Type/Venue**: Peer-reviewed paper, *Metals* (MDPI)
- **Date**: Jun 2024 (issue-dated)
- **Link**: <https://www.mdpi.com/2075-4701/14/6/734>
- **Why it matters (concise)**: Shows **low-temperature SPS/SPS-DC consolidation (373–573 K)** of Fe-N powders into magnets and reports measurable properties (e.g., saturation

magnetisation  $\sim 1.07$  T and coercivity  $\sim 0.20$  MA/m at 373 K for an SPS-DC sample), supporting plausibility but also highlighting temperature-stability constraints. [18]

### 3) Microstructural and Magnetic Evolution of $\alpha$ "-Fe<sub>16</sub>N<sub>2</sub> Bulk Magnets Consolidated by Spark Plasma Sintering

- **Authors/Org:** Marian Grigoras[19] et al.
- **Type/Venue:** Peer-reviewed paper, *Crystals* (MDPI)
- **Date:** Nov 2025
- **Link:** <https://doi.org/10.3390/cryst15110969>
- **Why it matters (concise):** Systematically maps SPS temperature/pressure trade-offs, reporting  **$\sim 80\%$  theoretical density**,  $M_s \sim 230$  A·m<sup>2</sup>/kg, and coercivity up to  $\sim 86.5$  kA/m under optimised conditions—useful evidence for process windows and remaining gaps to reach dense, high-(BH)<sub>max</sub> magnets. [20]

### 4) US20240047102A1 — Anisotropic iron nitride permanent magnets

- **Authors/Org:** Niron Magnetics, Inc.[21]
- **Type/Venue:** **Patent** (treat cautiously; engineering detail present)
- **Date:** Feb 2024
- **Link:** <https://patents.google.com/patent/US20240047102A1/en>
- **Why it matters (concise):** Claims concrete process concepts for **alignment and bonding** of iron-nitride nanoparticles (e.g., XRD intensity-ratio criteria, target squareness thresholds, and a method sketch with intrinsic coercivity ranges), indicating an industry push toward manufacturable rare-earth-free bonded magnets. [22]

### 5) Fabrication of L1<sub>0</sub>-ordered FeNi films by denitriding FeNiN(001) and FeNiN(110) films

- **Authors/Org:** Keita Ito[23] et al.
- **Type/Venue:** Peer-reviewed paper, *Journal of Alloys and Compounds*
- **Date:** Jun 2023
- **Link:** <https://doi.org/10.1016/j.jallcom.2023.169450>
- **Why it matters (concise):** Demonstrates a **denitridation route** to L1<sub>0</sub>-FeNi thin films and reports an FeNi long-range order parameter  **$S \approx 0.60$**  with  **$K_u \approx 0.55$  MJ/m<sup>3</sup>** for (110) films—strong plausibility evidence for anisotropy engineering, but still thin-film-limited for motor magnets. [24]

### 6) Origin of the high coercivity in FeNi inspired magnets

- **Authors/Org:** A. Hernando[25] et al.
- **Type/Venue:** Peer-reviewed paper, *Scientific Reports*
- **Date:** Jan 2026
- **Link:** <https://www.nature.com/articles/s41598-026-36990-5>
- **Why it matters (concise):** Reports FeNi-based microwires with **room-temperature coercivity  $\sim 440$  Oe** and argues the coercivity arises from microstructure/shape isolation rather than requiring L1<sub>0</sub>-FeNi—useful for plausibility (alternative hard-magnet pathways) but indicates performance still far below NdFeB-class levels. [26]

### 7) Direct Formation of Hard-Magnetic Tetrataenite in Bulk Alloy Castings (*retracted; include as contested evidence*)

- **Authors/Org:** Y. P. Ivanov[27] et al.
- **Type/Venue:** Peer-reviewed paper (**retracted**), *Advanced Science*
- **Date:** 2022 (received Jul 2022; retraction noted)

- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC9811435/>
- **Why it matters (concise):** Initially claimed bulk tetrataenite formation via casting at much higher cooling rates than meteorites, which—if true—would have been a major maturity jump; the paper is explicitly marked **retracted**, underscoring the difficulty of reproducible bulk FeNi hard-magnet synthesis. [28]

#### 8) Reinterpretation of Report of Tetrataenite in Bulk Alloy Castings

- **Authors/Org:** Owain S. Houghton[29] et al.
- **Type/Venue:** Peer-reviewed paper, *Advanced Science* (recorded in PubMed)
- **Date:** Epub Dec 2024 / Jan 2025 issue
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/39680740/>
- **Why it matters (concise):** Provides the corrective analysis: diffraction peaks and electron-diffraction reflections previously attributed to tetrataenite were instead linked to **(Fe,Ni)<sub>3</sub>P and oxidation**, and magnetic hysteresis showed **no expected high-coercivity regions**, lowering near-term maturity expectations for bulk FeNi magnets. [30]

#### 9) Roadmap towards optimal magnetic properties in L1<sub>0</sub>-MnAl permanent magnets

- **Authors/Org:** Yuxiao Jia[31] et al.
- **Type/Venue:** Peer-reviewed paper, *Acta Materialia*
- **Date:** Feb 2023
- **Link:** <https://doi.org/10.1016/j.actamat.2022.118654>
- **Why it matters (concise):** Proposes a manufacturing-relevant route to higher MnAl performance by suppressing twins via **grain/particle size < ~300 nm**, with analysis suggesting optimal coercivity at **~50–200 nm** and a pathway to higher texture (system-level readiness via predictable microstructure control). [32]

#### 10) Additive manufacturing of Mn–Al permanent magnets via laser powder bed fusion

- **Authors/Org:** (as cited in journal preview; author list not foregrounded in the abstract page)
- **Type/Venue:** Peer-reviewed paper, *Materialia* (Elsevier)
- **Date:** 2024
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S2589152923003058>
- **Why it matters (concise):** Demonstrates LPBF processing that converts  $\varepsilon \rightarrow \tau$  with annealing and reports measurable properties (e.g.,  $H_{ci} \approx 129$  kA/m and  $(BH)_{max} \approx 7.2$  kJ/m<sup>3</sup> along the print direction), providing plausibility evidence for **shape-flexible manufacturing** even though performance remains low vs mature magnet classes. [33]

#### 11) Engineering microstructure to improve coercivity of bulk MnBi magnet

- **Authors/Org:** Wei Tang[34] et al.
- **Type/Venue:** Peer-reviewed paper, *Journal of Magnetism and Magnetic Materials*
- **Date:** Sep 2022
- **Link:** <https://doi.org/10.1016/j.jmmm.2022.169912>
- **Why it matters (concise):** Addresses a core scaling blocker (coercivity collapse on densification): reports  $H_{cj}$  loss reduced **from ~70% to ~15%** by engineering non-magnetic grain-boundary phases, achieving **(BH)<sub>max</sub> ≈ 8.9 MGOe** in warm-sintered bulk MnBi—directly relevant to motor-grade material viability. [35]

#### 12) CMI scientists develop rare earth free magnet for use in industrial motors

- **Authors/Org:** Ames Laboratory[36] (with industry partners)
- **Type/Venue:** Authoritative national-lab project update (not peer-reviewed; used for maturity



signal)

- **Date:** May 2025

- **Link:** <https://www.ameslab.gov/news/cmi-scientists-develop-rare-earth-free-magnet-for-use-in-industrial-motors>

- **Why it matters (concise):** Reports a **MnBi bonded magnet** with high-temperature robustness (coercivity reportedly nearly doubles over a +100°C increase) and notes collaboration with an industrial partner testing the magnet in an **industrial pump motor**, progressing to **fatigue tests**—a meaningful step past lab coupon results. [37]

### 13) Ames Lab Technology Wins R&D 100 Award

- **Authors/Org:** Critical Materials Innovation Hub[38] / Ames Lab

- **Type/Venue:** Award/recognition notice (supporting maturity signal)

- **Date:** Aug 2025

- **Link:** <https://www.ameslab.gov/news/ames-lab-technology-wins-r-d-100-award>

- **Why it matters (concise):** Confirms external recognition for MnBi-based rare-earth-free permanent magnets and reiterates the high-temperature behavioural advantage (temperature-positive coercivity trend), suggesting progress toward application-relevant performance targets. [39]

### 14) Output exceeding 100 kW applicable for traction motors for BEVs and PHEVs verified on actual ferrite magnet motor

- **Authors/Org:** Proterial, Ltd.[40]

- **Type/Venue:** Industry technical release with measured prototype data (manufacturer doc)

- **Date:** Jul 2023

- **Link:** <https://www.proterial.com/e/press/2023/pdf/20230724en.pdf>

- **Why it matters (concise):** States that a high-performance ferrite magnet (NMFTM-15) was used to **build and evaluate an actual traction-motor prototype**, verifying **>100 kW output** (reported 102 kW measured) at up to **15,000 rpm**, showing rare-earth-free magnets can reach traction-relevant power in practice (with design trade-offs). [41]

### 15) Experimental Validation of a Spoke Type Ferrite Permanent Magnet Machine Design for Heavy-Duty Traction Applications

- **Authors/Org:** Marcelo D. Silva[42] et al.; affiliations include Uppsala University[43], Scania CV AB[44], Alstom[45]

- **Type/Venue:** Peer-reviewed paper, *IET Electric Power Applications* (open access)

- **Date:** Accepted Nov 2025 (received Apr 2025)

- **Link:** <https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/elp2.70133> (also mirrored PDF: <https://uu.diva-portal.org/smash/get/diva2:1950228/FULLTEXT01.pdf>)

- **Why it matters (concise):** Presents optimisation integrating demagnetisation and mechanical constraints and reports a **built and tested ferrite-PM spoke motor** intended to directly substitute a rare-earth motor of the same outer volume, with experimental results indicating demagnetisation resilience and **higher efficiency in field-weakening** than the REE baseline. [46]

### 16) Design, analysis and experimental evaluation of a novel high-speed high-power ferrite IPM machine for traction applications

- **Authors/Org:** (University of Sheffield collaboration; paper notes Innovate UK support)

- **Type/Venue:** Technical conference paper (measured prototype results)

- **Date:** 2022

- **Link:** [https://eprints.whiterose.ac.uk/id/eprint/192512/1/ECCE\\_conference-template\\_Khoa\\_Kais\\_GG\\_V3\\_Good.pdf](https://eprints.whiterose.ac.uk/id/eprint/192512/1/ECCE_conference-template_Khoa_Kais_GG_V3_Good.pdf)

- **Why it matters (concise):** Reports an **80 kW** ferrite IPM traction prototype (up to **12,000 rpm**) with measured vs FEA agreement and a stated **maximum efficiency of 97%**, supporting the “system-level compensation” thesis for rare-earth-free magnets in high-performance machines. [47]

#### 17) Sustainable ferrite permanent magnet fabrication: Recycling steel scale into high-performance strontium hexaferrite magnet

- **Authors/Org:** Kürşat İcin[48] et al.

- **Type/Venue:** Peer-reviewed paper, *Journal of the Indian Chemical Society*

- **Date:** Nov 2025

- **Link:** <https://doi.org/10.1016/j.jics.2025.102163>

- **Why it matters (concise):** Demonstrates a recycling-based ferrite supply route (steel scale +  $\text{SrCO}_3$ ) and reports magnetic properties including  **$H_c \approx 5526.6 \text{ Oe}$** ,  $M_r \approx 35.9 \text{ emu/g}$ ,  $M_s \approx 69.1 \text{ emu/g}$ , supporting plausibility of lower-impact manufacturing for scalable rare-earth-free magnets. [49]

#### 18) Emerging magnetic materials for electric vehicle drive motors

- **Authors/Org:** Christopher L. Rom[50] et al., National Renewable Energy Laboratory[51]

- **Type/Venue:** Authoritative review/roadmap-style article, *MRS Bulletin* (via NREL report PDF)

- **Date:** Jul 2024

- **Link:** <https://docs.nrel.gov/docs/fy24osti/88583.pdf>

- **Why it matters (concise):** Provides an expert synthesis of why many rare-earth-free candidates are **temperature-/process-sensitive** and argues that advances in **low-temperature synthesis/processing** are pivotal to commercialising alternatives beyond rare-earth magnets—directly supporting plausibility constraints and maturity bottlenecks. [52]

#### 19) Periodic Reporting (REFMAG): “Bulk rare earth free permanent magnets” (Horizon Europe project)

- **Authors/Org:** European Commission[53] (CORDIS project reporting)

- **Type/Venue:** Government/consortium programme evidence (multi-partner R&D)

- **Date:** Feb 2024 (reporting page)

- **Link:** <https://cordis.europa.eu/project/id/101069203/reporting>

- **Why it matters (concise):** Confirms an active EU-funded programme explicitly targeting **bulk rare-earth-free permanent magnets**, indicating geographically diverse investment and structured scaling pathways beyond single-lab demonstrations. [54]

#### 20) U.S. Department of Energy Critical Materials Assessment (2023)

- **Authors/Org:** U.S. Department of Energy[55]

- **Type/Venue:** Government assessment/roadmap context (supply-risk driver)

- **Date:** May 2023 (file-dated)

- **Link:** <https://www.energy.gov/sites/default/files/2023-05/2023-critical-materials-assessment.pdf>

- **Why it matters (concise):** Establishes the broader policy/industrial driver: criticality of materials and supply-chain risk as an explicit constraint on clean-energy deployment, strengthening the economic plausibility case for rare-earth-free magnet alternatives even if they require system redesign. [56]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 4

#### B) Why level 4 fits (mapping evidence → rubric)

- **What rules out levels 1–3 (i.e., why this is beyond “principle only” or “lab-prototype only”)**
- There is direct, application-context evidence of **functional motor prototypes** using rare-earth-free permanent magnets, including an established manufacturer reporting an **actual ferrite-magnet traction motor prototype** with **measured ~102 kW output** (traction-relevant scale). [\[41\]](#)
- Peer-reviewed experimental work shows **design + build + test** of rare-earth-free (ferrite) traction machines with strong efficiency claims and validated modelling/measurement agreement (e.g., **80 kW prototype**, stated **97% max efficiency**). [\[47\]](#)
- For non-ferrite alternatives, there is peer-reviewed progress on **manufacturing blockers** (e.g., MnBi bulk magnet densification preserving coercivity, with reported reduction of H<sub>cj</sub> loss from ~70% to ~15% and (BH)<sub>max</sub> ≈ 8.9 MGOe). [\[35\]](#)
- There is at least one credible signal of **industrial trial context** for MnBi bonded magnets (industrial pump motor testing progressing to fatigue testing), consistent with proof-of-concept use in a real machine environment. [\[57\]](#)

Taken together, these exceed “lab principle verified” and “lab prototype exists” because they include **system-level prototypes** and (in at least one case) **measured performance** at meaningful scale. [\[58\]](#)

- **What is still missing for level 5 (why not higher)**
- The evidence set does **not** consistently show that multiple rare-earth-free magnet chemistries (beyond ferrites) have reached production-prototype maturity with clearly disclosed **repeatable manufacturing yields, cost curves, and lifetime/quality metrics** at industrial scale. [\[59\]](#)
- Some of the most “NdFeB-replacement-aspirational” candidates have strong **scientific plausibility** but remain constrained by processing/phase-stability challenges (e.g., iron-nitride low-temperature consolidation constraints; FeNi tetrataenite bulk formation controversies), which is inconsistent with “production prototype in finishing phase.” [\[60\]](#)
- There is limited public evidence (within the strict 4-year window and using primarily technical sources) of **shipping products in increasing amounts** for these new rare-earth-free high-performance magnet families (rubric levels 6–7). [\[61\]](#)

#### C) Sub-component maturity snapshot and aggregation

- **Ferrite magnets + compensating motor topologies (spoke / PM-assisted SynRM / flux concentration) → 5 (upper-4 to 5)**
- Justification: multiple sources show traction-relevant prototypes and experimental validation, including manufacturer-reported **>100 kW** measured prototype results and peer-reviewed prototype testing/validation. [\[12\]](#)
- **MnBi permanent magnets for motor applications (bonded + bulk/warm-sintered) → 4**

- Justification: peer-reviewed work resolves a key manufacturing blocker (coercivity preservation in bulk) and credible national-lab reporting indicates early machine trials and fatigue testing, consistent with proof-of-concept in a relevant system. [5]
- **MnAl (L1<sub>0</sub>-MnAl) magnets → 3**
- Justification: strong materials roadmap and emerging manufacturing demonstrations exist (e.g., LPBF experiments), but reported energy products are still low in current demonstrations and broad production viability remains unproven. [6]
- **Iron nitride ( $\alpha$ "-Fe<sub>16</sub>N<sub>2</sub>) magnets → 3**
- Justification: multiple experimental papers show low-temperature densification routes and measured magnetic properties; patent activity indicates engineering direction, but compacts remain well short of dense, high-coercivity, high-(BH)max industrial magnets. [62]
- **FeNi tetrataenite / FeNi-inspired hard magnets → 2**
- Justification: thin-film anisotropy progress is real, but bulk manufacturing remains highly challenging; a recent high-profile bulk-casting claim was **retracted** and subsequent analysis supports that tetrataenite was not present, indicating the field is still in an early validation phase for bulk motor magnets. [63]

**Aggregation rationale to one score:** Because the ART explicitly describes a **family** spanning tiers (and the maturity differs strongly by chemistry and application), a simple average would under-represent the near-market ferrite pathway while over-representing very early-stage FeNi. The practical “whole-ART” readiness is best represented as **level 4**: at least one major tier (ferrite + topology compensation) is at/near late PoC to early production-prototype race, while the higher-performance rare-earth-free candidates are mostly prototype-stage with unresolved scale/manufacturing constraints. [64]

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<https://cordis.europa.eu/project/id/101069203/reporting>

## ART 07.053 Nano-Engineered Membranes for Low-Energy Desalination

### ART extraction

148. ART extraction

#### A) Primary capability claimed (what the ART aims to do)

- Deliver **higher water permeability at comparable salt rejection** in desalination-relevant membranes, so the same permeate quality can be achieved with **lower pressure/energy or fewer elements**.
- Extend **stable run time** by reducing fouling and scaling (less flux decline, better flux recovery) so plants need **less frequent cleaning and maintenance**.
- Maintain compatibility with **existing module/pressure-vessel hardware** (i.e., “drop-in” membrane element/cartridge form factors) while improving reliability and operability.

#### B) Key sub-components / variants

- **Nanostructured selective layers** (ultrathin polyamide variants, controlled nanovoids, “uniform pathways” via modified interfacial polymerisation or additives).
- **Thin-film nanocomposite (TFN) RO membranes** (nanofillers such as MOF nanosheets, graphene-derived additives, or other nanomaterials embedded in/near the polyamide layer).
- **Graphene-derived surface coatings/layers** (e.g., graphene oxide layers deposited/assembled with controllable density; “defect-coverage” coatings; tuned surface chemistry).
- **Anti-fouling / anti-scaling surface chemistries** (small-molecule grafting, methylation/charge control, hydrophilic or low-interaction-energy functional groups).
- **Manufacturing scale-up methods** (roll-to-roll casting/coating, large-area defect control, reproducibility, mechanical robustness under cyclic pressure).
- **Embedded monitoring / “smart” operation hooks** (sensing approaches for in-situ identification of concentration polarisation vs foulant deposition; improved control interfaces for cleaning cycles).

#### C) Maturity indicators that would count as strong evidence for this ART

- **Pilot-scale or roll-to-roll fabrication** (hundreds of m<sup>2</sup>-scale batches, reproducible performance across batches, not just lab coupons).
- **Desalination-relevant operating tests** (e.g., seawater-strength salinity and pressures; stable rejection; multi-cycle fouling/cleaning performance).
- **Demonstrated anti-fouling and/or anti-scaling metrics** (lower flux decline ratio, higher flux recovery ratio, longer cleaning intervals).
- **System-level energy/footprint analysis tied to membrane permeability** (quantified potential SEC reduction or pressure-vessel reduction with realistic constraints such as



concentration polarisation).

- **Commercial product evidence** (dated technical manuals/datasheets; large-scale orders/deployments; multiple major manufacturers involved).

## Evidence

149. Evidence (10–20 recent, reliable sources)

### 1) Pilot scale fabrication of low fouling seawater desalination thin film composite reverse osmosis membrane

**Author(s):** Parthapratim Bera[1] et al.

**Venue/type:** *Desalination* (peer-reviewed experimental paper)

**Date:** October 2024

**Link:** <https://doi.org/10.1016/j.desal.2024.117790>

**Why it matters:** Demonstrates **pilot-scale roll-to-roll** production (100 m<sup>2</sup>/batch) of a seawater TFC RO membrane where **PEG is incorporated during fabrication**, increasing pure water permeance from **1.4 to 2.2 LMH/bar** while maintaining **~98.4–98.8% NaCl rejection** and improving antifouling (flux recovery ratio **87% vs 67%**). [2]

### 2) Development and Industrial-Scale Fabrication of Next-Generation Low-Energy Membranes for Desalination

**Organisation/author(s):** Li May Goh[3] et al. (START, Nanyang Technological University—NTUitive)

**Venue/type:** *Membranes* (peer-reviewed “Communication”, strongly manufacturing-focused)

**Date:** May 2022

**Link:** <https://doi.org/10.3390/membranes12050540>

**Why it matters:** Provides an **industrial-scale fabrication method** that coats the PSf UF support directly onto a permeate carrier (removing non-woven backing), achieving **~9% leaf-thickness reduction** and reporting **defect-free RO membranes** with **94% salt rejection** and **40 LMH flux** (2000 mg/L NaCl, 15 bar)—concrete evidence toward **manufacturing/packaging innovations** that can lower energy by increasing membrane area per module volume. [4]

### 3) Thin film nanocomposite membrane incorporated with 2D-MOF nanosheets for highly efficient reverse osmosis desalination

**Author(s):** Yi Liu[5] et al.

**Venue/type:** *Journal of Membrane Science* (peer-reviewed experimental paper)

**Date:** July 2022

**Link:** <https://doi.org/10.1016/j.memsci.2022.120520>

**Why it matters:** Shows a TFN RO strategy using **ultrathin nickel-based 2D-MOF nanosheets**: water permeance increases to **50.0 L·m<sup>-2</sup>·h<sup>-1</sup>·MPa<sup>-1</sup>** (vs 20.6 baseline) while keeping **~99.2% NaCl rejection**, and reports strong antifouling behaviour (water permeance recovery ratio **96.9%** against humic acid). [6]

### 4) High-Performance Polyamide Reverse Osmosis Membrane Containing Flexible Aliphatic Ring for Water Purification

**Author(s):** Chi Jiang[7] et al.

**Venue/type:** *Polymers* (peer-reviewed experimental paper)

**Date:** February 2023

**Link:** <https://doi.org/10.3390/polym15040944>

**Why it matters:** Reports a modified interfacial-polymerisation chemistry (piperidine additive) achieving **2.96 LMH/bar** water permeance and **99.4% NaCl rejection**, plus an operational stability test showing performance remaining stable for **~45 h**—directly relevant to the “higher permeability at high rejection” claim. [8]

**5) Fouling-resistant reverse osmosis membranes grafted with 2-aminoethanethiol having a low interaction energy with charged foulants**

**Author(s):** Jun Xiao[9] et al.

**Venue/type:** *npj Clean Water* (peer-reviewed experimental paper; open access)

**Date:** April 2024

**Link:** <https://www.nature.com/articles/s41545-024-00326-5>

**Why it matters:** Uses a “design-for-low-interaction-energy” surface chemistry approach (AET grafting) that increases water permeance from **2.6 ± 0.1 to 3.2 ± 0.05 LMH/bar** (≈23%) and targets fouling by **small charged surfactants**, aligning with the ART’s anti-fouling mechanism emphasis. [10]

**6) Graphene Oxide Surface Modification of Reverse Osmosis Membrane via Langmuir–Blodgett Technique: Balancing Performance and Antifouling Properties**

**Author(s):** Dmitrii I. Petukhov[11] et al.

**Venue/type:** *Membranes* (peer-reviewed experimental paper; open access)

**Date:** August 2024

**Link:** <https://doi.org/10.3390/membranes14080172>

**Why it matters:** Demonstrates a controllable **graphene-oxide coating process** (Langmuir–Blodgett transfer) on a commercial RO membrane, reporting that at an optimal coating density the flux decline ratio drops from **38% to 18%** and flux recovery rises from **~65% to ~87%**, while NaCl rejection increases from **95.2% to 98.1%** (at the expense of some permeance). [12]

**7) Methylation of reverse osmosis membrane for superior anti-fouling performance via blocking carboxyl groups in polyamide**

**Author(s):** Yiwen Qin[13] et al.

**Venue/type:** *Nature Water* (peer-reviewed experimental paper; abstract accessible)

**Date:** January 2025

**Link:** <https://www.nature.com/articles/s44221-024-00371-x>

**Why it matters:** Reports an interfacial-polymerisation-stage methylation approach (dimethylamine grafting) achieving **3.84 LMH/bar** water permeance with **99.05% NaCl rejection**, and claims antifouling performance surpassing a named commercial antifouling RO membrane product—strong evidence that **surface chemistry control** can push both permeability and fouling resistance in desalination-style membranes. [14]

**8) Scalable aqueous-phase fabrication of reduced graphene oxide nanofiltration membranes by an integrated roll-to-roll process**

**Organisation/author(s):** Amirsalar R. Esfahani[15] et al.; indexed by U.S. Department of Energy Office of Scientific and Technical Information[16]

**Venue/type:** *Journal of Membrane Science* (peer-reviewed article; manufacturing evidence via OSTI record)

**Date:** April 2023

**Link:** <https://doi.org/10.1016/j.memsci.2023.121669>

**Why it matters:** While focused on nanofiltration, it provides rare **large-area manufacturing data** for graphene-derived membranes: reports **90 × 30 cm** roll-to-roll-fabricated rGO membranes (~100 nm thick, 2700 cm<sup>2</sup> area) and gives performance under harsh conditions, helping de-risk the ART's "defect-free manufacturing at scale" bottleneck for 2D-material-based membranes. [17]

**9) Dynamic Monitoring of Reverse Osmosis Process via Electrical Impedance Tomography: Enabling In Situ Visualization and Uncovering Distinct Roles of Concentration Polarization and Foulant Deposition in Flux Decline**

**Author(s):** Fei Gao[18] et al.

**Venue/type:** *Environmental Science & Technology* (peer-reviewed paper; access-limited but indexed with metadata and summary)

**Date:** January 2026

**Link:** <https://doi.org/10.1021/acs.est.5c15320>

**Why it matters:** Directly supports the ART's "embedded sensing/monitoring" variant by reporting an **in situ, noninvasive** approach (EIT-based imaging) to distinguish concentration polarisation vs foulant deposition contributions to flux decline—relevant to more reliable, feedback-driven operation and cleaning schedules. [19]

**10) Supercomputing and machine learning-aided optimal design of high permeability seawater reverse osmosis membrane systems**

**Author(s):** Jiu Luo[20] et al.

**Venue/type:** *Science Bulletin* (peer-reviewed modelling + optimisation paper)

**Date:** February 2023

**Link:** <https://doi.org/10.1016/j.scib.2023.01.039>

**Why it matters:** Quantifies plausibility of energy savings at the system level: reports modelling/optimisation where energy consumption could drop by **27.5% (to 1.66 kWh/m<sup>3</sup>)** with contributions attributed to high-permeability SWRO membranes (**12.2%**) and two-stage design (**14.5%**), and explicitly treats concentration polarisation constraints. [21]

**11) Quantifying the potential of high-performance RO membranes for seawater and hypersaline brine desalination: from module-scale modelling to experimental evaluation**

**Author(s):** Yu Jie Lim[22] et al.

**Venue/type:** *Desalination* (peer-reviewed modelling + experimental evaluation)

**Date:** December 2025

**Link:** <https://doi.org/10.1016/j.desal.2025.119394>

**Why it matters:** Ties membrane properties to scaling reality: modelling suggests tripling permeability (0.45→1.35 LMH/bar) can reduce HPRO energy consumption by **23%** or reduce pressure vessels by **62%**; also experimentally tests **12 state-of-the-art commercial RO membranes** at extreme conditions (e.g., **130 bar, 70 g/L NaCl**) and reports measured permeability and rejection ranges, providing a benchmark of how close current products are to high-performance targets. [23]

**12) Ultra low-pressure reverse osmosis membrane for desalination: Current challenges and future directions**

**Author(s):** P.T.P. Aryanti[24] et al.

**Venue/type:** *Desalination* (peer-reviewed review/roadmap-style paper)

**Date:** 2023 (April noted in indexing)

**Link:** <https://doi.org/10.1016/j.desal.2023.116650>

**Why it matters:** Synthesises the technical pathway to “lower-pressure RO” and frames key constraints: e.g., cites seawater pressure requirements up to **~70 bar**, defines ULPRO ambition of **<10 bar** operation with higher flux, and discusses nanomaterials/nanocomposites and packaging (e.g., hollow-fibre prospects) as routes and barriers—useful for maturity assessment and identifying what’s still missing. [25]

### 13) 2024 roadmap on membrane desalination technology at the water-energy nexus

**Organisation/author(s):** Antonio Politano[26] et al.

**Venue/type:** *JPhys Energy* roadmap (peer-reviewed roadmap, indexed in DOAJ)

**Date:** January 2024

**Link:** <https://doi.org/10.1088/2515-7655/ad2cf2>

**Why it matters:** Provides authoritative framing of maturity and bottlenecks for membrane desalination: states SWRO is **>70% of global desalination capacity**, and that energy consumption is typically **3–5 kWh/m<sup>3</sup>** versus a cited theoretical **~1.1 kWh/m<sup>3</sup>** at 50% recovery—context that supports why permeability/fouling improvements remain valuable yet bounded by system/thermodynamic limits. [27]

### 14) FilmTec Reverse Osmosis Membranes Technical Manual

**Organisation:** DuPont Water Solutions[28] (vendor technical doc)

**Venue/type:** Vendor technical manual (design/operation limits, element construction, troubleshooting)

**Date:** September 2025 (Rev. 18)

**Link:**

<https://www.dupont.com/content/dam/water/amer/us/en/water/public/documents/en/RO-NF-FilmTec-Manual-45-D01504-en.pdf>

**Why it matters:** A dated, detailed technical manual is strong “market maturity” evidence: it codifies engineering limits (pressure drop, feed pressure), element construction, and operational practices needed for large-scale deployment, indicating RO membrane elements are **industrialised consumables** integrated into standard plant design and operations. [29]

### 15) FilmTec Seawater Elements product documentation

**Organisation:** DuPont FilmTec (vendor technical doc)

**Venue/type:** Vendor product datasheet for seawater RO elements

**Date:** October 2024

**Link:**

<https://www.dupont.com/content/dam/water/amer/us/en/water/public/documents/en/RO-FilmTec-SW30-Seawater-PDS-45-D01519-en.pdf>

**Why it matters:** Dated product documentation for seawater elements supports “close-to-market / in-market” maturity—these documents typically specify standardised test conditions and minimum performance (flow, salt rejection), consistent with commercial procurement and deployment in SWRO plants. [30]

### 16) TORAY Report 2024

**Organisation:** Toray Industries[31] (annual/integrated reporting; industry deployment evidence)

**Venue/type:** Corporate report with deployment/order information

**Date:** November 2024

**Link:** [https://www.toray.com/ir/pdf/lib/lib\\_a541.pdf](https://www.toray.com/ir/pdf/lib/lib_a541.pdf)

**Why it matters:** Reports that Toray received an **order for reverse osmosis membranes** for

the **Yanbu 4** seawater desalination plant in Saudi Arabia, providing concrete evidence that advanced RO membranes are procured and deployed in **large infrastructure projects**, consistent with late-stage maturity in core RO element technology. [32]

#### **Maturity score and reasoning**

150. Maturity score (1–7) and reasoning

#### **A) Final maturity score: 6**

##### **Evidence-to-rubric mapping**

##### **Why the evidence rules out levels 1–5**

- The ART is not only a lab-verified concept: multiple sources show **pilot/industrial-scale manufacturing** of modified membranes compatible with standard spiral-wound architectures. The Bera et al. study reports **pilot-scale roll-to-roll SWRO membrane fabrication** (100 m<sup>2</sup>/batch) with quantified gains in permeance and antifouling while maintaining seawater-relevant rejection. [2]
- Manufacturing/process integration is explicitly demonstrated: Goh et al. describe **industrial-scale fabrication steps** (slot-die casting parameters, scaling from small batches up to large batches) and show a packaging-driven pathway to “low energy” via increased membrane area per housing. [4]
- There is clear evidence of **commercial productisation** in the broader class of high-performance RO membranes: a current vendor technical manual (Rev. Sept 2025) and seawater element product documentation (Oct 2024) indicate mature, standardised products delivered to design engineers and operators as deployable components. [33]
- Market-scale adoption of RO membranes in major infrastructure is evidenced by a large manufacturer reporting orders for SWRO plants (Toray’s Yanbu 4 order). [32]

Together, this combination (pilot-scale manufacturing + dated vendor manuals/datasheets + infrastructure orders) is most consistent with **Level 6: products delivered to customers; scaling and application expansion ongoing**.

##### **What is still missing to justify level 7 for this ART as written**

- The ART description’s more radical variants—especially **graphene-derived selective films as primary RO desalination layers** and **sensor-integrated “smart membrane cartridges”**—lack clear evidence of **broad, multi-customer commercial delivery at increasing volumes** and multi-year field reliability in desalination duty. The sensing thread is promising but still best evidenced as research/monitoring demonstration rather than a widely deployed standard module feature. [19]
- A level-7 case would be strengthened by public evidence of **multiple competing product lines** explicitly based on these nano-engineered variants (e.g., graphene-enabled coatings/elements) being shipped at scale, along with clear indicators of rising demand for those specific variants (not just RO generally). The roadmap also highlights that SWRO energy and recovery are still constrained by system and thermodynamic factors, implying that even better membranes must prove value under realistic concentration polarisation/fouling constraints. [34]

#### **C) Sub-component view and aggregation to one score**

Because the ART bundles materially different technology threads under the same “better RO

membranes” functionality, a sub-score view is appropriate; the final score is an average-weighted judgement emphasising the *core deliverable* (*membrane elements that drop into existing hardware*).

- **Scaled polyamide/TFC nano-engineering (additives, ultrathin-layer control, TFN fillers) → ~5–6**  
Evidence: pilot/roll-to-roll SWRO membrane modification with quantified improvements [2]; industrial-scale packaging/fabrication method for “low-energy” elements [4]; multiple lab demonstrations reaching high permeance at high rejection [35].
- **Graphene-derived surface coatings for fouling control / defect coverage → ~3–4**  
Evidence: controlled GO coating improves fouling metrics and can raise rejection, but with trade-offs and limited demonstration scope [12]; manufacturing scale-up for graphene-derived membranes is demonstrated in related contexts, but not yet clearly as mainstream RO desalination elements [17].
- **Embedded sensing / feedback-control enabling membranes → ~3**  
Evidence: EIT-based in situ monitoring appears as a research-level capability that supports the plausibility of “smart” operation but is not yet shown as a standardised shipped RO element feature. [19]
- **Commercial delivery of high-performance RO elements compatible with existing hardware → 6–7 for the baseline product class**  
Evidence: current technical manuals/datasheets and major plant orders indicate mature deployment of RO membrane products (even if not always explicitly “graphene-enabled”). [36]

**Aggregation rationale:** the ART’s *core value proposition*—better membranes in existing modules reducing energy/maintenance—is already in **commercial delivery and scaling** (supporting ≥6), while the “most radical” materials and smart-sensing variants lag (pulling the technology bundle below a confident 7). The resulting single-score best fit is **6**.

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[1] [10] <https://www.nature.com/articles/s41545-024-00326-5>

<https://www.nature.com/articles/s41545-024-00326-5>

[2] [15] <https://www.sciencedirect.com/science/article/pii/S0011916424005010>

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[3] [4] [16] [18] [22] [28] <https://www.mdpi.com/2077-0375/12/5/540>

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[5] [13] [17] [24] [26] <https://www.osti.gov/pages/biblio/2418561>

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[6] [9] [35] <https://www.sciencedirect.com/science/article/abs/pii/S0376738822002678>

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[7] [11] [19] <https://pubs.acs.org/doi/10.1021/acs.est.5c15320>

<https://pubs.acs.org/doi/10.1021/acs.est.5c15320>

[8] <https://pdfs.semanticscholar.org/2c00/720532ec287875ba8246228b7505e25f80b9.pdf>

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[12] <https://www.mdpi.com/2077-0375/14/8/172>

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[14] <https://www.nature.com/articles/s44221-024-00371-x>

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[20] [23] <https://www.sciencedirect.com/science/article/abs/pii/S0011916425008707>

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[25] [31] <https://www.sciencedirect.com/science/article/abs/pii/S0011916423002825>

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[27] [34] <https://doaj.org/article/ae7734adcc3a4047adaf8cd2033513c2>

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<https://www.dupont.com/content/dam/water/amer/us/en/water/public/documents/en/RO-FilmTec-SW30-Seawater-PDS-45-D01519-en.pdf>

[32] [https://www.toray.com/ir/pdf/lib/lib\\_a541.pdf](https://www.toray.com/ir/pdf/lib/lib_a541.pdf)

[https://www.toray.com/ir/pdf/lib/lib\\_a541.pdf](https://www.toray.com/ir/pdf/lib/lib_a541.pdf)

## ART 07.054 Ultra-Wide-Bandgap (UWBG) Power Semiconductors

### ART extraction

#### A) Primary capability claimed (what the ART does)

- Enable **power switches and diodes** that can block **higher voltages in thinner layers** and switch with **lower resistive loss** than silicon (and often beyond today's SiC/GaN limits),

enabling smaller, higher-efficiency converters.

- Operate at **higher junction temperatures** and potentially **higher switching frequencies**, reducing cooling and passive-component burden.
- Provide a route to **standardised power modules** (packaged devices) that integrate sensing/diagnostics while remaining “plug compatible” with conventional control interfaces (future-state claim; evidence target is modules + reliability + manufacturability).

## B) Key sub-components / variants (sub-threads to track)

- **$\beta$ -Ga<sub>2</sub>O<sub>3</sub> (gallium oxide) power diodes**: Schottky barrier diodes (SBD), heterojunction / p–n–style diodes using external p-type oxides (e.g., NiO, Cr<sub>2</sub>O<sub>3</sub>-based) to compensate for lack of native p-type Ga<sub>2</sub>O<sub>3</sub>. [1]
- **$\beta$ -Ga<sub>2</sub>O<sub>3</sub> power transistors** (lateral MOSFET/JFET-like structures; long-term aspiration toward robust vertical device architectures). [2]
- **Wafer and epitaxy scaling for  $\beta$ -Ga<sub>2</sub>O<sub>3</sub>** (melt growth, EFG/CZ-like methods, epilayer uniformity, defect density control, larger diameters). [3]
- **Thermal management / packaging for  $\beta$ -Ga<sub>2</sub>O<sub>3</sub>** (intrinsically low thermal conductivity → need advanced heat spreaders, double-sided cooling, heterogeneous integration). [4]
- **Diamond power devices** (Schottky/Schottky-pn concepts, high-temperature operation; materials/dopant activation constraints). [5]
- **Diamond MOSFETs (n-channel and p-channel)** as a prerequisite for diamond CMOS and, longer-term, broader diamond power-electronics ecosystems. [6]
- **$\beta$ -Ga<sub>2</sub>O<sub>3</sub>-on-diamond** (or on polycrystalline diamond) as an engineered heat-spreader platform to mitigate self-heating and enable higher current density / reliability. [7]

## C) Maturity indicators that would count as evidence

- **Device-level milestones**: multi-kV blocking with **credible on-resistance / PFOM**, temperature operation ( $\geq 150$ – $200$  °C for power;  $> 300$  °C for harsh environments), repeatable switching, and gate/oxide stability. [8]
- **System / circuit PoC**: devices used in **real power-converter prototypes** (e.g., DC–DC stage) with measured efficiency and waveforms. [9]
- **Reliability evidence**: thermal soak, thermal cycling / power cycling, interface stability (e.g., p–n heterojunction stability), failure mechanisms identified. [10]
- **Manufacturing readiness**: wafer diameter scaling, **defect-density reduction**, epi uniformity control, and documented yields for large-area devices. [11]
- **Commercialisation signals**: multiple well-capitalised industrial actors investing in substrates/devices, pilot lines, and early customer sampling (with measurable device specs). [12]
- **Module-level progress** (for the ART’s end-state): packaged power modules with thermal design, qualification testing, and early deployments—this is a key “missing rung” that would move maturity toward 4–6. [13]

## 2. Evidence (10–20 recent, reliable sources)

### 1) Ultra-wide bandgap semiconductor Ga<sub>2</sub>O<sub>3</sub> power diodes [14]

- **Authors/organisation**: Jincheng Zhang et al.
- **Venue/type**: *Nature Communications* (peer-reviewed experimental paper; open access)
- **Publication date**: July 2022
- **Link**: <https://www.nature.com/articles/s41467-022-31664-y>
- **What it reports / why it matters**: Demonstrates Ga<sub>2</sub>O<sub>3</sub> heterojunction PN diodes using hole

injection to achieve **8.32 kV breakdown**, **5.24 mΩ·cm<sup>2</sup> specific on-resistance**, and **13.2 GW/cm<sup>2</sup> PFOM**, directly supporting plausibility that Ga<sub>2</sub>O<sub>3</sub> can reach multi-kV class performance with competitive conduction loss. [14]

## 2) Vacuum Annealed β-Ga<sub>2</sub>O<sub>3</sub> Recess Channel MOSFETs With 8.56 kV Breakdown Voltage [2]

- **Authors/organisation:** Shivam Sharma et al.
- **Venue/type:** *IEEE Electron Device Letters* (peer-reviewed experimental paper; author PDF via NSF public access)
- **Publication date:** December 2022
- **Link:** <https://par.nsf.gov/servlets/purl/10444744>
- **What it reports / why it matters:** Reports a lateral field-plated β-Ga<sub>2</sub>O<sub>3</sub> MOSFET with **8.56 kV breakdown** (for Lgd = 60 μm) plus process insight that **vacuum annealing can improve/on-resistance recovery after etch damage** without reducing breakdown—evidence that key integration/process bottlenecks (etch damage recovery) are being actively engineered toward usable devices. [15]

## 3) 10-kV Ga<sub>2</sub>O<sub>3</sub> Charge-Balance Schottky Rectifier Operational at 200 °C [16]

- **Authors/organisation:** Yuan Qin et al. (incl. Virginia Tech and collaborators listed in the paper)
- **Venue/type:** *IEEE Electron Device Letters* (peer-reviewed experimental paper; author PDF via NSF public access)
- **Publication date:** August 2023
- **Link:** <https://par.nsf.gov/servlets/purl/10464205>
- **What it reports / why it matters:** Demonstrates a lateral Ga<sub>2</sub>O<sub>3</sub> SBD with **>10 kV breakdown** using a **NiO RESURF charge-balance** concept and shows **thermal stability up to 200 °C**, addressing two maturity-critical claims for power use: **multi-kV blocking** and **elevated-temperature operation**. [16]

## 4) Large-area β-Ga<sub>2</sub>O<sub>3</sub> Schottky barrier diode and its application in DC–DC converters [9]

- **Authors/organisation:** Wei Guo et al. (University of Science and Technology of China)
- **Venue/type:** *Journal of Semiconductors* (peer-reviewed experimental paper; PDF)
- **Publication date:** 2023 (issue 44(7))
- **Link:** <https://www.researching.cn/ArticlePdf/m00098/2023/44/7/072805.pdf>
- **What it reports / why it matters:** Shows a **large-area vertical β-Ga<sub>2</sub>O<sub>3</sub> SBD (1×1 mm<sup>2</sup>)** delivering **8 A forward current** and **612 V reverse breakdown**, then demonstrates a **β-Ga<sub>2</sub>O<sub>3</sub> SBD-based DC–DC converter with 95.81% efficiency**, providing system-level PoC evidence beyond single-device characterisation. [9]

## 5) Growth of bulk β-Ga<sub>2</sub>O<sub>3</sub> crystals from melt without precious-metal crucible by pulling from a cold container [17]

- **Authors/organisation:** A. Yoshikawa et al.
- **Venue/type:** *Scientific Reports* (peer-reviewed experimental paper; open access)
- **Publication date:** June 2024
- **Link:** <https://www.nature.com/articles/s41598-024-65420-7>
- **What it reports / why it matters:** Demonstrates a melt-growth route (OCCC) eliminating precious-metal crucibles and reports **β-Ga<sub>2</sub>O<sub>3</sub> crystals up to 46 mm diameter**, directly addressing the ART's manufacturability bottleneck (substrate cost/scale-up) and showing progress toward scalable wafer supply. [17]

## 6) 2 in. Bulk $\beta$ -Ga<sub>2</sub>O<sub>3</sub> Single Crystals Grown by EFG Method with High Wafer-Scale Quality [18]

- **Authors/organisation:** Ganrong Feng et al.
- **Venue/type:** *ACS Omega* (peer-reviewed experimental paper; free via PubMed Central)
- **Publication date:** April 2024
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11112554/>
- **What it reports / why it matters:** Reports **2-inch  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> bulk crystals** and wafer-quality metrics (e.g., **mean X-ray rocking curve FWHM ~60.8 arcsec** and **RMS roughness ~0.196 nm**), supporting the plausibility of wafer-scale substrates with epi-ready surface quality—an essential precursor to any “standardised module” supply chain. [18]

## 7) Third-generation gallium-oxide 100-mm epitaxial wafer with ten times fewer killer defects [19]

- **Authors/organisation:** Novel Crystal Technology, Inc.; Saga University; NEDO (New Energy and Industrial Technology Development Organization, Japan)
- **Venue/type:** **Industry/government programme press release** with quantitative manufacturing + prototype metrics (treat as vendor/government evidence; not peer review)
- **Publication date:** March 2022
- **Link:** <https://www.novelcrystal.co.jp/eng/2022/1162/>
- **What it reports / why it matters:** Reports a **100-mm Ga<sub>2</sub>O<sub>3</sub> epitaxial wafer** with **killer defect density reduced to ~0.7 cm<sup>-2</sup>** (claimed <1/10 of prior generation), plus quantified **film thickness (~10  $\mu$ m  $\pm$ 5%)** and **donor concentration (~1 $\times$ 10<sup>16</sup> cm<sup>-3</sup>  $\pm$ 7%)** uniformity and large-chip prototyping (up to **10 mm $\times$ 10 mm**)—strong maturity evidence for manufacturability, though still requiring independent validation for market readiness. [19]

## 8) Mitsubishi Electric Buys Stake in Novel Crystal Technology to Accelerate Development of Gallium-oxide Power Semiconductors [20]

- **Authors/organisation:** Mitsubishi Electric Corporation
- **Venue/type:** Industry corporate disclosure / press release (commercialisation signal; not a technical validation)
- **Publication date:** July 2023
- **Link:** <https://meus-semiconductors.com/news-events/mitsubishi-electric-buys-stake-in-novel-crystal-technology-to-accelerate-development-of-gallium-oxide-power-semiconductors>
- **What it reports / why it matters:** States Mitsubishi Electric has taken an **equity position** in a Ga<sub>2</sub>O<sub>3</sub> wafer supplier (NCT) to **accelerate development** of gallium-oxide power semiconductors—evidence of well-capitalised industrial involvement consistent with movement beyond “only academic curiosity,” even if product shipments at scale are not yet demonstrated. [20]

## 9) Reliable operation of Cr<sub>2</sub>O<sub>3</sub>:Mg/ $\beta$ -Ga<sub>2</sub>O<sub>3</sub> p–n heterojunction diodes during extended operation at 600 °C [10]

- **Authors/organisation:** W.A. Callahan et al. (document hosted via NREL/OSTI; APL paper)
- **Venue/type:** *Applied Physics Letters* (peer-reviewed experimental paper; open PDF)
- **Publication date:** April 2024
- **Link:** <https://docs.nrel.gov/docs/fy24osti/87958.pdf>
- **What it reports / why it matters:** Demonstrates extended high-temperature operation: diodes cycled **25 $\leftrightarrow$ 550 °C (30 cycles)** and soaked **140 h at 600 °C**, with quantified drift in

turn-on voltage and on-state resistance and interface chemical changes (Mg/MgO accumulation), giving rare, concrete **reliability evidence** for “high-T operation” claims while also exposing remaining stability gaps. [10]

#### 10) Van der Waals $\beta$ -Ga<sub>2</sub>O<sub>3</sub> thin films on polycrystalline diamond substrates [21]

- **Authors/organisation:** Jing Ning et al.
- **Venue/type:** *Nature Communications* (peer-reviewed experimental paper; open access)
- **Publication date:** August 2025
- **Link:** <https://www.nature.com/articles/s41467-025-63666-x>
- **What it reports / why it matters:** Reports  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> thin films grown on **high-thermal-conductivity polycrystalline diamond** via van der Waals coupling to address self-heating, explicitly targeting the key limitation that **wafer-scale single-crystal diamond** and lattice mismatch otherwise impose—evidence that the “Ga<sub>2</sub>O<sub>3</sub> + engineered diamond thermal platform” pathway is experimentally advancing. [21]

#### 11) Insight into Interfacial Heat Transfer of $\beta$ -Ga<sub>2</sub>O<sub>3</sub>/Diamond Heterostructures via the Machine Learning Potential [22]

- **Authors/organisation:** Zhanpeng Sun et al.
- **Venue/type:** *ACS Applied Materials & Interfaces* (peer-reviewed; author-archived PDF; computational + interface-physics focus)
- **Publication date:** June 2024
- **Link:** [https://cronfa.swan.ac.uk/Record/cronfa68005/Download/68005\\_\\_32619\\_\\_2b412c28aaad429f86a3db0d9c9f35cf.pdf](https://cronfa.swan.ac.uk/Record/cronfa68005/Download/68005__32619__2b412c28aaad429f86a3db0d9c9f35cf.pdf)
- **What it reports / why it matters:** Focuses on **thermal boundary resistance (TBR)** in  $\beta$ -Ga<sub>2</sub>O<sub>3</sub>/diamond stacks and cites experimental TBC levels (e.g., a reported  $\sim 179 \text{ MW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$  for interfacial bonding as a comparison point), clarifying that **interfaces—not just bulk diamond conductivity—can dominate real heat flow**, a core constraint for any “high-junction-temperature module” roadmap. [23]

#### 12) Wide Bandgap Power Electronics Strategic Framework [24]

- **Authors/organisation:** U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (AMMTO)
- **Venue/type:** Government strategic framework / roadmap report
- **Publication date:** January 2025
- **Link:** [https://www.energy.gov/sites/default/files/2025-01/AMMTO%20Draft%20WBG%20PE%20Strategic%20Framework\\_FINAL.pdf](https://www.energy.gov/sites/default/files/2025-01/AMMTO%20Draft%20WBG%20PE%20Strategic%20Framework_FINAL.pdf)
- **What it reports / why it matters:** Explicitly flags **gallium oxide** as offering **extremely high breakdown voltages** with potential for ultra-high-voltage applications, and frames packaging/passives as crucial to realising benefits—useful context for maturity scoring because it highlights that **system-level packaging** remains a central bottleneck even for advanced materials. [25]

#### 13) World’s First N-Channel Diamond Field-Effect Transistor [6]

- **Authors/organisation:** National Institute for Materials Science (NIMS), Japan
- **Venue/type:** National lab press release summarising a peer-reviewed result (links to *Advanced Science*)
- **Publication date:** January 2024
- **Link:** <https://www.nims.go.jp/eng/press/2024/01/202401250.html>



- **What it reports / why it matters:** Reports the first fabricated **n-channel diamond MOSFET** and cites **field-effect mobility  $\sim 150 \text{ cm}^2/\text{V}\cdot\text{s}$  at  $300^\circ\text{C}$** , a key plausibility milestone for diamond electronics (especially CMOS enablement), but still far from “power module” maturity (voltage/current rating, wafer supply, packaging). [6]

#### 14) Diamond p-Type Lateral Schottky Barrier Diodes with High Breakdown Voltage (4612 V at 0.01 mA/mm) [26]

- **Authors/organisation:** Zhuoran Han; Can Bayram

- **Venue/type:** *IEEE Electron Device Letters* (peer-reviewed experimental paper; bibliographic record with embedded abstract)

- **Publication date:** October 2023

- **Link:** <https://experts.illinois.edu/en/publications/diamond-p-type-lateral-schottky-barrier-diodes-with-high-breakdow/>

- **What it reports / why it matters:** Demonstrates diamond lateral SBDs with  $\text{Al}_2\text{O}_3$  field plates that remain **stable under 4612 V reverse bias** (vs 1159 V without field plate), plus rectifying ratios  $>10^7$ —evidence that diamond diodes can reach kV-class blocking, directly supporting plausibility while still not evidencing scaling/manufacturing maturity. [26]

#### 15) Vertical Schottky diode on (113) oriented homoepitaxial diamond [27]

- **Authors/organisation:** P. Hazdra et al.

- **Venue/type:** *Diamond and Related Materials* (peer-reviewed experimental paper; ScienceDirect preview includes metrics)

- **Publication date:** June 2024

- **Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S0925963524003935>

- **What it reports / why it matters:** Reports vertical diamond Schottky diode performance including  **$J_F \approx 100 \text{ A/cm}^2$  at 4 V** with  **$R_{\text{on,sp}} \approx 3.7 \text{ m}\Omega\cdot\text{cm}^2$**  and extremely low leakage ( $\approx 10^{-9} \text{ A/cm}^2$  regime), with discussion of **dopant activation depth/compensation** and breakdown field ( $\sim 3 \text{ MV/cm}$ ), illustrating concrete progress while also underscoring diamond’s dopant/termination challenges. [27]

#### 16) Dopants and defects in ultra-wide bandgap semiconductors [28]

- **Authors/organisation:** John L. Lyons; Darshana Wickramaratne; Anderson Janotti

- **Venue/type:** *Current Opinion in Solid State and Materials Science* (peer-reviewed review; ScienceDirect preview includes key claims)

- **Publication date:** June 2024

- **Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S1359028624000147>

- **What it reports / why it matters:** Synthesises that the “most serious materials challenge” is **conductivity control** and that many leading UWBG candidates (explicitly including  **$\text{Ga}_2\text{O}_3$  and diamond**) struggle to achieve **bipolar conductivity**, which directly impacts device architectures (e.g., junction termination, normally-off devices) and therefore slows maturity toward mass-manufacturable power modules. [28]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 3

#### B) Evidence-to-rubric mapping (why 3, why not lower, what is missing for 4+)



### What rules out levels 1–2 (purely theoretical / early lab verification)?

- Multiple independent peer-reviewed demonstrations show **multi-kV device prototypes** in  $\text{Ga}_2\text{O}_3$ , including **8.32 kV heterojunction PN diodes** with quantified low on-resistance and high PFOM [14], a **10-kV-class  $\text{Ga}_2\text{O}_3$  charge-balance Schottky rectifier** that remains operational up to **200 °C** [16], and **8.56 kV  $\beta\text{-Ga}_2\text{O}_3$  MOSFETs** with process steps explicitly aimed at manufacturable device recovery after etch damage. [2]
  - Diamond also has peer-reviewed kV-class diode evidence (e.g., stability to **4612 V** in lateral diamond SBDs with field plates) and vertical diode metrics demonstrating low on-resistance and very low leakage regimes. [29]
- These are beyond “operating principle in the lab” and constitute real device prototypes.

### What supports level 3 specifically (laboratory prototype demonstrated)?

- The evidence base is dominated by **laboratory prototypes** with headline performance numbers (kV blocking; temperature operation), plus early system demonstrations such as a  **$\text{Ga}_2\text{O}_3$ -diode DC–DC converter prototype** with measured **95.81% efficiency**. [9]
- Wafer and defect work shows meaningful manufacturing-relevant progress (e.g., **2-inch bulk EFG wafers with quantified rocking-curve/roughness metrics** and **100-mm epi wafer defect-density reduction claims**), but this is still best interpreted as “enabling infrastructure improving,” not yet a validated high-yield mass production supply chain. [11]
- Reliability/qualification evidence exists but is still at the “expose failure modes” stage: e.g., high-temperature cycling/soak experiments reveal interface-driven degradation mechanisms in  $\text{Ga}_2\text{O}_3$  heterojunction diodes, signalling active progress but not yet industrial qualification. [10]

### What is still missing for level 4 (PoC meeting commercialisation requirements) and level 5 (multiple actors racing to production prototypes)?

- The ART’s end-state is **standardised power modules** with robust packaging, diagnostics, and high-temperature/high-voltage qualification. Current evidence is mostly **device-level and early circuit PoC**, not sustained proof that packaged modules meet commercial reliability requirements such as long power-cycling life, repeatable thermal impedance, high-voltage partial discharge robustness, and manufacturable packaging stacks at scale. [13]
- Thermal management remains a recognised blocking issue ( $\text{Ga}_2\text{O}_3$ ’s low thermal conductivity; interface-limited heat flow even when diamond is introduced), and the “ $\text{Ga}_2\text{O}_3$ -on-diamond” approach is still in the experimental/heterostructure stage rather than a proven manufacturable module platform. [7]
- There are strong commercialisation signals (e.g., a major industrial actor taking an equity stake in a  $\text{Ga}_2\text{O}_3$  wafer supplier), but this alone does not demonstrate “production prototype finishing phase” or “products delivered in increasing amounts.” [20]

### C) Sub-component maturity breakdown and aggregation to one score

- **$\beta\text{-Ga}_2\text{O}_3$  power diodes (SBD, heterojunction/PN concepts): maturity ~4 (upper-3 to 4)** based on kV-class devices with strong PFOM and temperature operation [30] plus at least one converter-level PoC. [9]
- **$\beta\text{-Ga}_2\text{O}_3$  transistors (MOSFET-class): maturity ~3** because devices exist at multi-kV breakdown (evidence of prototype success) but broader commercial requirements

(packaging, ruggedness, lifetime, gate stack qualification) are not yet evidenced at module level. [31]

- **Wafer/epi scale-up for Ga<sub>2</sub>O<sub>3</sub>: maturity ~3–4** because multi-inch and 100-mm class efforts show quantified defect/uniformity progress, including 2-inch bulk wafer quality metrics and 100-mm epi uniformity/defect claims. [11]
- **Diamond power diodes: maturity ~3** (kV-class lateral blocking has been shown; vertical diode structures show strong conduction/leakage metrics), but scaling and doping/termination constraints remain central, keeping it in prototype territory rather than production readiness. [32]
- **Diamond MOSFETs (especially n-channel): maturity ~2–3** because a first n-channel MOSFET demonstration exists with high-temperature mobility, but evidence of power-device voltage/current classes and manufacturability is still sparse. [6]
- **Ga<sub>2</sub>O<sub>3</sub>-on-diamond thermal platforms: maturity ~2–3** because experimental heterostructure demonstrations exist, but interface/thermal boundary constraints and wafer-scale integration remain active research topics. [7]

**Aggregation:** Because the ART explicitly bundles **two distinct UWBG material families (Ga<sub>2</sub>O<sub>3</sub> and diamond)** that are at different maturity levels, and because the “standardised module” outcome depends on the slowest elements (thermal packaging + wafer quality + reliability), an **average-weighted assessment yields ~3 overall**, rather than assigning the maximum sub-score. [33]

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[1] [8] [14] [30] <https://www.nature.com/articles/s41467-022-31664-y>

<https://www.nature.com/articles/s41467-022-31664-y>

[2] [15] [31] <https://par.nsf.gov/servlets/purl/10444744>

<https://par.nsf.gov/servlets/purl/10444744>

[3] [17] <https://www.nature.com/articles/s41598-024-65420-7>

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[7] [21] <https://www.nature.com/articles/s41467-025-63666-x>

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[9] <https://www.researching.cn/ArticlePdf/m00098/2023/44/7/072805.pdf>

<https://www.researching.cn/ArticlePdf/m00098/2023/44/7/072805.pdf>

[10] <https://docs.nrel.gov/docs/fy24osti/87958.pdf>

<https://docs.nrel.gov/docs/fy24osti/87958.pdf>

[11] [18] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11112554/>

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[12] [20] <https://meus-semiconductors.com/news-events/mitsubishi-electric-buys-stake-in-novel-crystal-technology-to-accelerate-development-of-gallium-oxide-power-semiconductors>

<https://meus-semiconductors.com/news-events/mitsubishi-electric-buys-stake-in-novel-crystal-technology-to-accelerate-development-of-gallium-oxide-power-semiconductors>

[13] [24] [25] [33] Microsoft Word - AMMTO WBG PE Strategic Framework\_DRAFT

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[16] <https://par.nsf.gov/servlets/purl/10464205>

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[26] [29] [32] <https://experts.illinois.edu/en/publications/diamond-p-type-lateral-schottky-barrier-diodes-with-high-breakdown/>

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<https://www.sciencedirect.com/science/article/abs/pii/S1359028624000147>

## ART 07.055 Solid Hydrogen Storage Materials for Safe, Dense Fuel

### ART extraction

#### Primary capability claimed

- Convert hydrogen storage from a high-pressure/cryogenic containment problem into a **materials-based** storage problem by storing hydrogen in **solids** (reversible “sponge” behaviour: charge by pressure/temperature; discharge by heat/pressure swing).
- Achieve **higher volumetric density at lower pressures** than compressed gas storage, enabling safer, container-like or cartridge form factors, with passive safety features.

- Enable **modular, instrumented storage modules** (heat exchangers + sensors + control) that can be integrated into familiar geometries and refuelling/handling workflows.

#### Key sub-components and variants

- **Reversible metal hydrides** (e.g., TiFe- and TiMn-based alloys; AB/AB<sub>2</sub>/HEA families) with engineered heat management and impurity tolerance.
- **Metal hydride systems** (tanks/modules) with thermal coupling (e.g., PCM heat buffers), embedded heat exchangers, safety interlocks, and controlled discharge.
- **Metal hydride compressors / infrastructure components** that use hydrides for compression/conditioning, linking storage to refuelling.
- **Cryo-adsorption in porous solids** (MOFs / ZIFs / engineered carbons): hydrogen stored by physisorption onto high-surface-area internal pores at cryogenic temperatures.
- **Shaping & densification** of porous adsorbents (monoliths/pellets/extrudates) to improve packing density and volumetric performance (without crippling porosity).
- **Standardisation / measurement reproducibility** (inter-laboratory benchmarks, reference materials, and protocols for adsorption storage).

#### Maturity indicators that would constitute evidence

- Demonstrated **system-level prototypes** (kg-scale hydrogen stored/released with controlled rates; integration with electrolyser/fuel cell; long-duration operation).
- Evidence of **scale-up or industrial production** of storage materials (kg-scale alloy batches; repeatable shaping lines such as extrusion/pelletisation).
- **Safety validation** beyond paper design (risk studies + experimentally supported hazard claims; self-limiting release behaviour; no spontaneous ignition on exposure).
- **Field or pre-field demonstrations** (containerised modules, on-vehicle trials, microgrid pilots; validated charge/discharge efficiency and rates).
- Signs of **commercial readiness**: product families with specifications, government procurement/NEPA documentation, funded demonstrations, integration into “real” infrastructure.

#### Evidence (10–20 recent, reliable sources)

##### Peer-reviewed materials and engineering evidence

##### **Monolithic MOF densification reaching high volumetric H<sub>2</sub> at lower pressures - Title:**

Densified HKUST-1 Monoliths as a Route to High Volumetric and Gravimetric Hydrogen Storage Capacity

- **Authors/organisation:** D. G. Madden et al. (research groups including University-based MOF teams)

- **Venue/type:** Peer-reviewed experimental paper (Journal of the American Chemical Society)

- **Date:** July 2022

- **Link:** <https://docs.nrel.gov/docs/fy22osti/83773.pdf>

- **Why it matters:** Reports a densified monolithic MOF storing **46 g H<sub>2</sub>/L (50 bar, 77 K)** and delivering **41–42 g H<sub>2</sub>/L** under a combined temperature–pressure swing (25–50 bar/77 K → 5 bar/160 K), indicating practical densification can cut operating pressure versus compressed gas and benchmark materials. [1]

**Room-temperature reversible hydrides with long cycling stability** - **Title:** High-entropy hydrides for fast and reversible hydrogen storage at room temperature: binding-energy engineering via first-principles calculations and experiments

- **Authors/organisation:** A. Mohammadi et al.
- **Venue/type:** Peer-reviewed experimental + modelling paper (Acta Materialia)
- **Date:** September 2022
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S1359645422004980>
- **Why it matters:** Demonstrates multi-principal element alloys forming reversible hydrides at **room temperature**, with **fast kinetics**, **no activation/catalyst treatment**, and **stability for at least 1000 cycles**, addressing key durability/kinetics bottlenecks for low-temperature metal-hydride storage. [2]

**Industrial-level production of a TiFe alloy for a ~50 kg H<sub>2</sub> storage plant** - **Title:**

TiFe<sub>0.85</sub>Mn<sub>0.05</sub> alloy produced at industrial level for a hydrogen storage plant

- **Authors/organisation:** J. Barale et al.
- **Venue/type:** Peer-reviewed experimental paper (International Journal of Hydrogen Energy)
- **Date:** August 2022
- **Link:** <https://www.sciencedirect.com/science/article/pii/S0360319922029536>
- **Why it matters:** Uses **industrial-scale alloy synthesis (5 kg batch)** in the context of a **~50 kg H<sub>2</sub>** storage plant target, directly speaking to manufacturability and scale-up of the active metal-hydride material rather than only lab grams. [3]

**Validated metal-hydride tank design achieving high volumetric H<sub>2</sub> density** - **Title:**

Numerical simulation and experimental validation of Ti<sub>0.95</sub>Zr<sub>0.05</sub>Mn<sub>0.9</sub>Cr<sub>0.9</sub>V<sub>0.2</sub> alloy in a metal hydride tank for high-density hydrogen storage

- **Authors/organisation:** L. Zhan et al.
- **Venue/type:** Peer-reviewed (model + experimental validation) paper (International Journal of Hydrogen Energy)
- **Date:** November 2022
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0360319922041209>
- **Why it matters:** Reports a self-designed MH tank model validated against experiment and cites a **tank volumetric storage density** figure (55.1 g H<sub>2</sub>/L for the tank design context), evidencing engineering maturity around thermal/kinetic modelling and prototype tank design—not just material powder capacity. [4]

**Metal-hydride compressor integrated into small refuelling station** - **Title:** A metal hydride compressor for a small scale H<sub>2</sub> refuelling station

- **Authors/organisation:** Researchers linked to turbine/university + industrial partners (incl. industrial gas context)
- **Venue/type:** Peer-reviewed prototype/system paper (International Journal of Hydrogen Energy)
- **Date:** October 2023
- **Link:** <https://www.sciencedirect.com/science/article/pii/S0360319923024527>
- **Why it matters:** Demonstrates a **two-stage metal-hydride compressor** using commercial alloys, compressing hydrogen from **28 bar to 250 bar** (RT to 150 °C) with an average **104 NL/min** flow, integrating hydrides into refuelling infrastructure components that are tightly coupled to storage logistics. [5]

**Improving adsorbent thermal management and shaping robustness** - **Title:** Improved thermal management in HKUST-1 composites upon graphite flakes incorporation: hydrogen adsorption properties

- **Authors/organisation:** J. Farrando-Pérez et al.
- **Venue/type:** Peer-reviewed experimental paper (International Journal of Hydrogen Energy)
- **Date:** December 2023
- **Link:** <https://www.sciencedirect.com/science/article/pii/S0360319923028033>
- **Why it matters:** Shows that adding graphite flakes can reduce shaping damage (reported <10% BET loss vs 40% for pure HKUST-1 at a conforming step) while maintaining cryogenic adsorption, including a reported ~18.7 g/L volumetric excess uptake for a monolith at 0.1 MPa and -195 °C—directly targeting the “materials + heat transfer + shaping” bundle needed for practical adsorption tanks. [6]

**Mechanical densification to raise MOF deliverable capacity under TPS operation** - **Title:** Improving hydrogen storage performance of UiO-67 and MOF-177 under temperature-pressure swing conditions via densification

- **Authors/organisation:** R. Murugavel et al.
- **Venue/type:** Peer-reviewed experimental + modelling paper (International Journal of Hydrogen Energy)
- **Date:** May 2025
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0360319925003623>
- **Why it matters:** Reports binder-free monolithic engineering increasing bulk density by ~70% and improving deliverable capacity by 14–42% vs powders, with deliverable capacities around 47 and 44 g/L for densified MOF-177 and UiO-67 under 77 K/100 bar → 160 K/5 bar TPS—evidence that “cartridge-style” adsorbent shaping is advancing beyond powder performance claims. [7]

#### Measurement reproducibility and scale-oriented adsorbent shaping

**Pelletised ZIF-8 produced via continuous/mechanicochemical methods; usable hydrogen metric reported** - **Title:** ZIF-8 Pellets as a Robust Material for Hydrogen Cryo-Adsorption Tanks

- **Authors/organisation:** R. Balderas-Xicohtencatl et al.
- **Venue/type:** Peer-reviewed experimental paper (ACS Applied Energy Materials)
- **Date:** February 2023 (online)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/37771502/>
- **Why it matters:** Reports ZIF-8 made through twin-screw extrusion (industrialisation-relevant) and pelletisation without porosity loss, with a stated ~31 g usable H<sub>2</sub>/L of pellet under a TPS assumption (77 K/100 bar → 117 K/5 bar), and notes cycling without degradation—key maturity evidence for robust “packed bed” cryo-adsorbent cartridges. [8]

**Inter-laboratory study proposing ZIF-8 pellets as a reference material** - **Title:** Establishing ZIF-8 as a reference material for hydrogen cryoadsorption: an interlaboratory study

- **Authors/organisation:** J. A. Villajos et al.
- **Venue/type:** Peer-reviewed inter-lab benchmark paper (ChemPhysChem)
- **Date:** January 2024 (Epub) / March 2024 (issue)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/38165137/>
- **Why it matters:** Reports hydrogen uptake measured at 77 K up to 100 bar across 9 laboratories / 15 experimental setups, with stated ~3–4% relative standard deviation



between 10–100 bar, directly reducing a major maturity blocker: inconsistent adsorption measurement and the lack of reference materials for certification-grade datasets. [9]

### System prototypes, application demonstrations, and deployment signals

#### Low-pressure containerised metal-hydride storage integrated with electrolyser + fuel cell

**Title:** Risk Management in a Containerized Metal Hydride Storage System

- **Authors/organisation:** A. Rosino Messa et al.

- **Venue/type:** Peer-reviewed safety engineering + prototype description (Hydrogen Safety journal)

- **Date:** 2024

- **Link:** <https://hysafejournal.org/articles/10/files/66f3dc7304f2d.pdf>

- **Why it matters:** Describes a HyCARE container prototype storing **up to 40 kg H<sub>2</sub> in 12 TiFe-based MH tanks** at **<50 barg** and **<100 °C**, with experimentally supported safety claims (e.g., MH exposure to air/water did not cause spontaneous ignition; release rate is self-limited), directly evidencing “safe, dense, low-pressure module” plausibility. [10]

#### Vehicle-adjacent prototype: solid-state storage device integrated into a fuel-cell forklift module

**Title:** Optimisation design of solid-state hydrogen storage device for fuel cell forklift

- **Authors/organisation:** J. Ye et al.

- **Venue/type:** Peer-reviewed engineering paper (Journal of Alloys and Compounds)

- **Date:** January 2024

- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0925838823035454>

- **Why it matters:** Reports an optimised solid-state storage device with **1.5 kg effective H<sub>2</sub> capacity, 97.6% refuelling completion within 30 min**, and confirmed forklift operation for **~6 hours** under rated conditions—clear evidence of application-level integration beyond laboratory canisters. [11]

#### US government-funded plan for a mobile metal-hydride refuelling system and multi-site fabrication

**Title:** Metal Hydride-Based Hydrogen Storage Supporting Onsite Hydrogen Infrastructure at WGL/Washington Gas

- **Authors/organisation:** U.S. Department of Energy [12] (NEPA determination memo)

- **Venue/type:** Authoritative government project documentation (NEPA categorical exclusion memo)

- **Date:** June 2024

- **Link:** <https://www.energy.gov/sites/default/files/2024-09/CX-031126.pdf>

- **Why it matters:** Documents federal funding to GKN Hydrogen [13] to **design, fabricate, and test a mobile hydrogen refuelling system**, including metal-hydride alloy loading in Bruneck [14] and assembly/testing in Carlsbad [15], followed by a two-year demonstration—strong maturity evidence that prototype-to-demonstration pathways are being executed with real infrastructure sites. [16]

#### Megawatt-scale demonstration platform with ~500 kg class metal-hydride storage commissioned

**Title:** Heavy Metal Debut: A World-Class Metal Hydride System

- **Authors/organisation:** National Renewable Energy Laboratory [17]

- **Venue/type:** National lab feature story describing commissioned demonstration (authoritative institutional publication)

- **Date:** November 2024 (last updated January 2026)

- **Link:** <https://www.nrel.gov/news/detail/program/2024/heavy-metal-debut-a-world-class->

metal-hydride-system

- **Why it matters:** States a commissioned demonstration at the lab's Flatirons Campus integrating an electrolyser (~**1.25 MW PEM**) and a fuel cell (~**1 MW PEM**) with a metal-hydride system storing **up to ~500 kg H<sub>2</sub>**, signalling tangible scaling to hundreds-kg class storage modules and system integration testing. [18]

**DOE Annual Merit Review slide deck: large-scale hydride mega-tank validation plan -**

**Title:** High Efficacy Validation of Hydride Mega Tanks at the ARIES Lab ("HEVHY METAL")

- **Authors/organisation:** National Renewable Energy Laboratory [17] (project presentation)

- **Venue/type:** Authoritative government programme review presentation (DOE Hydrogen Program Annual Merit Review, 2022)

- **Date:** June 2022

- **Link:**

[https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063\\_christensen\\_2022\\_p.pdf](https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063_christensen_2022_p.pdf)

- **Why it matters:** Lays out a structured plan and milestones for validating charge/discharge rates and capacity for **~520 kg H<sub>2</sub>** class metal-hydride storage integrated with megawatt-scale infrastructure, which supports maturity assessment via formal programme milestones and validation criteria. [19]

**Vendor technical doc: containerised HY2 product suite and safety claims - Title:**

Hydrogen Solid State Storage (presentation)

- **Authors/organisation:** Vendor technical doc by GKN Hydrogen [13] (hosted by Italian fire safety site)

- **Venue/type:** Vendor technical doc (presentation with measurable specifications)

- **Date:** November 2022

- **Link:** <https://www.vigilfuoco.it/sites/default/files/2024-07/7.%2015112022%20-%20GKN%20%20-%20GRUBER.pdf>

- **Why it matters:** Presents a product suite (HY2MINI/HY2MEDI/HY2MEGA) with stated storage quantities (e.g., **25 kg, 60 kg, 120 kg**, and a case study scale of **500 kg H<sub>2</sub>**) and emphasises low-pressure operation and self-limiting release as safety features; useful as maturity signal but should be treated cautiously as vendor-optimistic. [20]

**Techno-economic and lifecycle evidence for scaled systems**

**LCA of the HyCARE large-scale solid-state storage prototype - Title:** Life cycle assessment for the determination of the environmental impacts of an advanced large-scale hydrogen storage system from HyCARE EU project

- **Authors/organisation:** E. S. Alves et al.

- **Venue/type:** Peer-reviewed applied study (Journal of Cleaner Production)

- **Date:** July 2025

- **Link:** <https://www.sciencedirect.com/science/article/pii/S0959652625011862>

- **Why it matters:** Uses a functional unit of **storing 46 kg H<sub>2</sub> over 50 years** for an advanced HyCARE storage concept and compares configurations (with/without PCM; vs gaseous tube storage), evidencing that the field is progressing into engineering trade-offs and lifecycle considerations typical of post-prototype decision-making. [21]

**Startup/government feasibility evidence for cryo-adsorption monoliths**

**UK feasibility report claiming high volumetric cryo-adsorption capacities in monolithic MOFs (pre-commercial) - Title:** Immaterial – Phase 1 Feasibility Study Report (Monolithic MOFs for enhanced cryo-adsorbed hydrogen storage)

- **Authors/organisation:** Immaterial[22] (client: UK government department)

- **Venue/type:** Government-commissioned feasibility report / technical study (public report; not peer-reviewed)

- **Date:** October 2022

- **Link:**

[https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117\\_Immaterial\\_Final\\_Feasibility\\_Report\\_Public\\_.pdf](https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117_Immaterial_Final_Feasibility_Report_Public_.pdf)

- **Why it matters:** Reports monolithic MOF results such as **45 g/L at 25 bar and 77 K** (Gen 1) and **59 g/L at 100 bar and 77 K** (Gen 2), and describes an initial demonstrator design concept for a **6 kg H<sub>2</sub>** tank; credibility is limited by non-peer-review but still useful for maturity signals about targeted demonstrators and performance targets. [23]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 4**

#### **Justification mapped to the rubric**

#### **Why the evidence rules out levels 1–2 (theory-only / lab principle only):**

Multiple peer-reviewed experimental papers demonstrate both (a) material-level reversible storage performance and (b) engineering near the device level: high-entropy alloys with reversible room-temperature operation and long cycling, plus multiple metal-hydride tank/device papers and demonstrations. [24]

#### **Why the evidence rules out level 3 (lab prototype only):**

There is clear evidence of **functional prototype systems** integrated into realistic application contexts:

- A containerised metal-hydride storage prototype (HyCARE) specifying storage mass, pressure/temperature bounds, and risk management/safety barriers. [10]
- A solid-state storage device integrated into a fuel-cell forklift power module with measured refuelling completion time and operational duration. [11]
- A commissioned **hundreds-kg class** metal-hydride demonstration at a national lab site integrated with megawatt-scale hydrogen infrastructure (electrolyser + fuel cell). [25]

Together these exceed “laboratory prototype” and satisfy the rubric’s requirement for a demonstrable system that can meet functional requirements of intended applications.

#### **Why level 4 fits (PoC demonstrated with viability signals):**

Level 4 requires a functional PoC that meets commercialisation requirements in functionality/viability for production, or plausibly lower cost at scale. The dossier shows:

- Engineering prototypes with defined operating envelopes and safety/risk controls (HyCARE). [26]
- Large-scale validation plans and commissioning within real infrastructure contexts (DOE Annual Merit Review milestones; national lab commissioning). [27]
- Manufacturing and supply-chain signals (industrial-level alloy batch production; extrusion/pelletisation approaches; DOE-funded fabrication/testing across multiple sites). [28]

These collectively justify “PoC” status for the **metal-hydride system variant** and show narrowing of major blockers (heat management, safety, manufacturability pathways).

#### **What is still missing to justify level 5 or higher:**

To reach level 5–6, the evidence would need stronger, verifiable signals of **repeatable product deployment at scale**, such as:

- multiple independent, well-capitalised competitors shipping comparable systems in meaningful volume,
- multi-year field performance datasets (cycle life under real duty cycles; impurity exposure; maintenance costs),
- certification/C&S milestones (type approvals, codes & standards adoption specific to these modules),
- and clear evidence of scaled manufacturing investment translating into deliveries and unit cost trajectories.

The current evidence is dominated by demonstrations, feasibility studies, and early product-suite claims rather than documented high-volume customer deliveries. [29]

#### **Sub-scores and aggregation (bundle reasoning)**

##### **Reversible metal-hydride storage modules (systems + tanks): maturity ≈ 4–5**

- Strongest evidence: containerised HyCARE prototype (40 kg H<sub>2</sub> at <50 bar, <100 °C) and national-lab commissioning of ~500 kg class metal-hydride system integrated with megawatt infrastructure. [30]
- Supporting evidence: forklift-integrated solid-state storage device and government-funded mobile refuelling system plan. [31]
- Interpretation: Functionality and integration appear PoC-level (4), with some signs of scaling and productisation (pushing toward 5), but not enough verified volume deployment.

##### **Porous adsorbent cryo-adsorption storage (MOFs/ZIFs with shaping): maturity ≈ 3–4**

- Strongest evidence: peer-reviewed densified monoliths (high volumetric H<sub>2</sub> metrics) and pelletised ZIF-8 demonstrating reproducible uptake and a usable-capacity framing; inter-lab reference-material study reduces measurement uncertainty—critical for standardisation and commercial claims. [32]
- Feasibility evidence: UK feasibility report claims 45–59 g/L monolith capacities and outlines a route to a 6 kg H<sub>2</sub> demonstrator, but remains non-peer-review and thus a weaker maturity signal. [33]
- Interpretation: Material and shaping advances are strong, but system-level deployment (particularly with cryogenic balance-of-plant) appears earlier than metal hydrides.

#### **Aggregation to one ART score:**

Because the ART description covers both **metal hydrides** and **porous adsorbents** serving the same overall function (solid(ish) hydrogen storage with safer form factors), the overall maturity is best treated as an **average weighted toward the more deployment-proximate hydride systems**, yielding **Score 4**. [34]

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[1] [32] <https://docs.nrel.gov/docs/fy22osti/83773.pdf>

<https://docs.nrel.gov/docs/fy22osti/83773.pdf>

[2] [24] <https://www.sciencedirect.com/science/article/abs/pii/S1359645422004980>  
<https://www.sciencedirect.com/science/article/abs/pii/S1359645422004980>

[3] [17] [28] <https://www.sciencedirect.com/science/article/pii/S0360319922029536>  
<https://www.sciencedirect.com/science/article/pii/S0360319922029536>

[4] <https://www.sciencedirect.com/science/article/abs/pii/S0360319922041209>  
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[5] <https://www.sciencedirect.com/science/article/pii/S0360319923024527>  
<https://www.sciencedirect.com/science/article/pii/S0360319923024527>

[6] <https://www.sciencedirect.com/science/article/pii/S0360319923028033>  
<https://www.sciencedirect.com/science/article/pii/S0360319923028033>

[7] <https://www.sciencedirect.com/science/article/abs/pii/S0360319925003623>  
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[8] <https://pubmed.ncbi.nlm.nih.gov/37771502/>  
<https://pubmed.ncbi.nlm.nih.gov/37771502/>

[9] <https://pubmed.ncbi.nlm.nih.gov/38165137/>  
<https://pubmed.ncbi.nlm.nih.gov/38165137/>

[10] [12] [13] [14] [15] [26] [30] [34]  
<https://hysafejournal.org/articles/10/files/66f3dc7304f2d.pdf>  
<https://hysafejournal.org/articles/10/files/66f3dc7304f2d.pdf>

[11] [22] [31] <https://www.sciencedirect.com/science/article/abs/pii/S0925838823035454>  
<https://www.sciencedirect.com/science/article/abs/pii/S0925838823035454>

[16] <https://www.energy.gov/sites/default/files/2024-09/CX-031126.pdf>  
<https://www.energy.gov/sites/default/files/2024-09/CX-031126.pdf>

[18] [25] [29] <https://www.nrel.gov/news/detail/program/2024/heavy-metal-debut-a-world-class-metal-hydride-system>  
<https://www.nrel.gov/news/detail/program/2024/heavy-metal-debut-a-world-class-metal-hydride-system>

[19] [27]  
[https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063\\_christensen\\_2022\\_p-pdf.pdf?sfvrsn=863974c3\\_0](https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063_christensen_2022_p-pdf.pdf?sfvrsn=863974c3_0)  
[https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063\\_christensen\\_2022\\_p-pdf.pdf?sfvrsn=863974c3\\_0](https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/ta063_christensen_2022_p-pdf.pdf?sfvrsn=863974c3_0)

[20] <https://www.vigilfuoco.it/sites/default/files/2024-07/7.%2015112022%20-%20GKN%20%20-%20GRUBER.pdf>

<https://www.vigilfuoco.it/sites/default/files/2024-07/7.%2015112022%20-%20GKN%20%20-%20GRUBER.pdf>

[21] <https://www.sciencedirect.com/science/article/pii/S0959652625011862>

<https://www.sciencedirect.com/science/article/pii/S0959652625011862>

[23] [33]

[https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117\\_Immaterial\\_Final\\_Feasibility\\_Report\\_Public\\_.pdf](https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117_Immaterial_Final_Feasibility_Report_Public_.pdf)

[https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117\\_Immaterial\\_Final\\_Feasibility\\_Report\\_Public\\_.pdf](https://assets.publishing.service.gov.uk/media/64678f5143fe01000cac65e2/HYS2117_Immaterial_Final_Feasibility_Report_Public_.pdf)

## Group 8 - Energy Generation, Storage & Conversion

### ART 08.056 Fusion Energy Reactors

#### ART extraction

#### Parsed ART claims

##### A) Primary capability (what the ART claims it can do)

- Deliver a controllable, continuously operating fusion heat source (and ultimately electricity or high-temperature process heat) from light-isotope fuels, with no combustion emissions and relatively small volumes of long-lived waste (as described in the ART).
- Operate as an industrial facility with dense diagnostics, fast feedback control, shielding, and remote/robotic maintenance in “hot” (high-radiation) environments (as described in the ART).

##### B) Key sub-components / variants (sub-threads of the bundle)

- **Magnetic confinement:** tokamaks and stellarators (plasma shaping, heating, and control).
- **Inertial confinement / inertial fusion energy (IFE):** laser-driven implosions (indirect drive and direct drive), plus the repetition-rate and target-supply engineering needed for power production. [1]
- **High-field magnet technology:** high-temperature superconductors (HTS), demountable joints, cryogenics, quench detection/protection. [2]
- **Plasma sensing + fast control:** real-time control systems, advanced control methods (including machine learning) that can handle high-dimensional plasma shaping and constraints. [3]
- **Neutron-tolerant materials / components:** reduced-activation structural steels, plasma-facing components/divertors, irradiation hardening/embrittlement and lifetime under reactor conditions. [4]
- **Fuel cycle:** tritium breeding blankets, tritium handling and accountancy, startup tritium inventory constraints, safety and safeguards interfaces. [5]



- **Remote handling / hot-cell-style maintenance:** remotely controlled tools, connectors, and workflows for rapid component replacement to support high availability. [6]

### C) “Maturity indicators” that would count as evidence for this ART

- **Physics plausibility:** experimentally demonstrated ignition/burning-plasma milestones (IFE), and reactor-relevant D-T plasma behaviour/validation (magnetic confinement). [7]

- **Engineering plausibility:** long-pulse, actively cooled plasma-facing components and heat-exhaust control; validated high-field magnet prototypes at representative scale; demonstrated remote maintenance prototypes and procedures. [8]

- **Path-to-market maturity:** credible pilot-plant/demonstration planning by major public programmes; identifiable regulatory pathway; and proof that key bottlenecks (materials lifetime, tritium self-sufficiency, availability/uptime) are moving from “known unknowns” to demonstrated solutions. [9]

### Evidence (10–20 recent, reliable sources)

1) **Title:** Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment

**Authors/organisation:** H. Abu-Shawareb[10] et al. (Indirect Drive ICF Collaboration; reported via Lawrence Livermore National Laboratory[11] / National Ignition Facility[12] records)

**Venue/type:** Peer-reviewed paper (Physical Review Letters; indexed by OSTI)

**Publication date:** February 2024

**Link (URL):** <https://www.osti.gov/biblio/2283994>

**Why it matters (1–2 sentences):** Reports a NIF implosion (5 Dec 2022) with **target gain ~1.5**, where **2.05 MJ** of laser energy produced **~3.1 MJ** fusion yield—an unequivocal physics plausibility milestone (scientific breakeven at the target). [13]

2) **Title:** Demonstration of hot-spot fuel gain exceeding unity in direct-drive inertial confinement fusion implosions

**Authors/organisation:** C. A. Williams[14] et al.

**Venue/type:** Peer-reviewed paper (Nature Physics)

**Publication date:** 5 February 2024 (version of record; issue date May 2024)

**Link (URL):** <https://www.nature.com/articles/s41567-023-02363-2>

**Why it matters (1–2 sentences):** Demonstrates **hot-spot fuel gain > 1** in **direct-drive** ICF, strengthening plausibility that non-indirect-drive schemes can reach burning-plasma-relevant regimes and offering a second, independent experimental track toward IFE concepts. [15]

3) **Title:** Future for inertial-fusion energy in Europe: a roadmap

**Authors/organisation:** Dimitri Batani[16] et al.

**Venue/type:** Peer-reviewed review / roadmap (High Power Laser Science and Engineering)

**Publication date:** Published online 28 September 2023

**Link (URL):** <https://www.cambridge.org/core/journals/high-power-laser-science-and-engineering/article/future-for-inertialfusion-energy-in-europe-a-roadmap/CA1BC0917BDCF29906B9D30799D945E9>

**Why it matters (1–2 sentences):** Converts recent ignition milestones into an engineering-centred European roadmap, explicitly identifying power-plant-relevant gaps such as **high-repetition-rate**, **high-energy lasers**, target supply, and supporting infrastructure—evidence that IFE is plausible but still far from plant-class maturity. [17]

4) **Title:** Overview of T and D–T results in JET with ITER-like wall

**Authors/organisation:** C. F. Maggi[18] et al. (JET Contributors)

**Venue/type:** Peer-reviewed paper (Nuclear Fusion; open access PDF via institutional repository)

**Publication date:** November 2024 (issue information indicates 01.11.2024)

**Link (URL):**

[https://research.chalmers.se/publication/543057/file/543057\\_Fulltext.pdf](https://research.chalmers.se/publication/543057/file/543057_Fulltext.pdf)

**Why it matters (1–2 sentences):** Synthesises reactor-relevant **T and D-T** campaigns with an ITER-like Be/W wall, including goals such as sustaining **≥10 MW fusion power for 5 s**, and documenting achieved records such as **59 MJ** sustained D-T fusion energy (recorded as “new world record” in the paper’s conclusions). [19]

5) **Title:** Overview of deuterium-tritium nuclear operations at JET

**Authors/organisation:** R. Villari[20] et al.

**Venue/type:** Peer-reviewed paper (Fusion Engineering and Design; open access)

**Publication date:** August 2025 (Volume 217)

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0920379625003308>

**Why it matters (1–2 sentences):** Frames JET as an integrated **nuclear tokamak** testbed: two DT campaigns (2021 and 2023) produced **>1.5×10<sup>21</sup>** 14.1 MeV neutrons and generated data for **activation, materials damage, water activation, electronics effects**, and **licensing-relevant** benchmarking—evidence of progression from plasma physics toward plant-adjacent nuclear engineering questions. [21]

6) **Title:** Overview of the first Wendelstein 7-X long-pulse campaign with fully water-cooled plasma facing components

**Authors/organisation:** O. Grulke[22] et al. (device: Wendelstein 7-X[23])

**Venue/type:** Peer-reviewed paper (Nuclear Fusion)

**Publication date:** 15 August 2024

**Link (URL):**

[https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview\\_of\\_the\\_first\\_Wendelstein\\_7-X\\_long\\_pulse\\_campaign\\_with\\_fully\\_water-cooled\\_plasma\\_facing\\_components.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview_of_the_first_Wendelstein_7-X_long_pulse_campaign_with_fully_water-cooled_plasma_facing_components.pdf)

**Why it matters (1–2 sentences):** Reports a long-pulse, actively cooled campaign with **up to 480 s (8 min)** discharge length and **~1.3 GJ** total heating energy, demonstrating (a) the practicality of extensive water-cooling of plasma-facing components and (b) controlled divertor heat-exhaust scenarios—key precursors for steady-state reactor operation. [24]

7) **Title:** Recent progress of JT-60SA project toward plasma operation

**Authors/organisation:** H. Shirai[25] et al. (device: JT-60SA[26]; joint Japan–Euratom Broader Approach)

**Venue/type:** Peer-reviewed paper (Nuclear Fusion)

**Publication date:** 2024 (paper file indicates Nuclear Fusion 64 (2024) 112008)

**Link (URL):**

[https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent\\_progress\\_of\\_JT-60SA\\_project\\_toward\\_plasma\\_operation.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent_progress_of_JT-60SA_project_toward_plasma_operation.pdf)

**Why it matters (1–2 sentences):** Documents superconducting-tokamak commissioning and risk-mitigation engineering (e.g., insulation reinforcement, voltage-to-ground reductions,

improved interlocks), and records first plasma milestones (e.g., first plasma achieved 23 Oct 2023) as an ITER-relevant operational learning platform. [27]

8) **Title:** Updated baseline presented (34th ITER Council)

**Authors/organisation:** ITER Organization[28]

**Venue/type:** Authoritative programme update (official project baseline status)

**Publication date:** 20 June 2024

**Link (URL):** <https://www.iter.org/node/20687/updated-baseline-presented>

**Why it matters (1–2 sentences):** Provides schedule-grade maturity evidence for the leading magnetic-confinement flagship: the proposed baseline includes **deuterium-deuterium fusion operation in 2035** and explicitly frames re-baselining around **licensing and technical risk reduction**—a candid view of time-to-scale constraints. [29]

9) **Title:** ITER progresses into new baseline

**Authors/organisation:** Pietro Barabaschi[30] et al. (“ITER Contributors”)

**Venue/type:** Peer-reviewed / programme paper (Fusion Engineering and Design)

**Publication date:** June 2025 (Volume 215)

**Link (URL):**

<https://www.sciencedirect.com/science/article/abs/pii/S0920379625001905>

**Why it matters (1–2 sentences):** Captures an engineering-management and integration view of ITER’s revised baseline in a citable technical venue, reinforcing that large-scale fusion programmes are still in a risk-reduction phase rather than a plant-replication phase. [31]

10) **Title:** Balance of plant conceptual design of EU DEMO integrating different breeding blanket concepts

**Authors/organisation:** Matteo Zaupa[32] et al.

**Venue/type:** Peer-reviewed paper (Fusion Engineering and Design; open access)

**Publication date:** March 2024 (Volume 200)

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0920379624000887>

**Why it matters (1–2 sentences):** Treats the fusion plant as a whole system: explicitly targets “**several hundred MWs of net electricity**” and analyses how different tritium-breeding blanket choices cascade into balance-of-plant and power-conversion design, evidencing that DEMO-class work is active but remains conceptual. [33]

11) **Title:** Replacement strategy of the EU-DEMO and CFETR breeding blanket pipes

**Authors/organisation:** Rocco Mozzillo[34] et al.

**Venue/type:** Peer-reviewed paper (Fusion Engineering and Design; open access)

**Publication date:** May 2024 (Volume 202)

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0920379624001649>

**Why it matters (1–2 sentences):** Quantifies a major availability bottleneck: for blanket maintenance, **320 pipes** would need to be cut/removed/rewelded, and the paper reports progress toward **manufactured prototypes** and dedicated test benches (including collaboration with China’s CRAFT/ASIPP) intended to reduce downtime. [35]

12) **Title:** Impact of neutron irradiation on the tensile properties of advanced EUROFER97-type steels

**Authors/organisation:** O. Kachko[36] et al.

**Venue/type:** Peer-reviewed paper (Journal of Nuclear Materials; ScienceDirect record)

**Publication date:** 2024 (month not shown in the accessible abstract record)

**Link (URL):**

<https://www.sciencedirect.com/science/article/abs/pii/S0022311524002782>

**Why it matters (1–2 sentences):** Addresses a central feasibility constraint for D-T fusion: irradiation hardening and embrittlement of RAFM steels (EUROFER97) under relevant temperature windows (noted challenges below ~350 °C), directly linking neutron exposure to reduced ductility/toughness—evidence that materials lifetime remains a key maturity limiter. [37]

13) **Title:** UK Fusion Materials Roadmap 2.0

**Authors/organisation:** UK Atomic Energy Authority[38] (roadmap document)

**Venue/type:** Authoritative roadmap/report (national fusion materials roadmap)

**Publication date:** September 2025 (published file timing and document framing as “Roadmap 2025”)

**Link (URL):** <https://www.ukaea.org/wp-content/uploads/2025/09/uk-materials-roadmap-2-0.pdf>

**Why it matters (1–2 sentences):** Consolidates plant-readiness “gap lists” across magnets/shielding, tritium breeding, high-temperature and radiation-hardened materials, and explicitly states that D-T plants must breed tritium but practical routes (materials selection, barriers/coatings, retention) remain unresolved and require coordinated testing infrastructure. [39]

14) **Title:** Investigating the application of Kalman Filters for real-time accountancy in fusion fuel cycles

**Authors/organisation:** H. B. Flynn[40]; George Larsen

**Venue/type:** Peer-reviewed paper (Fusion Engineering and Design)

**Publication date:** March 2022 (Volume 176)

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0920379622000370>

**Why it matters (1–2 sentences):** Focuses on a concrete “fusion plant operations” requirement—**tritium accountancy** under continuous operation and noisy measurements—and demonstrates modelling/estimation methods (Kalman filtering) aimed at meeting stringent inventory tracking; this underlines that fuel-cycle instrumentation and state estimation are active R&D, not solved commodities. [41]

15) **Title:** The SPARC Toroidal Field Model Coil Program

**Authors/organisation:** Zachary Hartwig[42] et al. (MIT PSFC / CFS programme; device pathway toward SPARC[43])

**Venue/type:** Preprint with substantial engineering detail (arXiv)

**Publication date:** August 2023 (arXiv submission year; exact posting date not required for window compliance)

**Link (URL):** <https://arxiv.org/abs/2308.12301>

**Why it matters (1–2 sentences):** Reports representative-scale HTS magnet testing with quantitative performance: **20.1 T peak field-on-conductor**, **40.5 kA** terminal current, and demountable joints operating in the **~0.5–2.0 nΩ** range at **20 K**—strong plausibility evidence for compact high-field magnetic confinement approaches. [44]

16) **Title:** Development of a high current density, high temperature superconducting cable for pulsed magnets

**Authors/organisation:** Charlie Sanabria[45] et al.

**Venue/type:** Peer-reviewed paper (Superconductor Science and Technology; indexed by OSTI)

**Publication date:** 23 September 2024

**Link (URL):** <https://www.osti.gov/pages/biblio/2447881>

**Why it matters (1–2 sentences):** Provides an HTS “supply-chain-ready” advancement for fusion magnets (REBCO cable technology for pulsed magnets), supporting maturation of one of the most capital-intensive and schedule-critical subsystems for magnetic fusion reactors. [46]

17) **Title:** Development of the optical remote handling connector for ITER Divertor Operational Instrumentation

**Authors/organisation:** Janne Lyytinen[47] et al.

**Venue/type:** Peer-reviewed paper (Fusion Engineering and Design; open access)

**Publication date:** September 2023 (Volume 194)

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0920379623003186>

**Why it matters (1–2 sentences):** Demonstrates plant-style maintainability engineering: designs and **tests a full-size mock-up** remote-handling connector under **high-vacuum ( $\sim 10^{-5}$  Pa), high-temperature (up to 350 °C), and high radiation dose (up to 1 GGy)** constraints, including industrial manipulator connect/disconnect trials—direct evidence of progress toward robotic maintenance in hazardous environments. [48]

18) **Title:** Magnetic control of tokamak plasmas through deep reinforcement learning

**Authors/organisation:** Jonas Degraeve[49] et al.

**Venue/type:** Peer-reviewed paper (Nature)

**Publication date:** 16 February 2022

**Link (URL):** <https://www.nature.com/articles/s41586-021-04301-9>

**Why it matters (1–2 sentences):** Shows a credible pathway to the ART’s “fast control + digital twin” operating style: a controller architecture that can autonomously learn to command a plasma’s magnetic control coils under constraints, reducing design effort for new configurations—relevant to future high-availability operations where control complexity scales up. [50]

19) **Title:** Regulatory Framework for Fusion Systems (availability of preliminary proposed rule language; public meeting)

**Authors/organisation:** U.S. Nuclear Regulatory Commission[51] (Federal Register notice)

**Venue/type:** Authoritative regulatory document (Federal Register)

**Publication date:** 4 October 2023

**Link (URL):** <https://www.federalregister.gov/documents/2023/10/04/2023-21988/regulatory-framework-for-fusion-systems>

**Why it matters (1–2 sentences):** Establishes a concrete near-term licensing pathway: NRC is considering amendments to its **byproduct material** regulations (10 CFR Parts 20/30/51) to create a technology-inclusive fusion regulatory framework, responding to NEIMA’s direction to establish a framework by **31 Dec 2027**—a key maturity prerequisite for commercial deployment. [52]

20) **Title:** Fusion Energy Strategy 2024

**Authors/organisation:** U.S. Department of Energy[\[53\]](#)

**Venue/type:** Authoritative strategy/roadmap report (government programme strategy)

**Publication date:** June 2024

**Link (URL):** <https://www.energy.gov/sites/default/files/2024-06/fusion-energy-strategy-2024.pdf>

**Why it matters (1–2 sentences):** Provides explicit maturity framing: targets private-sector-led fusion pilot plants in the **2030s** and highlights “commercialisation risks” such as **materials**, **supply chains**, and **fuel isotopes**, including the need for **startup tritium and lithium-6** even if plants ultimately breed their own tritium. [\[54\]](#)

**Maturity score (1–7) and reasoning**

**Final maturity score**

**Final maturity score: 3**

**Evidence-to-rubric mapping**

**What evidence rules out levels 1–2 (i.e., why this is beyond “principle verified”)?**

- Multiple subthreads have moved past theoretical plausibility into **repeatable laboratory and facility-scale demonstrations** of key enabling functions:
- IFE has peer-reviewed demonstrations of **energy gain metrics exceeding unity** (target gain at NIF; hot-spot fuel gain in direct-drive). [\[55\]](#)
- Magnetic fusion has reactor-relevant **D–T operational campaigns** with ITER-like wall materials, documented in a recent peer-reviewed synthesis (JET) and a nuclear-operations engineering overview (activation, materials damage, benchmarking for licensing). [\[56\]](#)
- Stellarator development has crossed an engineering threshold for long-pulse operations with **fully water-cooled plasma-facing components** and substantial delivered energy over minutes, directly addressing the shift from “short physics shots” to “thermally managed operation.” [\[24\]](#)
- High-field magnet technology has been demonstrated at representative scale with quantified performance (20.1 T class HTS coil) and parallel work on manufacturable HTS cables. [\[2\]](#)

These collectively meet the rubric’s Level-3 condition: **laboratory / facility prototypes show previously blocking problems are being solved in practice**, though cost, durability, and integrated plant operability are not yet proven at scale. [\[57\]](#)

**What evidence is still missing to justify Level 4 (PoC meeting commercialisation requirements)?**

Level 4 would require an integrated prototype that convincingly meets commercialisation requirements (continuous high-duty operation, practical heat extraction and power conversion, fuel sustainability, and maintainability/availability). The evidence set still shows major gaps:

- **Plant-integrated power production and availability** remain largely conceptual or programme-planned: EU DEMO balance-of-plant work is explicitly “conceptual design,” and ITER timelines place D-D operation in **2035**, underscoring distance from commercial PoC. [\[58\]](#)
- **Materials lifetime under fusion neutron spectra** is still a limiting uncertainty, with recent



work emphasising irradiation-induced hardening/embrittlement challenges in key candidate structural steels. [4]

- **Tritium self-sufficiency** is not yet demonstrated in an operating fusion machine; authoritative strategy documents emphasise the need for **startup tritium** and staged closure of fuel-cycle gaps, and technical work continues on high-fidelity tritium accountancy methods. [59]

- **Remote maintenance at plant scale** is progressing (e.g., full-size connector mock-ups and DEMO blanket pipe maintenance concepts with prototypes), but these are still subsystem validations rather than integrated, high-availability plant demonstrations. [60]

- **Regulatory pathways** are emerging (e.g., NRC rulemaking activity), but broad, internationally harmonised fusion licensing practice and standardised safety cases are not yet “routine,” which is typically needed before PoC-to-product transitions. [61]

Given these gaps, the whole ART cannot credibly be scored as Level 4+ today: the sector has **strong prototypes and fast progress**, but it is not yet at “commercialisation-requirements-met” PoC for an electricity-producing, tritium-self-sufficient fusion plant. [62]

### Sub-component breakdown and aggregation

Because “fusion energy reactors” is a bundled ART with heterogeneous maturity across subsystems, the score is best treated as an **average-weighted plant readiness** rather than the maximum of any one subthread.

- **Inertial confinement fusion (physics milestone subthread) → 3**
- Target/physics energy-gain milestones are experimentally demonstrated, but a power-plant-relevant repetition-rate system and target supply chain are explicitly future work in roadmaps. [63]
- **Magnetic confinement plasma + nuclear operations → 3**
- Reactor-relevant D-T operations and nuclear engineering benchmarking exist, but ITER’s schedule and ongoing baseline revisions indicate remaining integration and risk-reduction work before pilot-plant-like operations. [64]
- **Stellarator long-pulse, actively cooled PFCs → 3**
- Minutes-scale discharges with water-cooled components are a major step, but still below steady-state commercial duty cycles and without a full power-plant fuel cycle. [24]
- **HTS magnets and superconducting infrastructure → 3**
- Representative-scale, quantified coil demonstrations and cable developments exist, but fleet manufacturing and long-life under reactor neutron environments remain to be proven for power-plant deployment. [65]
- **Fuel cycle (tritium) and breeding blankets → 2–3**
- The need for startup tritium and the difficulty of accountancy and self-sufficiency are explicitly recognised in authoritative strategy and technical studies, while DEMO/blanket maintenance shows design/prototype activity rather than operational closure. [66]

- **Remote handling / maintainability engineering → 3 (with some elements approaching 4)**
- Full-size mock-ups and maintenance concepts with prototypes exist (connectors; blanket pipe handling), but not yet as an integrated “plant turnaround” system proven under full nuclear conditions and commercial availability targets. [60]

**Aggregation rationale:** The strongest components (plasma physics milestones, long-pulse cooled operation, and HTS magnet prototypes) justify Level 3, but fuel-cycle closure, materials lifetime, and plant-level availability still anchor the overall ART below Level 4. This supports a single overall score of **3** rather than a maximum-based 4+. [67]

[1] [7] [13] [34] [55] [63] <https://www.osti.gov/biblio/2283994>

<https://www.osti.gov/biblio/2283994>

[2] [10] [12] [23] [38] [43] [44] [57] [65] <https://arxiv.org/abs/2308.12301>

<https://arxiv.org/abs/2308.12301>

[3] [16] [30] <https://www.sciencedirect.com/science/article/pii/S0920379624004915>

<https://www.sciencedirect.com/science/article/pii/S0920379624004915>

[4] [26] [36] [37] [42] [51] [67]

<https://www.sciencedirect.com/science/article/abs/pii/S0022311524002782>

<https://www.sciencedirect.com/science/article/abs/pii/S0022311524002782>

[5] [9] [32] [40] [45] [54] [59] [62] [66] <https://www.energy.gov/sites/default/files/2024-06/fusion-energy-strategy-2024.pdf>

<https://www.energy.gov/sites/default/files/2024-06/fusion-energy-strategy-2024.pdf>

[6] [48] [60] <https://www.sciencedirect.com/science/article/pii/S0920379623003186>

<https://www.sciencedirect.com/science/article/pii/S0920379623003186>

[8] [24] [28]

[https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview\\_of\\_the\\_first\\_Wendelstein\\_7-X\\_long\\_pulse\\_campaign\\_with\\_fully\\_water-cooled\\_plasma\\_facing\\_components.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview_of_the_first_Wendelstein_7-X_long_pulse_campaign_with_fully_water-cooled_plasma_facing_components.pdf)

[https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview\\_of\\_the\\_first\\_Wendelstein\\_7-X\\_long\\_pulse\\_campaign\\_with\\_fully\\_water-cooled\\_plasma\\_facing\\_components.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162804594/Overview_of_the_first_Wendelstein_7-X_long_pulse_campaign_with_fully_water-cooled_plasma_facing_components.pdf)

[11] [17] <https://www.cambridge.org/core/journals/high-power-laser-science-and-engineering/article/future-for-inertialfusion-energy-in-europe-a-roadmap/CA1BC0917BDCF29906B9D30799D945E9>

<https://www.cambridge.org/core/journals/high-power-laser-science-and-engineering/article/future-for-inertialfusion-energy-in-europe-a-roadmap/CA1BC0917BDCF29906B9D30799D945E9>

[14] [27] [https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent\\_progress\\_of\\_JT-60SA\\_project\\_toward\\_plasma\\_operation.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent_progress_of_JT-60SA_project_toward_plasma_operation.pdf)

[https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent\\_progress\\_of\\_JT-60SA\\_project\\_toward\\_plasma\\_operation.pdf](https://acris.aalto.fi/ws/portalfiles/portal/162313809/Recent_progress_of_JT-60SA_project_toward_plasma_operation.pdf)

[15] <https://www.nature.com/articles/s41567-023-02363-2>

<https://www.nature.com/articles/s41567-023-02363-2>

[18] [41] <https://www.sciencedirect.com/science/article/abs/pii/S0920379622000370>

<https://www.sciencedirect.com/science/article/abs/pii/S0920379622000370>

[19] [49] [56] [64] [https://research.chalmers.se/publication/543057/file/543057\\_Fulltext.pdf](https://research.chalmers.se/publication/543057/file/543057_Fulltext.pdf)

[https://research.chalmers.se/publication/543057/file/543057\\_Fulltext.pdf](https://research.chalmers.se/publication/543057/file/543057_Fulltext.pdf)

[20] [52] [61] <https://www.federalregister.gov/documents/2023/10/04/2023-21988/regulatory-framework-for-fusion-systems>

<https://www.federalregister.gov/documents/2023/10/04/2023-21988/regulatory-framework-for-fusion-systems>

[21] [22] [25] <https://www.sciencedirect.com/science/article/pii/S0920379625003308>

<https://www.sciencedirect.com/science/article/pii/S0920379625003308>

[29] <https://www.iter.org/node/20687/updated-baseline-presented>

<https://www.iter.org/node/20687/updated-baseline-presented>

[31] <https://www.sciencedirect.com/science/article/abs/pii/S0920379625001905>

<https://www.sciencedirect.com/science/article/abs/pii/S0920379625001905>

[33] [53] [58] <https://www.sciencedirect.com/science/article/pii/S0920379624000887>

<https://www.sciencedirect.com/science/article/pii/S0920379624000887>

[35] <https://www.sciencedirect.com/science/article/pii/S0920379624001649>

<https://www.sciencedirect.com/science/article/pii/S0920379624001649>

[39] <https://www.ukaea.org/wp-content/uploads/2025/09/uk-materials-roadmap-2-0.pdf>

<https://www.ukaea.org/wp-content/uploads/2025/09/uk-materials-roadmap-2-0.pdf>

[46] <https://www.osti.gov/pages/biblio/2447881>

<https://www.osti.gov/pages/biblio/2447881>

[47] [50] <https://www.nature.com/articles/s41586-021-04301-9>

<https://www.nature.com/articles/s41586-021-04301-9>

## ART 08.057 Small Modular Fission Reactors (SMRs)

151. ART extraction

### Primary capability claimed (1–3 bullets)

- Deliver **firm, high-density nuclear electricity** in smaller, repeatable units (tens to a few hundreds of MWe) rather than bespoke gigawatt-scale megaprojects.
- **Reduce construction risk and schedule** via standardised designs, factory fabrication of major components, and modular delivery/assembly.
- Improve safety and operability using **passive / inherent safety features** (e.g., natural circulation, gravity-fed cooling), plus high instrumentation and remote-support operations.

### Key sub-components / variants (3–7 sub-threads)

- **Light-water SMRs (LWR-SMRs)**: integral PWRs and natural-circulation BWRs (closest to existing nuclear industrial base).
- **Non-light-water “advanced” SMRs**: high-temperature gas-cooled reactors (HTGRs), sodium-cooled fast reactors, molten-salt concepts (often more dependent on novel fuels/supply chains).
- **Passive decay-heat removal architectures**: isolation condensers, passive containment cooling, natural circulation loops, gravity-driven injection, etc.
- **Manufacturing & modular construction**: heavy forgings, nuclear-grade QA, repeatable module fabrication, transport logistics, site assembly.
- **Licensing/regulatory pathways**: design certification/approval, construction licence issuance, generic design assessments, multi-jurisdiction harmonisation efforts.
- **Fuel supply & back-end**: conventional LEU for many LWR-SMRs; **HALEU** (5–20% enrichment) for many advanced SMRs; spent-fuel handling, storage, and ultimate disposal.
- **Digital operations**: instrumentation, diagnostics, cyber-secure remote monitoring, and “digital twin”/model-based planning (varies by design and regulator acceptance).

### What “maturity evidence” should look like for this ART

- **Regulatory milestones**: design certification/approval and/or **construction licences** granted for FOAK projects; progressing generic assessments.
- **Project execution evidence**: site permits, EPC contracting, long-lead procurement, first nuclear concrete, module manufacturing milestones.
- **Supply-chain readiness**: qualified nuclear-grade manufacturing capacity; standards/codes maturity; evidence of repeatable QA processes.
- **Fuel readiness**: secured fuel pathways (LEU or HALEU) with credible timelines and licensed facilities.
- **Operational readiness**: staffing/remote-support concepts accepted by regulators; credible cybersecurity and instrumentation approaches.
- **Commercial traction**: multiple well-capitalised vendors and utilities moving beyond studies towards financed builds and repeat orders.

### Evidence (10–20 recent, reliable sources)

152. Evidence (10–20 recent, reliable sources)

### Evidence selection notes

All sources below have a visible publication date (or “last updated/modified” date) within the strict window **February 2022–February 2026**. The set is intentionally weighted toward **regulators, national agencies, and technical programme documents** because those best evidence market proximity (licensing, construction authority, supply-chain constraints) for nuclear fission deployments.

### Annotated source list

#### 1) NuScale Small Modular Reactor Design Certification

Organisation: U.S. Nuclear Regulatory Commission[1]

Venue/type: Regulatory final rule (Federal Register)

Publication date: **January 2023** (effective **February 2023**)

Link: <https://www.federalregister.gov/documents/2023/01/19/2023-00729/nuscale-small-modular-reactor-design-certification>

Annotation: The rule **certifies the NuScale standard SMR design**, enabling future applicants to reference the certified design in licensing applications—strong evidence that an SMR design has crossed major safety and regulatory review thresholds. This directly supports technical plausibility and shows maturity beyond prototype-only status. [2]

#### 2) NuScale Power, LLC; NuScale US460 Small Modular Reactor; Standard Design Approval

Organisation: U.S. Nuclear Regulatory Commission

Venue/type: Regulatory notice (Federal Register)

Publication date: **June 2025** (SDA issued **May 2025**)

Link: <https://www.federalregister.gov/documents/2025/06/04/2025-10123/nuscale-power-llc-nuscale-us460-small-modular-reactor-standard-design-approval>

Annotation: Confirms NRC issuance of a **Standard Design Approval (SDA)** allowing the NuScale US460 SMR design to be referenced in construction/operating licence applications, and notes completion of NRC staff technical review (FSER). This is high-grade maturity evidence for an LWR-SMR pathway. [3]

#### 3) Standard Design Approval for the NuScale US460 Power Plant Design (approval letter + enclosed SDA)

Organisation: NuScale Power, LLC[4]

Venue/type: Regulator letter + approval documentation (official PDF)

Publication date: **May 2025**

Link:

[https://content.govdelivery.com/attachments/USNRC/2025/05/29/file\\_attachments/3275315/Standard%20Design%20Approval%20SDA%20for%20the%20NuScale%20US460%20Power%20Plant%20Design.pdf](https://content.govdelivery.com/attachments/USNRC/2025/05/29/file_attachments/3275315/Standard%20Design%20Approval%20SDA%20for%20the%20NuScale%20US460%20Power%20Plant%20Design.pdf)

Annotation: Provides concrete regulatory details: the US460 design is **~250 MWt / 77 MWe per module** and the SDA is valid **15 years**, and states that issuance signifies completion of NRC technical review. This directly evidences “design frozen + regulator-reviewed” maturity rather than a lab or paper concept. [5]

#### 4) Combined phases 1 and 2 pre-licensing vendor design review – GEH Nuclear Energy (executive summary)

Organisation: Canadian Nuclear Safety Commission[6]

Venue/type: Regulator pre-licensing design review summary report

Publication date: **March 2023** (date modified shown)

Link: <https://www.cnsccsn.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/geh-nuclear-energy-executive-summary/>

Annotation: CNSC reports reviewing **200+ design documents** and concludes the vendor understands regulatory requirements and that CNSC staff did **not identify fundamental barriers to licensing**, while listing remaining technical areas (e.g., severe-accident analysis, decommissioning programme detail). This is strong evidence of plausibility plus a clear picture of “what remains” before broader deployment. [7]

#### 5) **Commission authorises a construction licence for one BWRX-300 at the Darlington New Nuclear Project**

Organisation: Canadian Nuclear Safety Commission (news release with decision summary)

Venue/type: Regulator decision / construction licence announcement

Publication date: **April 2025**

Link: <https://www.canada.ca/en/nuclear-safety-commission/news/2025/04/commission-authorizes-ontario-power-generation-inc-to-construct-1-bwrx-300-reactor-at-the-darlington-new-nuclear-project-site.html>

Annotation: Announces issuance of a **power reactor construction licence** to Ontario Power Generation Inc.[8] to construct **one** BWRX-300 SMR, including licence validity to **2035** and reference to a public hearing process. A construction licence is among the strongest near-market maturity indicators available for SMRs. [9]

#### 6) **Darlington New Nuclear Project (licensing status overview page)**

Organisation: Canadian Nuclear Safety Commission

Venue/type: Regulator project status page (official)

Publication date: **January 2026** (date modified shown)

Link: <https://www.cnsccsn.gc.ca/eng/reactors/new-reactor-power-plant-projects/new-reactor-power-plant-facilities/darlington-new-nuclear-project/>

Annotation: Consolidates key maturity facts in one regulator source: the project includes **site preparation, construction, and operation** of up to 4 reactors; it confirms the facility now **holds a licence to construct** (valid until **March 2035**) and documents prior licence stages. This supports assessment of real project progression beyond paper licensing. [10]

#### 7) **Generic Design Assessment of the BWRX-300: Step 2 Summary Report**

Organisation: Office for Nuclear Regulation[11]

Venue/type: Regulator generic design assessment report (PDF)

Publication date: **December 2025**

Link: <https://www.onr.org.uk/media/taufoxsv/bwrx-300-gda-step-2-summary-report.pdf>

Annotation: The report describes the BWRX-300 as a **~870 MWth / ~300 MWe** natural-circulation BWR and focuses on novelty such as **advanced construction techniques** and the **isolation condenser system**; it states ONR did **not identify fundamental shortfalls** that would prevent permissioning (subject to future evidence). It also records design claims such as **multi-day passive cooling without power/operator action**, which is central to the ART's passive-safety premise. [12]

#### 8) **GDA Step 2 of the Rolls-Royce SMR: fundamental assessment**

Organisations: Environment Agency[13] and Natural Resources Wales[14]



Venue/type: Regulator publication (GDA Step 2 suite; official government page)

Publication date: **July 2024**

Link: <https://www.gov.uk/government/publications/gda-step-2-of-the-rolls-royce-smr-fundamental-assessment>

Annotation: Documents that the UK regulators completed **Step 2** of Generic Design Assessment for the **Rolls-Royce 470 MWe SMR design**, including a public summary and full report set, and provides the formal timeline (Step 1 began April 2022; Step 2 began April 2023). This is concrete evidence of active, staged licensing progress for another major SMR vendor. [15]

#### 9) **Pathways to Commercial Liftoff: Advanced Nuclear**

Organisation: U.S. Department of Energy [16]

Venue/type: Government roadmap / commercialisation report (PDF)

Publication date: **September 2024**

Link: <https://gain.inl.gov/content/uploads/4/2024/11/DOE-Advanced-Nuclear-Liftoff-Report.pdf>

Annotation: This report explicitly covers **small modular reactors** and frames the pathway from FOAK to NOAK, including “committed orderbook,” “project delivery,” and “industrialization” levers. It is strong evidence that commercial-scale deployment barriers are now dominated by financing, delivery, and industrial base—not basic scientific feasibility. [17]

#### 10) **Final HALEU EIS Summary (DOE/EIS-0559): support for commercial production of HALEU**

Organisation: U.S. Department of Energy

Venue/type: Government environmental impact statement (EIS) summary (PDF)

Publication date: **October 2024**

Link: <https://www.energy.gov/sites/default/files/2024-12/FINAL%20HALEU%20EIS%20Summary.pdf>

Annotation: DOE describes a programme to acquire (via procurement) HALEU enriched **≥19.75% and <20% U-235** over a **10-year** period, including enrichment and deconversion activities—direct evidence that fuel supply is a central gating factor for many advanced SMR variants. It also highlights that follow-on licensing/permits and site-specific analyses are required before facilities operate, reinforcing maturity constraints outside the reactor hardware itself. [18]

#### 11) **The NEA Small Modular Reactor Dashboard: Volume II**

Organisation: OECD Nuclear Energy Agency [19]

Venue/type: International agency assessment / dashboard report (PDF)

Publication date: **July 2023**

Link: [https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/the-nea-small-modular-reactor-dashboard\\_c30b50a8/e586e483-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/the-nea-small-modular-reactor-dashboard_c30b50a8/e586e483-en.pdf)

Annotation: Provides a structured global snapshot of progress across **licensing, siting, financing, supply chain, engagement, and fuel** for a set of SMR designs, using verifiable public sources and explicit criteria. This is useful maturity evidence because it evaluates more than “is it buildable”—it tracks real-world readiness dimensions needed for deployment. [20]

### 12) **The NEA Small Modular Reactor Dashboard: Second Edition (overview page + metadata)**

Organisation: OECD Nuclear Energy Agency

Venue/type: International agency publication page (methods + headline counts)

Publication date: **February 2024** (timestamp shown on page metadata)

Link: [https://www.oecd-neo.org/jcms/pl\\_90816/the-nea-small-modular-reactor-dashboard-second-edition](https://www.oecd-neo.org/jcms/pl_90816/the-nea-small-modular-reactor-dashboard-second-edition)

Annotation: Defines SMRs as typically **≤300 MWe** (some 1–10 MWe) and emphasises modular manufacturing/portability/scalability; it states the edition identified **98** SMR technologies and included **56** in the assessment, with a progress cutoff of **10 November 2023**. This evidences a large, competitive development ecosystem—supporting the rubric’s “many well-capitalised actors competing” criterion. [21]

### 13) **Advanced Reactor Codes and Standards Collaborative Workshop: meeting summary & attachments**

Organisation: Electric Power Research Institute[22]

Venue/type: Technical workshop summary (codes/standards; PDF)

Publication date: **November 2023**

Link: [https://arcsc.azurewebsites.net/Files/11-30-23\\_ARCSC\\_Workshop\\_Summary\\_Final\\_w-Attachments%282%29.pdf](https://arcsc.azurewebsites.net/Files/11-30-23_ARCSC_Workshop_Summary_Final_w-Attachments%282%29.pdf)

Annotation: Documents a multi-stakeholder effort (including standards bodies, national labs, and vendors) to close gaps in **consensus codes and standards** for advanced reactors, including SMRs, and notes a compiled list of **~1000** nuclear-related standards/projects. This is direct evidence that non-reactor engineering infrastructure (standards, qualification, conformance) is an active maturity bottleneck being worked in parallel with reactor licensing. [23]

### 14) **TANDEM Deliverable D4.1: status report on safety analysis in Europe from operational flexibility and cogeneration viewpoint**

Organisation: TANDEM project consortium (public deliverable)

Venue/type: Euratom-funded technical report (PDF)

Publication date: **February 2023** (issued **8 March 2023**)

Link: [https://tandemproject.eu/wp-content/uploads/2023/03/TANDEM\\_D4\\_1\\_Status\\_report\\_on\\_safety\\_analysis\\_in\\_Europe\\_from\\_the\\_operational\\_flexibility\\_andcogeneration\\_viewpoint\\_V1.pdf](https://tandemproject.eu/wp-content/uploads/2023/03/TANDEM_D4_1_Status_report_on_safety_analysis_in_Europe_from_the_operational_flexibility_andcogeneration_viewpoint_V1.pdf)

Annotation: Concludes that European studies on safety aspects of integrating **light-water SMRs into hybrid energy systems for cogeneration** were limited and therefore draws on broader nuclear cogeneration experience (e.g., desalination, district heating, process heat). This matters for plausibility and maturity because it highlights that “SMR + heat” deployment requires additional safety-case and systems-integration work beyond the reactor core. [24]

### 15) **TANDEM Deliverable D4.5: summary report on safety case studies for an SMR with cogeneration**

Organisation: TANDEM project consortium (public deliverable)

Venue/type: Euratom-funded technical report (PDF)

Publication date: **June 2025**

Link: [https://tandemproject.eu/wp-content/uploads/2025/12/D4\\_5\\_summary\\_report\\_on\\_safety\\_case\\_studies\\_for\\_a\\_smr\\_with\\_c](https://tandemproject.eu/wp-content/uploads/2025/12/D4_5_summary_report_on_safety_case_studies_for_a_smr_with_c)

ogeneration\_V1.pdf

Annotation: Summarises safety-case studies and methods for SMRs operating with cogeneration and flexibility, including evaluation of assessment tools and identification of further needs for implementation in hybrid systems. This is maturity-relevant evidence that “reactor-as-a-heat-plant” safety cases are still being formalised rather than fully standardised. [25]

#### 16) **Small Modular Reactors in Denmark: A Technology and Cost Review (Task 1 report)**

Organisation: Danish Energy Agency[26] (prepared with VTT Technical Research Centre of Finland[27] and Ea Energy Analyses[28])

Venue/type: Government-commissioned technology & cost review (PDF)

Publication date: **January 2026**

Link: <https://ens.dk/media/7783/download>

Annotation: Provides a comparative screening of SMR designs and explicitly discusses the “economy of modularity,” passive safety, licensing, fuel/waste management, and cost drivers; it also summarises design features (e.g., isolation condenser passive cooling in BWRX-300) and notes the linkage between maturity and real construction/licensing progress. This is practical maturity evidence because it combines technical design attributes with cost and regulatory readiness considerations in a national context. [29]

#### 17) **Survey on R&D Status of Japanese SMRs in OECD/NEA Activities (2022–2023) — JAEA-Review 2024-040**

Organisation: Japan Atomic Energy Agency[30]

Venue/type: National laboratory technical review report (PDF)

Publication date: **September 2024**

Link: <https://jopss.jaea.go.jp/pdfdata/JAEA-Review-2024-040.pdf>

Annotation: Discusses the SMR safety knowledge base, including how water-cooled SMRs leverage existing LWR experience while still requiring verification for novel components, and emphasises the role of **integral thermal-hydraulic test facilities** and experiments to demonstrate passive systems. This supports plausibility (physics/engineering basis) while underscoring where maturity depends on validated analysis methods and licensing acceptance. [31]

#### 18) **Fuel Fabrication Starts for MARVEL Microreactor (programme evidence for factory-built, remotely monitored nuclear units)**

Organisations: U.S. Department of Energy; Idaho National Laboratory[32]

Venue/type: Government programme update with hard milestones (official DOE article)

Publication date: **February 2024**

Link: <https://www.energy.gov/ne/articles/fuel-fabrication-starts-marvel-microreactor>

Annotation: Reports that fuel fabrication began, gives a first-fuel-shipment expectation (spring 2025), and states MARVEL is intended to evaluate **remote monitoring and autonomous control technologies** plus microgrid integration—directly relevant to the ART’s “high automation + remote support” operational claims (even though MARVEL is a microreactor rather than a 100–300 MWe SMR). This is concrete maturity evidence for the digital/operational sub-thread. [33]

**Maturity score (1–7) and reasoning**

**Final maturity score**

## 5

**Evidence-to-rubric mapping**

**Why the evidence rules out lower levels (1–4):** - Multiple SMR designs have passed **major regulator review milestones** that are far beyond lab demonstration: NRC design certification for an SMR design (final rule in early 2023) and subsequent Standard Design Approval for the uprated US460 configuration in 2025. [\[34\]](#)

- A Western regulator has issued an actual **construction licence** for an SMR project (BWRX-300 at Darlington), which indicates that the project has moved beyond proof-of-concept into regulated infrastructure execution. [\[35\]](#)

- UK regulators have completed staged generic assessments (e.g., Step 2 for BWRX-300 and Rolls-Royce SMR), supporting the interpretation that these are not speculative concepts but designs being methodically aligned to deployment requirements. [\[36\]](#)

These facts exceed rubric levels 1–4 because they demonstrate not just “working principles” or “lab prototypes,” but regulatory endorsement processes designed for **commercial nuclear construction and operation**.

**Why the score is not yet 6 (products delivered at increasing scale):** - The strongest public evidence is concentrated in **licensing approvals and early project execution authority**, not in repeated deliveries of operating SMR plants to multiple customers. A construction licence is a critical gate, but it is not the same as **multiple modules in commercial operation** with demonstrated “economy of serial production.” [\[37\]](#)

- Multiple sources still characterise deployment success as dependent on FOAK-to-NOAK learning curves, “industrialization,” and an emergent orderbook—signals of a technology that is post-PoC but not yet in broad-scale delivery mode. [\[38\]](#)

- For a substantial subset of advanced SMR variants, **fuel supply (HALEU)** remains an explicit, programme-level bottleneck, indicating that even if reactor hardware is mature, the ecosystem required for scaling is not fully in place. [\[39\]](#)

Together, this best fits **Level 5**: multiple well-capitalised actors progressing through finishing-phase design/licensing and into first builds, with significant investments and accelerating progress—but without “increasing amounts” of delivered, operating SMR products.

**Sub-component breakdown and aggregation****Light-water SMRs for grid power and cogeneration (integral PWRs, natural-circulation BWRs) → ~5**

Supporting evidence: NRC certification/SDA for NuScale; CNSC construction licence and ongoing regulator oversight for BWRX-300; UK GDA Step 2 work. [\[40\]](#)

**Advanced SMRs requiring novel fuels and/or higher enrichments (e.g., HALEU-dependent designs) → ~4–5 (closer to 4 where HALEU is mandatory)**

Supporting evidence: DOE HALEU EIS shows HALEU production is still being stood up as a strategic supply-chain effort; DOE Liftoff frames the remaining work as commercialization/industrialization and supply chain; JAEA review highlights knowledge-base gaps and verification needs for advanced technologies. [\[41\]](#)

**Industrialisation enablers: codes/standards harmonisation, QA, manufacturing readiness → ~4–5**

Supporting evidence: ARCSC documents the scale and active organisation of standards-gap closure and harmonisation work across many SDOs and stakeholders, which is necessary for repeatable module manufacturing. [23]

**Digital/remote operations thread (instrumentation, remote monitoring, autonomous control testing) → ~3–4 (demonstration-focused)**

Supporting evidence: DOE MARVEL milestone reporting indicates active testing of remote monitoring/autonomous control in a nuclear context, but the system is a microreactor test bed rather than a commercially delivered SMR fleet. [33]

**Aggregation to one score (ART as a whole):**

I use a **weighted average leaning toward the light-water SMR path**, because it best matches the ART's near- to mid-term claim of repeatable, tens-to-hundreds of MWe “packaged plants” and is the variant with the most concrete regulatory/construction evidence. The resulting overall maturity is **5**, with advanced-fuel SMRs and digital-operations elements pulling the average down from hypothetical Level 6 readiness. [42]

[1] [22] [23] [arcsc.azurewebsites.net](https://arcsc.azurewebsites.net)

[https://arcsc.azurewebsites.net/Files/11-30-23\\_ARCSC\\_Workshop\\_Summary\\_Final\\_w-Attachments%282%29.pdf](https://arcsc.azurewebsites.net/Files/11-30-23_ARCSC_Workshop_Summary_Final_w-Attachments%282%29.pdf)

[2] [4] [8] [14] [32] [34] [40] <https://www.federalregister.gov/documents/2023/01/19/2023-00729/nuscale-small-modular-reactor-design-certification>

<https://www.federalregister.gov/documents/2023/01/19/2023-00729/nuscale-small-modular-reactor-design-certification>

[3] Federal Register :: NuScale Power, LLC; NuScale US460 Small Modular Reactor; Standard Design Approval

<https://www.federalregister.gov/documents/2025/06/04/2025-10123/nuscale-power-llc-nuscale-us460-small-modular-reactor-standard-design-approval>

[5] [content.govdelivery.com](https://content.govdelivery.com)

[https://content.govdelivery.com/attachments/USNRC/2025/05/29/file\\_attachments/3275315/Standard%20Design%20Approval%20SDA%20for%20the%20NuScale%20US460%20Power%20Plant%20Design.pdf](https://content.govdelivery.com/attachments/USNRC/2025/05/29/file_attachments/3275315/Standard%20Design%20Approval%20SDA%20for%20the%20NuScale%20US460%20Power%20Plant%20Design.pdf)

[6] [16] [17] [38] Pathways to Commercial Liftoff: Advanced Nuclear

<https://gain.inl.gov/content/uploads/4/2024/11/DOE-Advanced-Nuclear-Liftoff-Report.pdf>

[7] <https://www.cnscccsn.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/geh-nuclear-energy-executive-summary/>

<https://www.cnscccsn.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/geh-nuclear-energy-executive-summary/>

[9] [26] [35] [37] [42] Commission authorizes Ontario Power Generation Inc. to construct 1 BWRX-300 reactor at the Darlington New Nuclear Project site - Canada.ca

<https://www.canada.ca/en/nuclear-safety-commission/news/2025/04/commission-authorizes-ontario-power-generation-inc-to-construct-1-bwrx-300-reactor-at-the-darlington-new-nuclear-project-site.html>

[10] Darlington New Nuclear Project

<https://www.cnsccsn.gc.ca/eng/reactors/new-reactor-power-plant-projects/new-reactor-power-plant-facilities/darlington-new-nuclear-project/>

[11] [15] [27] GDA Step 2 of the Rolls-Royce SMR: fundamental assessment - GOV.UK

<https://www.gov.uk/government/publications/gda-step-2-of-the-rolls-royce-smr-fundamental-assessment>

[12] [30] [36] ONR Project Assessment Report - Generic Design Assessment of the BWRX-300 - Step 2 Summary Report

<https://www.onr.org.uk/media/taufoxsv/bwrx-300-gda-step-2-summary-report.pdf>

[13] [19] [33] Fuel Fabrication Starts for MARVEL Microreactor | Department of Energy

<https://www.energy.gov/ne/articles/fuel-fabrication-starts-marvel-microreactor>

[18] [28] [39] [41] Environmental Impact Statement for Department of Energy Activities in Support of Commercial Production of High-Assay Low-Enriched Uranium (HALEU)

<https://www.energy.gov/sites/default/files/2024-12/FINAL%20HALEU%20EIS%20Summary.pdf>

[20] The NEA Small Modular Reactor Dashboard (EN)

[https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/the-nea-small-modular-reactor-dashboard\\_c30b50a8/e586e483-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/the-nea-small-modular-reactor-dashboard_c30b50a8/e586e483-en.pdf)

[21] [https://www.oecd-nea.org/jcms/pl\\_90816/the-nea-small-modular-reactor-dashboard-second-edition](https://www.oecd-nea.org/jcms/pl_90816/the-nea-small-modular-reactor-dashboard-second-edition)

[https://www.oecd-nea.org/jcms/pl\\_90816/the-nea-small-modular-reactor-dashboard-second-edition](https://www.oecd-nea.org/jcms/pl_90816/the-nea-small-modular-reactor-dashboard-second-edition)

[24] tandemproject.eu

[https://tandemproject.eu/wp-content/uploads/2023/03/TANDEM\\_D4\\_1\\_Status\\_report\\_on\\_safety\\_analysis\\_in\\_Europe\\_from\\_the\\_operational\\_flexibility\\_andcogeneration\\_viewpoint\\_V1.pdf](https://tandemproject.eu/wp-content/uploads/2023/03/TANDEM_D4_1_Status_report_on_safety_analysis_in_Europe_from_the_operational_flexibility_andcogeneration_viewpoint_V1.pdf)

[25] tandemproject.eu

[https://tandemproject.eu/wp-content/uploads/2025/12/D4\\_5\\_summary\\_report\\_on\\_safety\\_case\\_studies\\_for\\_a\\_smr\\_with\\_cogeneration\\_V1.pdf](https://tandemproject.eu/wp-content/uploads/2025/12/D4_5_summary_report_on_safety_case_studies_for_a_smr_with_cogeneration_V1.pdf)



[29] ens.dk

<https://ens.dk/media/7783/download>

[31] jopss.jaea.go.jp

<https://jopss.jaea.go.jp/pdfdata/JAEA-Review-2024-040.pdf>

## ART 08.058 Thin-film solar cells

### ART extraction

- **Primary capability**
- Manufacture photovoltaic power-generating surfaces by depositing micrometre-scale semiconductor layers (“thin films”) onto substrates (glass, metal foils, flexible polymers), enabling lightweight, conformable, and potentially retrofittable “solar skins”.
- Enable new deployment form-factors (semi-transparent/colour-tunable/textured laminates; curved or nonplanar integration) rather than only maximising peak efficiency on rigid panels.
- Improve real-world output and maintainability via integration-friendly interconnects, bypassing/shading tolerance, diagnostics, and (in some variants) embedded electronics and monitoring.
- **Key sub-components / variants**
- **Commercial thin-film module families** (e.g., CdTe glass/glass utility modules).
- **Chalcopyrite thin films (CIGS/ACIGS)** for flexible laminates and BIPV-style integration (roof membranes, metal roofs, transport surfaces).
- **Organic photovoltaics (OPV)** as ultralight, flexible films (including building integration).
- **Perovskite thin films** as single-junction devices and as **thin-film-on-wafer tandems** (e.g., perovskite–silicon modules).
- **Manufacturing pathways:** roll-to-roll printing/coating, slot-die/blade coating, vapour/evaporation steps, laser scribing/interconnects.
- **Reliability package stack:** encapsulation/barrier films, edge seals, moisture/oxygen management, thermal cycling tolerance, mechanical fatigue resistance.
- **Power management elements:** interconnect architectures, bypass diodes / string reconfiguration approaches, and integration with standard inverters/DC loads.
- **Maturity indicators that would count as evidence**
- **GW-scale manufacturing & shipments**, customer deliveries, bankable warranties, and demonstrable capacity expansion financing.
- **Independent certified** cell/module efficiencies on **large areas** ( $\text{cm}^2 \rightarrow \text{m}^2$ ) and demonstrated low-lab-to-module performance loss.

- **Reliability qualification evidence:** damp-heat, thermal cycling, UV/illumination stability, mechanical bending/fatigue, and documented encapsulation/process strategies that meet mainstream PV standards.
- **Field deployments / production-format prototypes** (industrial-format panels/modules; BIPV roof systems; transport retrofits) with measurable performance.
- **Multiple well-capitalised actors / consortia activity**, including roadmaps and standardisation progress indicating credible scaling paths.

## Evidence

Evidence (10–20 recent, reliable sources)

## Annotated sources

### 1) Annual Report on Form 10-K for the fiscal year ended 31 December 2024

Authors/organisation: First Solar, Inc.[1]

Venue/type: Regulatory filing (Form 10-K; production & capacity disclosure)

Publication date: Feb 2025

Link:

[https://s202.q4cdn.com/499595574/files/doc\\_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf](https://s202.q4cdn.com/499595574/files/doc_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf)

Reports installed nameplate production capacity of ~21 GW, and that in 2024 it produced 15.5 GW and sold 14.1 GW of solar modules—strong direct evidence of large-scale thin-film (CdTe) commercial maturity and customer delivery. It also reports a 23.1% CdTe research-cell efficiency certified by National Renewable Energy Laboratory[2], signalling continued headroom in the underlying thin-film technology base. [3]

### 2) Series 7 TR1 U.S. module datasheet (505–540 W thin-film CdTe module)

Authors/organisation: First Solar, Inc.

Venue/type: Vendor technical doc (datasheet with electrical, mechanical, durability and warranty specifications)

Publication date: Jan 2023

Link: <https://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-7/Series-7-TR1-Datasheet.ashx>

Provides product-grade metrics (e.g., 505–540 W nameplate, module efficiency up to 19.3%, temperature coefficients, glass/glass construction with edge seal) and bankability signals (30-year linear performance warranty; 0.3%/yr warranted degradation). This is concrete evidence that thin-film modules are engineered for long life and standardised deployment at scale. [4]

### 3) Cadmium Telluride Photovoltaics Perspective Paper

Authors/organisation: U.S. Department of Energy[5] (Solar Energy Technologies Office)

Venue/type: Government technical perspective / roadmap report

Publication date: Jan 2025

Link: <https://www.energy.gov/sites/default/files/2025-01/DOE%20SETO%20CdTe%20Photovoltaics%20Perspective%20Paper.pdf>

Quantifies CdTe's market position (e.g., ~34% of the United States[6] utility-scale PV market in 2022 and ~3% of global PV) and frames the scaling constraints (materials supply,

manufacturing and cost structure), directly supporting both plausibility and near-/mid-term scaling realism. [7]

#### 4) Photovoltaics Report

Authors/organisation: Fraunhofer Institute for Solar Energy Systems ISE[8]

Venue/type: Authoritative technical market/technology report

Publication date: Oct 2025 (updated)

Link:

<https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

Shows that thin-film remains commercially present but a minority share (reported as ~2–3% of global production, with ~16 GW thin-film out of ~703 GW total module production in 2024), indicating maturity for some variants but limited diffusion overall—important for judging “how close to scaling” the broader thin-film family is. [9]

#### 5) Trends in Photovoltaic Applications 2025 (IEA PVPS Task 1)

Authors/organisation: International Energy Agency Photovoltaic Power Systems Programme[10]

Venue/type: Authoritative international market/technology report

Publication date: 2025 (report year)

Link: [https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS\\_Trends\\_2025-.pdf](https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS_Trends_2025-.pdf)

Provides recent technology benchmarking: reports that crystalline silicon dominates (>98% of cell production), while thin-film module efficiencies span roughly ~14% (OPV) up to ~19.9% (CdTe) and ~19.2% (CIGS), and discusses fast progress in emerging tandems (e.g., perovskite–silicon tandem cell records cited for 2024). This contextualises thin film as both “market real” and “still niche” depending on variant and use-case. [11]

#### 6) Solar cell efficiency tables (Version 64)

Authors/organisation: Martin A. Green[12] et al.

Venue/type: Peer-reviewed benchmark compilation in Progress in Photovoltaics: Research and Applications[13]

Publication date: Jun 2024 (accepted; 2024 publication)

Link: <https://docs.nrel.gov/docs/fy24osti/90199.pdf>

Defines strict inclusion rules (independent measurement by recognised test centres, minimum areas for cells/submodules/modules) and compiles best independently confirmed efficiencies—useful for plausibility filtering (separating certified results from marketing claims) across thin-film categories and module scales. [14]

#### 7) A roadmap for tandem photovoltaics

Authors/organisation: Kirstin Alberi[15] et al.

Venue/type: Peer-reviewed review/roadmap in Joule[16]

Publication date: Mar 2024

Link: <https://docs.nrel.gov/docs/fy24osti/86496.pdf>

Synthesises what is still needed for tandems (including thin-film-on-wafer architectures like perovskite–silicon) to commercialise: measurement protocols, interconnection choices, reliability and manufacturing compatibility. This directly supports maturity assessment for the “next” thin-film wave (especially perovskite-based tandems). [17]

### 8) **High-concentration silver alloying and steep back-contact gallium grading enabling copper indium gallium selenide solar cell with 23.6% efficiency**

Authors/organisation: Jan Keller[18] et al.

Venue/type: Peer-reviewed paper in Nature Energy[19]

Publication date: Feb 2024

Link: <https://www.nature.com/articles/s41560-024-01472-3>

Reports a **23.64% certified** (Ag,Cu)(In,Ga)Se<sub>2</sub> (ACIGS) thin-film cell via Ag alloying, Ga grading and RbF post-deposition treatment—strong plausibility evidence that thin-film chalcopyrites can achieve very high performance, supporting both stand-alone and tandem roles. [20]

### 9) **Increase in the efficiency and stability of large-area flexible organic photovoltaic modules via improved electrical contact**

Authors/organisation: Xin Lu[21] et al.

Venue/type: Peer-reviewed paper (Nature Energy)

Publication date: Apr 2024

Link: <https://www.nature.com/articles/s41560-024-01501-1>

Demonstrates **certified** flexible OPV module efficiencies of **14.04%** (41 cm<sup>2</sup> active area) and **13.10%** (370 cm<sup>2</sup> active area, Voc ≈ 103.51 V) and reports retention of **~90%** of initial efficiency after **912 h** continuous illumination—direct evidence that flexible thin-film PV can scale in area while addressing stability and interconnect losses. [22]

### 10) **Large-area organic photovoltaic modules with 14.5% certified world record efficiency**

Authors/organisation: Robin Basu[23] et al.

Venue/type: Peer-reviewed report in Joule

Publication date: Apr 2024

Link: <https://www.sciencedirect.com/science/article/pii/S2542435124000990>

Achieves a **204 cm<sup>2</sup>** OPV module with **14.5% certified** efficiency on total module area (15.0% on active area) and emphasises “industry-relevant” processing (ambient air, non-halogenated solvents) with low upscaling loss—key for judging manufacturability of thin-film “skins.” [24]

### 11) **The first demonstration of entirely roll-to-roll fabricated perovskite solar cell modules under ambient room conditions**

Authors/organisation: H. C. Weerasinghe[25] et al.

Venue/type: Peer-reviewed paper in Nature Communications[26]

Publication date: Mar 2024

Link: <https://www.nature.com/articles/s41467-024-46016-1>

Reports roll-to-roll printed perovskite modules made entirely with industrial roll-to-roll tools under ambient conditions, reaching up to **15.5%** for small-area cells and **11.0%** for serially interconnected module cells; includes a cost projection of **~\$0.7/W** at **1,000,000 m<sup>2</sup>/yr** production in Australia[27]. This is direct feasibility evidence for high-throughput manufacturing. [28]

### 12) **Efficient and stable perovskite mini-module via high-quality homogeneous perovskite crystallization and improved interconnect**

Authors/organisation: Haitao Zhou[29] et al.

Venue/type: Peer-reviewed paper (Nature Communications)

Publication date: Aug 2024

Link: <https://www.nature.com/articles/s41467-024-50962-1>

Reports a **certified quasi-steady-state PCE of 22.73%** for a **14.61 cm<sup>2</sup>** perovskite mini-module and **>90%** retention after **1000 h** continuous operation under illumination—strong maturity evidence for perovskite thin films moving toward module-relevant areas with meaningful stability. [30]

### 13) Room temperature nondestructive encapsulation via self-crosslinked fluorosilicone polymer enables damp heat-stable sustainable perovskite solar cells

Authors/organisation: Tao Wang[31] et al.

Venue/type: Peer-reviewed paper (Nature Communications; via PubMed Central)

Publication date: Mar 2023

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10008636/>

Demonstrates room-temperature encapsulation that maintains **98%** of normalised performance after **1000 h damp heat** and **95%** after **220 thermal cycles**, explicitly framed as meeting IEC 61215 requirements; also reports very high lead-leakage suppression in water exposure tests. This directly addresses a primary thin-film (especially perovskite) bottleneck: moisture/thermal cycling and safety. [32]

### 14) Package Development for Reliability Testing of Perovskites

Authors/organisation: E. Ashley Gaulding[33] et al.

Venue/type: Peer-reviewed paper in ACS Energy Letters[34]

Publication date: Aug 2022

Link: <https://pubs.acs.org/doi/10.1021/acsenerylett.2c01168>

Presents a packaging strategy (polyisobutylene-based, low thermal budget) designed to enable outdoor and accelerated testing for perovskite devices while scaling beyond tiny lab samples—evidence of the field’s move from “cell physics” toward bankability and qualification pathways. [35]

### 15) HeliaSol® 436-2000-CFF technical datasheet

Authors/organisation: Heliatek GmbH[36]

Venue/type: Vendor technical doc (product datasheet for flexible organic solar film)

Publication date: Apr 2025 (Rev 04)

Link:

[https://www.heliatek.com/fileadmin/user\\_upload/pdf\\_documents/Datasheet\\_HeliaSol\\_436-2000\\_Website\\_EN.pdf](https://www.heliatek.com/fileadmin/user_upload/pdf_documents/Datasheet_HeliaSol_436-2000_Website_EN.pdf)

Specifies a flexible, self-adhesive thin-film solar product (claimed <2 kg/m<sup>2</sup>, ~2 mm thick solar film, minimum bending radius 50 cm) with standard-oriented specs and warranties (5-year product, 20-year performance). It is concrete evidence that “solar skins” exist as deliverable products—though at lower efficiency than mainstream modules. [37]

### 16) Flextron CIGS Solar PV Modules — Product specification

Authors/organisation: BIPVco[38]

Venue/type: Vendor technical doc (BIPV laminate module specification)

Publication date: 2024 (document filename/path indicates 2024)

Link: <https://bipvco.com/wp-content/uploads/2024/11/Flextron-CIGS-Specification-2024.pdf>

Describes flexible thin-film CIGS modules intended for factory- or site-lamination onto metal / membrane roofs, including low mass (2–3 kg/m<sup>2</sup>), “up to 17%” efficiency, integrated diodes mitigating shading losses, and 10-year material / 25-year performance warranties—evidence of near-market integrated thin-film roof systems. [39]

### 17) 55 Wp CIGS HV Solar Panel — Product Data Sheet (Transportation)

Authors/organisation: Green Energy[40]

Venue/type: Vendor technical doc (transport-oriented flexible CIGS panel datasheet)

Publication date: May 2024 (Rev 05/24)

Link: <https://greenenergy.pro/wp-content/uploads/2024/06/GE24-DataSheet-55WpHVSolarPanel.pdf>

Provides measurable “solar skin” specs: flexible CIGS panel ~3 mm thick, claimed <3.5 kg/m<sup>2</sup> installed with glue, IEC EN61730 + EN61215 stated certification, and a 25-year performance guarantee with defined retention (≥90% after 10 years; 80% after 25). This is concrete evidence of thin-film laminates targeting transport/retrofit use cases where rigid modules are impractical. [41]

### 18) Oxford PV and Fraunhofer ISE develop full-sized tandem PV module with record efficiency of 25 percent

Authors/organisation: Oxford PV + Fraunhofer ISE

Venue/type: Prototype demo (research institute press release with calibrated performance metrics)

Publication date: Jan 2024

Link: [https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424\\_ISE\\_e\\_PI\\_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf](https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424_ISE_e_PI_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf)

Reports an industrial-format glass-glass perovskite–silicon tandem module with **25%** efficiency and **421 W** output over **1.68 m<sup>2</sup>**, produced using mass-production-compatible equipment and low-temperature interconnection/encapsulation processes. This is strong “module-format” maturity evidence for thin-film perovskite layers in tandem configurations. [42]

### 19) Advances in photovoltaics — Technology trends for solar energy

Authors/organisation: European Patent Office[43]

Venue/type: Authoritative technology insight report

Publication date: Jul 2025

Link: <https://link.epo.org/web/business/technology-insight-reports/en-epo-technology-insight-report-advances-in-photovoltaics.pdf>

Provides an independent cross-technology landscape view (including perovskite and organic thin films) useful for maturity inference: it evidences broad multi-actor innovation activity beyond a single company and helps triangulate which thin-film subfamilies are drawing sustained R&D and IP investment. [44]

### Maturity score and reasoning

**Final maturity score: 6**

### Why the evidence rules out levels 1–5

Thin-film PV is not merely a lab-demonstrated principle or a single proof-of-concept: at least one thin-film branch (CdTe modules) is operating at massive commercial scale, with explicit GW-level production and sales disclosed for 2024 (15.5 GW produced; 14.1 GW sold) and substantial installed nameplate capacity (~21 GW). [45]

In parallel, there are multiple “skin-like” thin-film products available with published electrical/mechanical data and warranties (CIGS roof laminates and flexible CIGS transport



panels, plus OPV films), showing that integration as laminates/coatings is already in customer-deliverable form rather than remaining purely academic. [46]

### Why the score is not 7

Across the full ART concept (thin-film “family of coated surfaces and laminates” spanning CdTe, CIGS, OPV and perovskites), maturity is uneven. Authoritative market data indicate thin film overall remains a small fraction of global PV production (~2–3%), suggesting that, outside specific winners like CdTe utility modules, “thin-film skins everywhere” has not yet reached broad, rising mainstream demand. [47]

Moreover, the most transformative thin-film variants for novel form factors—especially perovskite modules and perovskite-based tandems—are progressing rapidly (certified ~22.7% mini-module performance and meaningful 1000 h operational stability; roll-to-roll manufacturing demonstrations), but still require longer-term bankability-grade field evidence, manufacturing yield stability, and widespread certification/insurance acceptance before qualifying as “competing products delivered and demand rising” at market-wide scale. [48]

### What evidence is still missing to justify level 7 for the ART as a whole

Level 7 would require broad competitive delivery growth across multiple thin-film “skin” product types (not only CdTe utility panels), with clear indicators that demand is rising materially in those new form-factor segments (e.g., BIPV laminates and OPV films becoming standard building products, and perovskite modules/tandems shipping in substantial volumes across multiple vendors). Current evidence shows strong prototypes and early productisation (including industrial-format tandem modules) but does not yet demonstrate market-wide scaling of the skin-like variants comparable to mainstream PV adoption. [49]

### Sub-component maturity breakdown and aggregation approach

Because the thin-film “family” spans materially different deployment modes and maturity states, the overall score is **average-weighted** (not “max”), with weight implicitly influenced by evidence of scale and deployment breadth.

- **CdTe utility-scale thin-film modules** → ~7 (mass production + large deliveries; mature datasheets/warranties). Key sources: Form 10-K production/sales at multi-GW scale and product datasheets. [50]
- **Flexible/BIPV CIGS laminates (roof + transport/retrofit)** → ~6 (deliverable products with published specs and warranties; still niche compared with mainstream PV). Key sources: Flextron specification; 55 Wp transport CIGS datasheet. [51]
- **OPV flexible films/modules** → ~5–6 (certified module efficiencies and multi-hundred-hour illumination stability in peer-reviewed work; commercial film products exist, but comparatively low efficiency and unclear scaling to large volumes). Key sources: Nature Energy OPV module paper; Joule OPV record module; HeliaSol datasheet. [52]
- **Perovskite modules and perovskite–silicon tandems** → ~4–5 (high certified mini-module performance and early manufacturing-route demonstrations; industrial-format module prototypes exist; reliability packaging work is increasingly standard-oriented, but broad market shipment/field-bankability evidence is still developing). Key sources: perovskite mini-module; roll-to-roll module paper; perovskite

encapsulation paper; industrial-format tandem module press release; tandem roadmap. [53]

### Aggregation to one score

With **one branch clearly at 7 (CdTe modules), several “skin-like” product branches around 5–6 (CIGS laminates, OPV films), and a fast-advancing but not yet broadly shipped branch around 4–5 (perovskite modules/tandems)**, the evidence supports a consolidated **ART maturity score of 6**: products exist and are being delivered (in some cases at very large scale), application areas are expanding into form-factor-driven niches, but the “full family” of thin-film skins is not yet at broad, multi-vendor, demand-rising maturity consistent with rubric level 7. [54]

[1] [15] [21] [41] <https://greenenergy.pro/wp-content/uploads/2024/06/GE24-DataSheet-55WpHVSolarPanel.pdf>

<https://greenenergy.pro/wp-content/uploads/2024/06/GE24-DataSheet-55WpHVSolarPanel.pdf>

[2] [31] [32] <https://pmc.ncbi.nlm.nih.gov/articles/PMC10008636/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC10008636/>

[3] [16] [25] [29] [45] [50] [54]

[https://s202.q4cdn.com/499595574/files/doc\\_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf](https://s202.q4cdn.com/499595574/files/doc_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf)

[https://s202.q4cdn.com/499595574/files/doc\\_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf](https://s202.q4cdn.com/499595574/files/doc_financials/2024/q4/e79628c5-f033-4b44-aae3-57b8fdd52106.pdf)

[4] [12] <https://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-7/Series-7-TR1-Datasheet.ashx>

<https://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-7/Series-7-TR1-Datasheet.ashx>

[5] [42] [49] [https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424\\_ISE\\_e\\_PI\\_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf](https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424_ISE_e_PI_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf)

[https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424\\_ISE\\_e\\_PI\\_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf](https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2024/0424_ISE_e_PI_Oxford-PV-and-Fraunhofer-ISE-develop-full-sized-Tandem-PV-Module-with-record-efficiency-of-25-percent.pdf)

[6] [7] [26] <https://www.energy.gov/sites/default/files/2025-01/DOE%20SETO%20CdTe%20Photovoltaics%20Perspective%20Paper.pdf>

<https://www.energy.gov/sites/default/files/2025-01/DOE%20SETO%20CdTe%20Photovoltaics%20Perspective%20Paper.pdf>

[8] [19] [24] [38] <https://www.sciencedirect.com/science/article/pii/S2542435124000990>

<https://www.sciencedirect.com/science/article/pii/S2542435124000990>

[9] [10] [47]

<https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

<https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf>

[11] [https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS\\_Trends\\_2025-.pdf](https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS_Trends_2025-.pdf)

[https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS\\_Trends\\_2025-.pdf](https://iea-pvps.org/wp-content/uploads/2025/10/IEA-PVPS_Trends_2025-.pdf)

[13] [28] <https://www.nature.com/articles/s41467-024-46016-1>

<https://www.nature.com/articles/s41467-024-46016-1>

[14] <https://docs.nrel.gov/docs/fy24osti/90199.pdf>

<https://docs.nrel.gov/docs/fy24osti/90199.pdf>

[17] <https://docs.nrel.gov/docs/fy24osti/86496.pdf>

<https://docs.nrel.gov/docs/fy24osti/86496.pdf>

[18] [22] [36] [43] [52] <https://www.nature.com/articles/s41560-024-01501-1>

<https://www.nature.com/articles/s41560-024-01501-1>

[20] [27] <https://www.nature.com/articles/s41560-024-01472-3>

<https://www.nature.com/articles/s41560-024-01472-3>

[23] [33] [39] [46] [51] <https://bipvco.com/wp-content/uploads/2024/11/Flextron-CIGS-Specification-2024.pdf>

<https://bipvco.com/wp-content/uploads/2024/11/Flextron-CIGS-Specification-2024.pdf>

[30] [48] [53] <https://www.nature.com/articles/s41467-024-50962-1>

<https://www.nature.com/articles/s41467-024-50962-1>

[34] [37]

[https://www.heliatek.com/fileadmin/user\\_upload/pdf\\_documents/Datasheet\\_HeliaSol\\_436-2000\\_Website\\_EN.pdf](https://www.heliatek.com/fileadmin/user_upload/pdf_documents/Datasheet_HeliaSol_436-2000_Website_EN.pdf)

[https://www.heliatek.com/fileadmin/user\\_upload/pdf\\_documents/Datasheet\\_HeliaSol\\_436-2000\\_Website\\_EN.pdf](https://www.heliatek.com/fileadmin/user_upload/pdf_documents/Datasheet_HeliaSol_436-2000_Website_EN.pdf)

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<https://pubs.acs.org/doi/10.1021/acsenergylett.2c01168>

[44] <https://link.epo.org/web/business/technology-insight-reports/en-epo-technology-insight-report-advances-in-photovoltaics.pdf>

<https://link.epo.org/web/business/technology-insight-reports/en-epo-technology-insight-report-advances-in-photovoltaics.pdf>

## ART 08.059 Bionic Leaf Technology

### ART extraction

#### Primary capability claimed

- A **sunlight-driven, leaf-like panel/tile** that couples **light capture and chemical conversion inside the same device**, enabling “artificial photosynthesis” rather than a separated “PV electricity → separate chemical plant” architecture.
- Direct conversion of simple inputs (water plus a carbon source such as CO<sub>2</sub> or dissolved inorganic carbon) into **storable reduced molecules** (e.g., H<sub>2</sub>, formate-like liquids, syngas, multi-carbon liquids).
- A **modular, sealed, fluid-handling form factor** with embedded sensing/control to support distributed production and remote operation.

#### Key sub-components or variants

- **Light absorbers** (e.g., silicon, perovskite, tandem stacks, photoelectrodes such as BiVO<sub>4</sub>/hematite).
- **Catalyst systems** for (i) water oxidation and (ii) CO<sub>2</sub> reduction (to CO/syngas, formate, alcohols) or alternative paired oxidation reactions (e.g., biomass/plastic oxidation to reduce required voltage).
- **Encapsulation / barrier layers** to protect moisture/ion-sensitive absorbers while permitting charge transfer and chemical contact where needed.
- **Flow-field / microchannel / reactor engineering** (gas diffusion electrodes, flow cells, modular manifolds) to manage mass transport, heat, and intermittent operation.
- **Separation and product handling** (gas separation, avoiding cross-over, liquid product collection; sometimes via paired-product strategies).
- **Scaling strategies** (cell-to-module arrays, “artificial tree”/panel assemblies, outdoor prototypes).
- **Instrumentation and control** (pressure/flow regulation, outdoor operation protocols, monitoring for degradation).

#### What maturity indicators would constitute strong evidence

- **Bias-free (unassisted) operation** with quantified solar-to-fuel / solar-to-hydrogen efficiency and verified product selectivity.
- **Large-area scaling with limited performance loss** ( $\geq 10\text{--}100\text{ cm}^2$ , progressing to  $\geq 0.1\text{--}1\text{ m}^2$  modules/arrays) plus manufacturable deposition/assembly routes.
- **Durability under realistic conditions** (hundreds to thousands of hours at relevant illumination, temperature cycling; outdoor demonstration).
- **Integrated product separation/handling** at the device/module level (especially for mixed gas products and for liquid products like formate).
- **Field trials / relevant-environment demonstrations** with logged operating data and clear degradation/maintenance pathways.

- **Evidence of industrialization push:** multiple funded consortia, pilot systems, or early customer deployments, and credible pathways for cost, safety, and maintainability.

#### **Evidence (10–20 recent, reliable sources)**

##### **1) Solar Panel Technologies for Light-to-Chemical Conversion**

- Authors/Org: Multi-author academic team (lead author V. Andrei; corresponding E. Reisner)
- Venue/type: Peer-reviewed “Account” article (thin-film solar-fuels panel classes and scale-up considerations)
- Publication date: **Dec 2022** (issue date)
- Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC9730848/>
- Why it matters: Synthesizes the “solar chemistry panel” framing (artificial leaves vs photocatalyst sheets) and explicitly foregrounds manufacturability, scale-up losses, and performance metrics needed to compare panel-like solar-to-chemical devices—directly aligning with the ART’s panel/tile premise. [1]

##### **2) The 2022 solar fuels roadmap**

- Authors/Org: Large international author team; hosted as an open report PDF (NREL document server)
- Venue/type: Authoritative roadmap (Journal of Physics D: Applied Physics “Roadmap”)
- Publication date: **Jun 2022**
- Link: <https://docs.nrel.gov/docs/fy22osti/83517.pdf>
- Why it matters: Provides consensus-like commercialization-oriented targets and bottlenecks (efficiency, stability, scale-up, cost/footprint, membranes/ions/photons management), useful for evaluating whether “bionic leaf” systems are still prototypes or approaching market readiness. [2]

##### **3) Artificial Photosynthesis Project**

- Authors/Org: **NEDO** (Japan’s New Energy and Industrial Technology Development Organization)
- Venue/type: Government program description (R&D themes include photocatalysts, separation membranes, CO<sub>2</sub>-to-chemical catalysts)
- Publication date: **Apr 2022** (“Last Updated”)
- Link: [https://www.nedo.go.jp/english/activities/activities\\_EV\\_00296.html](https://www.nedo.go.jp/english/activities/activities_EV_00296.html)
- Why it matters: Demonstrates sustained national-program investment in core enabling elements highlighted in the ART (photocatalysts, separation membranes, CO<sub>2</sub>-to-chemicals catalysis), supporting plausibility and multi-year development continuity. [3]

##### **4) Floating perovskite–BiVO<sub>4</sub> devices for scalable solar fuel production**

- Authors/Org: Multi-institution academic team
- Venue/type: Peer-reviewed experimental paper
- Publication date: **Aug 2022**
- Link: <https://www.nature.com/articles/s41586-022-04978-6>
- Why it matters: Demonstrates lightweight, flexible “artificial leaves” with reported unassisted solar-to-fuel efficiencies (H<sub>2</sub> and CO cases), scale-up to **100 cm<sup>2</sup>** devices, and **outdoor gas-collection testing**—directly addressing the ART’s modular panel and deployment concepts. [4]

##### **5) Back-illuminated photoelectrochemical flow cell for efficient CO<sub>2</sub> reduction**

- Authors/Org: Academic team (China/Singapore-linked affiliations via the paper)

- Venue/type: Peer-reviewed experimental paper (open access via PMC)
- Publication date: **Nov 2022**
- Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC9675791/>
- Why it matters: Shows **flow-cell reactor engineering** (decoupling light absorption from catalytic sites) achieving **solar-to-fuel efficiency of 2.42% for CO with ~90% Faradaic efficiency**, and high-rate operation in a flow configuration—evidence that microchannel/flow architectures can be integrated with photoelectrodes (a key “panel interior” claim). [5]

#### 6) Renewable formate from sunlight, biomass and carbon dioxide in a photoelectrochemical cell

- Authors/Org: Multi-institution academic team
- Venue/type: Peer-reviewed experimental paper
- Publication date: **Feb 2023**
- Link: <https://www.nature.com/articles/s41467-023-36726-3>
- Why it matters: Demonstrates **solar-powered formate** production using paired photoanodic biomass oxidation with photocathodic CO<sub>2</sub> reduction; reports **>85% Faradaic efficiencies** at both photoelectrodes, **32% lower cell voltage** vs conventional OER-paired designs, and a **23.3  $\mu\text{mol cm}^{-2} \text{h}^{-1}$**  formate yield—directly relevant to bionic-leaf production of transportable liquid intermediates and to separation simplification. [6]

#### 7) An artificial leaf device built with earth-abundant materials for combined H<sub>2</sub> production and storage as formate with efficiency >10%

- Authors/Org: Multi-institution European academic collaboration (paper lists institutions across Italy/Germany/Switzerland/Spain)
- Venue/type: Peer-reviewed experimental paper
- Publication date: **Feb 2023** (first published)
- Link: <https://pubs.rsc.org/en/content/articlehtml/2023/ee/d2ee03215e>
- Why it matters: Reports an integrated PV/EC “artificial-leaf-type” flow cell producing **formate + H<sub>2</sub>** with **>10% solar-to-fuel efficiency**, operating around **~17 mA cm<sup>-2</sup>**, and giving quantified formate productivity—evidence for practical device engineering using earth-abundant materials and for liquid energy carriers as “panel-edge” products. [7]

#### 8) Solar-driven liquid multi-carbon fuel production using a standalone perovskite–BiVO<sub>4</sub> artificial leaf

- Authors/Org: Academic team (UK)
- Venue/type: Peer-reviewed experimental paper
- Publication date: **May 2023** (published online)
- Link: [https://www.np.phy.cam.ac.uk/wp-content/uploads/sites/50/2024/06/natenergy23\\_bivo4leaf.pdf](https://www.np.phy.cam.ac.uk/wp-content/uploads/sites/50/2024/06/natenergy23_bivo4leaf.pdf)
- Why it matters: Demonstrates unassisted (“wireless standalone”) CO<sub>2</sub>-to-multi-carbon liquid products (ethanol/n-propanol) over an artificial leaf, albeit at early-stage rates (reported accumulation after ~20 h), which is central to plausibility for “bionic leaf → higher-value reduced liquids” beyond H<sub>2</sub>. [8]

#### 9) SUNER-C / SUNERGY Technological Roadmap (Deliverable D3.1)

- Authors/Org: SUNER-C consortium / SUNERGY initiative (Europe-wide)
- Venue/type: Consortium roadmap/report
- Publication date: **Nov 2023** (final version date shown in document history)
- Link: <https://sunergy-initiative.eu/wp-content/uploads/2024/05/D7-D3.1->



Technological-roadmap.pdf

- Why it matters: Provides an EU-centered roadmap framing for solar-to-chemicals/fuels, including timelines, TRL thinking, and ecosystem participation across academia/industry/policy—useful maturity evidence for whether bionic-leaf concepts are moving from lab novelty toward coordinated scale-up. [9]

#### 10) Natural leaf-inspired solar water splitting system

- Authors/Org: Academic team (Republic of Korea)

- Venue/type: Peer-reviewed experimental paper (Applied Catalysis B: Environmental)

- Publication date: **Mar 2023** (journal issue month)

- Link:

<https://www.sciencedirect.com/science/article/abs/pii/S092633732201027X>

- Why it matters: Implements a monolithic “leaf-inspired” architecture using crystalline-silicon interdigitated back contact (IBC) design to avoid catalyst light-blocking and reports **~8.4% solar-to-hydrogen** at the “artificial leaf” level—evidence that leaf-like geometry choices can materially affect optical/electrical integration. [10]

#### 11) Thermally integrated photoelectrochemical devices with perovskite/silicon tandem solar cells: a modular approach for scalable direct water splitting

- Authors/Org: Multi-organization European team (includes JRC Ispra outdoor testing context in-methods)

- Venue/type: Peer-reviewed experimental paper

- Publication date: **2024** (journal year; article discusses 72 h outdoor test conditions)

- Link: <https://pubs.rsc.org/en/content/articlehtml/2024/se/d4se00547c>

- Why it matters: Shows **module scaling from cell-scale to 342 cm<sup>2</sup> active area** and an **outdoor 72 h test** with quantified hydrogen volumes and STH\* efficiency computation; also documents practical control constraints (e.g., pressure/flow handling), aligning with the ART’s emphasis on thermal/fluid management and operational robustness. [11]

#### 12) A scalable integrated solar device for the autonomous production of green methane

- Authors/Org: Multi-organization European team

- Venue/type: Peer-reviewed experimental paper (system-scale demonstration; “open archive” on ScienceDirect)

- Publication date: **Aug 2024** (journal issue date)

- Link: <https://www.sciencedirect.com/science/article/pii/S254243512400240X>

- Why it matters: Reports a **TRL 5** autonomous device (**~2 m<sup>2</sup>**) combining integrated photoelectrochemical H<sub>2</sub> production with biomethanation, operating **72 h outdoors** and producing methane with a reported **~5.5% solar-to-fuel yield**—strong maturity evidence for integrated “sunlight-to-molecule” hardware operating in the field, even if the architecture is partly PV+electrolyzer. [12]

#### 13) Modular perovskite–BiVO<sub>4</sub> artificial leaves towards syngas synthesis on a m<sup>2</sup> scale

- Authors/Org: Academic team (UK)

- Venue/type: Peer-reviewed experimental paper (open access)

- Publication date: **Jan 2025** (first published; accepted Jan 2025)

- Link: <https://pubs.rsc.org/en/content/articlelanding/2025/ee/d4ee05780e>

- Why it matters: Demonstrates manufacturable scaling steps (e.g., **vacuum-processed 10 cm<sup>2</sup> PV devices** sustaining ~1 V photovoltage; **36 h** unassisted operation) and a **0.7 × 0.5 m<sup>2</sup> “artificial tree”** reactor with a 10×10 leaf array benchmarked in an **outdoor**

**demonstration**—direct evidence for modular scaling and real-world operation of leaf-like solar-fuel units. [13]

**14) Direct air capture of CO<sub>2</sub> for solar fuel production in flow**

- Authors/Org: Academic team (UK)
- Venue/type: Peer-reviewed experimental paper (open access)
- Publication date: **Feb 2025**
- Link: <https://www.nature.com/articles/s41560-025-01714-y>
- Why it matters: Addresses a key feasibility bottleneck in the ART—**carbon feed supply**—by integrating CO<sub>2</sub> capture from air with light-driven utilization in a **flow reactor** for syngas production, explicitly envisioning diurnal capture/convert operation (relevant to intermittency and system integration). [14]

**15) A standalone bismuth vanadate–silicon artificial leaf achieving 8.4% efficiency for hydrogen production**

- Authors/Org: Academic team
- Venue/type: Peer-reviewed experimental paper (open access)
- Publication date: **Mar 2025**
- Link: <https://www.nature.com/articles/s41467-025-58102-z>
- Why it matters: Reports a BiVO<sub>4</sub> photoanode stable for **>520 h** under standard illumination, a standalone artificial leaf at **8.4% STH**, and **scale-up to 441 cm<sup>2</sup>** (with performance under natural sunlight), directly supporting plausibility for larger-area, longer-lived leaf modules. [15]

**16) Scalable and durable module-sized artificial leaf with a solar-to-hydrogen efficiency over 10%**

- Authors/Org: Academic team (Republic of Korea)
- Venue/type: Peer-reviewed experimental paper (open access)
- Publication date: **May 2025**
- Link: <https://www.nature.com/articles/s41467-025-59597-2>
- Why it matters: Demonstrates a mini-module artificial leaf of **16 cm<sup>2</sup>** (4×4 array) achieving **11.2% module-level STH** in unbiased water splitting, with reported **140 h** stability for 1 cm<sup>2</sup> photoelectrodes—strong evidence that >10% efficiency can persist beyond single tiny cells and into module-style assembly. [16]

**17) Semi-artificial leaf interfacing organic semiconductors and enzymes for solar chemical synthesis**

- Authors/Org: Academic team (UK and collaborators)
- Venue/type: Peer-reviewed experimental paper (open access)
- Publication date: **Nov 2025**
- Link: <https://www.sciencedirect.com/science/article/pii/S2542435125003460>
- Why it matters: Demonstrates a biohybrid “leaf” producing **H<sub>2</sub> or formate** in bicarbonate solution with reported photocurrents (up to **–8 mA cm<sup>–2</sup>**) and **~10 h** operation, and reports a formate solar-to-fuel efficiency and Faradaic yield—evidence that “leaf-like” panels can extend beyond purely inorganic catalysts to selective liquid products, albeit still at early efficiency/durability levels. [17]

**18) (Industry milestone; use cautiously) SunHydrogen demonstrates 100 cm<sup>2</sup> and 1 m<sup>2</sup> green hydrogen panels with reported efficiency**

- Authors/Org: SunHydrogen (company communication referencing external test context)
- Venue/type: Industry announcement / technical milestone (not peer-reviewed; includes quantitative claims)
- Publication date: **Dec 2024**
- Link: <https://sunhydrogen.com/news-posts/sunhydrogen-successfully-produces-green-hydrogen-from-a-100cm2-green-hydrogen-panel-and-demonstrates-a-1m2-panel/>
- Why it matters: Indicates claims of **module-area progression** (100 cm<sup>2</sup> to 1 m<sup>2</sup>) and a reported solar-to-hydrogen efficiency number for 100 cm<sup>2</sup> modules, which—if independently validated—would be maturity-relevant evidence that “panelized” artificial-leaf concepts are being pursued beyond academia; however, this remains non-peer-reviewed and should be treated as indicative rather than definitive. [18]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 4**

#### **Why the evidence rules out lower levels**

A maturity score below 4 would imply the ART is still largely at “operating principle shown” or “lab prototype only, without convincing prototype viability.” Multiple independent sources in the last four years show **functional, integrated solar-to-chemical prototypes** that go beyond single-cell benchtop demonstrations:

- **Outdoor / relevant-environment demonstrations** at multi-module scales are explicitly reported, including a **TRL 5** integrated device operating **72 h outdoors** for methane production (a full “sunlight-to-molecule” chain), and large-area integrated photoelectrochemical module work with quantified outdoor performance. [19]
- **Module/array scaling** has been demonstrated for both water splitting and CO<sub>2</sub>-to-syngas directions, including devices scaled to **hundreds of cm<sup>2</sup>** and assemblies reaching **sub-m<sup>2</sup> to m<sup>2</sup>-class reactor footprints** for outdoor benchmarking. [20]
- **Efficiency thresholds relevant to practical discussion** (often ~10% for solar-to-hydrogen) are met in at least one module-sized artificial leaf (16 cm<sup>2</sup> at >10% STH) and in a PV/EC “artificial leaf-type” formate/H<sub>2</sub> device (>10% combined solar-to-fuel), supporting the claim that key performance is not restricted to tiny proof cells. [21]

Taken together, this is best described as **Proof-of-Concept prototyping in increasingly realistic configurations**, rather than merely a verified scientific model or small lab-only prototype.

#### **What is still missing to justify the next higher level (5)**

Score 5 requires evidence that **several well-capitalized market actors** are competing to develop production prototypes post-PoC, or that a production prototype is clearly near launch with investments and manufacturing readiness.

The current evidence base still shows gaps that keep the ART below 5:

- **Durability is far from “field years”**. Even strong results are in the ~10–520 hour range or multi-day field tests, whereas roadmaps emphasize multi-year module lifetimes and scale-up stability as key commercialization barriers. [22]

- **Manufacturing and cost evidence remains limited.** While vacuum processing and modular designs are promising, there is not yet strong public evidence of repeatable, high-yield manufacturing lines, standardized balance-of-system designs, or cost curves approaching commercial solar hardware. [23]
- **Product separation / safe containment at the module edge** remains a core unresolved engineering theme—explicitly noted even in advanced “leaf” papers (e.g., gas separation challenges in module architectures) and in roadmaps focusing on membranes, scale-up, and system integration. [24]
- **Industry traction evidence is scattered and not yet dispositive:** one company announcement provides some scale claims, but it is not peer-reviewed or independently audited in the way a “products shipping” or “finishing production prototype” narrative would require. [18]

#### Sub-score breakdown (bundle assessment) and aggregation

Because “bionic leaf” is a bundle spanning multiple conversion chemistries, maturity varies by sub-thread.

- **Solar-to-hydrogen leaf-style modules → ~4**
- Rationale: Demonstrated module-sized, unbiased water splitting with >10% STH at 16 cm<sup>2</sup> and durability data into the 100+ hour range; other work shows hundreds of hours component durability and scaling into hundreds of cm<sup>2</sup>. [25]
- **Solar-to-formate / syngas (CO<sub>2</sub> reduction to C<sub>1</sub> products) in integrated/flow devices → ~4**
- Rationale: Multiple peer-reviewed demonstrations show high Faradaic efficiencies, reduced voltage via paired oxidation, flow-reactor integration, and m<sup>2</sup>-scale array demonstrations for syngas direction; still short on long-life and commodity-scale separation handling. [26]
- **Solar-to-multi-carbon liquids (e.g., ethanol/n-propanol) in standalone leaves → ~3**
- Rationale: A notable scientific milestone exists for unassisted production of multi-carbon liquids using a standalone artificial leaf, but yields/time-on-stream and robustness are still at laboratory demonstration levels. [8]
- **Integrated systems with operational control in relevant environments (pilot-like demos) → ~4**
- Rationale: Outdoor demonstrations document practical constraints (flow/pressure handling, degradation diagnosis, coupled reactor operation) consistent with PoC operation in relevant environments. [27]

**Aggregation method:** average-based across sub-components (because product targets and application paths differ materially), yielding ~3.75 → rounded to **4**. The best-evidenced sub-threads (solar-to-H<sub>2</sub> and solar-to-syngas/formate in modular reactors) reach PoC-style maturity, but the multi-carbon-liquid “bionic leaf” branch and overall commercialization readiness (durability/manufacturing/market actors) do not yet justify 5. [28]

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[1] <https://pmc.ncbi.nlm.nih.gov/articles/PMC9730848/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC9730848/>

- [2] <https://docs.nrel.gov/docs/fy22osti/83517.pdf>  
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- [6] [26] <https://www.nature.com/articles/s41467-023-36726-3>  
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[https://www.np.phy.cam.ac.uk/wp-content/uploads/sites/50/2024/06/natenergy23\\_bivo4leaf.pdf](https://www.np.phy.cam.ac.uk/wp-content/uploads/sites/50/2024/06/natenergy23_bivo4leaf.pdf)
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- [14] <https://www.nature.com/articles/s41560-025-01714-y>  
<https://www.nature.com/articles/s41560-025-01714-y>
- [15] [22] <https://www.nature.com/articles/s41467-025-58102-z>

<https://www.nature.com/articles/s41467-025-58102-z>

[16] [21] [24] [25] <https://www.nature.com/articles/s41467-025-59597-2>

<https://www.nature.com/articles/s41467-025-59597-2>

[17] <https://www.sciencedirect.com/science/article/pii/S2542435125003460>

<https://www.sciencedirect.com/science/article/pii/S2542435125003460>

[18] <https://www.sunhydrogen.com/news-posts/tech-update-dec17>

<https://www.sunhydrogen.com/news-posts/tech-update-dec17>

## ART 08.060 Grid-Scale Energy Storage

### ART extraction

#### A) Primary capability (claimed by the ART)

- Provide **grid-scale, long-duration electricity storage** that can shift energy across **hours to multi-day (and potentially longer)** periods to reduce supply–demand timing mismatches.
- Operate as **infrastructure-like “storage plants”** sized independently by **power (MW)** and **energy (MWh/GWh)**, designed for durability, predictable maintenance, and siteable near existing grid infrastructure.
- Integrate **bidirectional power electronics + sensing + control software** to schedule charging/discharging against forecasts and operational constraints, while satisfying safety and permitting requirements.

#### B) Key sub-components / variants (technology bundle)

- **Electrochemical LDES:** iron–air / metal–air (low-cost, lower efficiency, multi-day); flow batteries (vanadium, all-iron and variants), other aqueous chemistries.
- **Mechanical LDES:** pumped-storage hydropower; compressed air energy storage (CAES) (incl. salt-cavern variants); other “working-fluid” stores.
- **Thermal-to-electric storage:** engineered sensible/latent heat media + power block (e.g., Stirling / Brayton / other conversion), pumped-thermal concepts.
- **Chemical carriers for longer horizons:** bidirectional hydrogen (electrolyser + storage + conversion back to power), potentially multi-week/seasonal.
- **System integration layer:** grid interconnection and reliability performance, modelling/valuation methods, digital monitoring and operational control.
- **Non-technical gating layer:** permitting, safety standards/testing, financing structures (cap-and-floor / cost-share / bankability), end-of-life and recycling.

#### C) Maturity indicators that would constitute strong evidence

Evidence that materially increases confidence in **plausibility** and **maturity** includes:

- **Grid-connected deployments** at tens to hundreds of MW (or more) and documented **discharge durations ≥10 hours**, including *multi-day* demonstrations.
- **Independent measurement & verification**, safety testing, and documented failure-mode management (thermal runaway risk, gas handling, corrosion/cycling wear).
- Authoritative **cost/performance benchmarks** (e.g., installed cost ranges, LCOS, round-trip efficiency, lifetime/cycle assumptions) and **technology roadmaps** defining concrete scaling pathways.
- Emergence of **standardised market/policy mechanisms** that make projects financeable



(e.g., cap-and-floor, public cost-share, valuation frameworks).

- Evidence of **multiple competing suppliers** and signs of early **manufacturing scale-up** (project pipelines, signed agreements, delivered plants).

## Evidence

### Evidence dossier

1) **Title:** Achieving the Promise of Low-Cost Long Duration Energy Storage

**Authors/organisation:** U.S. Department of Energy[1]

**Venue/type:** Government technical report (cross-technology synthesis; Storage Innovations 2030 / Storage Shot context)

**Publication date:** August 2024

**Link:** [https://www.energy.gov/sites/default/files/2024-](https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf)

[08/Achieving%20the%20Promise%20of%20Low-](https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf)

[Cost%20Long%20Duration%20Energy%20Storage\\_FINAL\\_08052024.pdf](https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf)

This report consolidates innovations and R&D “pathways” across multiple LDES classes (electrochemical, mechanical, thermal, chemical) to reduce cost toward the Storage Shot framing and explicitly treats LDES as a **portfolio** rather than a single battery. It matters as an authoritative, engineering-grounded roadmap that connects **technical levers** to **commercialisation bottlenecks** across the technology family. [2]

2) **Title:** Pathways to Commercial Liftoff: Long Duration Energy Storage

**Authors/organisation:** U.S. Department of Energy[1] (hosted copy)

**Venue/type:** Government roadmap/report (commercialisation and market adoption)

**Publication date:** March 2023

**Link:** [https://www.sandia.gov/app/uploads/sites/256/2023/09/Pathways-to-Commercial-Liftoff-LDES-May-5\\_UPDATED.pdf](https://www.sandia.gov/app/uploads/sites/256/2023/09/Pathways-to-Commercial-Liftoff-LDES-May-5_UPDATED.pdf)

The report estimates the **U.S. grid may need 225–460 GW of LDES capacity** by 2050 for a net-zero pathway (with ~\$330B cumulative capital cited) and notes the non-PSH LDES supply chain was **<1 GW deployed as of 2022**, implying urgent scale-up needs. It matters because it provides a **quantified market pull** (deployment ranges, investment magnitude) and explicitly identifies why commercial liftoff is constrained by valuation, revenue certainty, and industrialisation. [3]

3) **Title:** 2022 Grid Energy Storage Technology Cost and Performance Assessment

**Authors/organisation:** Pacific Northwest National Laboratory[4] (for DOE Energy Storage Grand Challenge)

**Venue/type:** National-lab technical report / cost & performance benchmark

**Publication date:** August 2022

**Link:**

<https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf>

This benchmark report compares installed cost ranges and performance assumptions across major storage technologies and explicitly expands analysis to include **24-hour and 100-hour** system durations (enabling longer-duration LCOS comparisons beyond 2–10 hours). It matters because it anchors plausibility and maturity with **cross-technology cost/performance baselines** used by policymakers, labs, and investors. [5]

4) **Title:** Technology Strategy Assessment – Flow Batteries (Findings from Storage Innovations 2030)

**Authors/organisation:** U.S. Department of Energy[1]

**Venue/type:** Government technology strategy assessment (technology roadmap)

**Publication date:** July 2023

**Link:** [https://www.energy.gov/sites/default/files/2023-](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Flow%20Batteries.pdf)

[07/Technology%20Strategy%20Assessment%20-%20Flow%20Batteries.pdf](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Flow%20Batteries.pdf)

This assessment sets out RD&D “flight paths” for flow batteries under the Long-Duration Storage Shot framing (10+ hour systems) and identifies where innovations must reduce cost and improve durability to reach widespread grid deployment. It matters because flow batteries are a core “power/energy decoupled” architecture aligned with the ART’s **MW vs MWh sizing** concept. [6]

5) **Title:** Technology Strategy Assessment – Thermal Energy Storage (Findings from Storage Innovations 2030)

**Authors/organisation:** U.S. Department of Energy[1]

**Venue/type:** Government technology strategy assessment (technology roadmap)

**Publication date:** July 2023

**Link:** [https://www.energy.gov/sites/default/files/2023-](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Thermal%20Energy%20Storage.pdf)

[07/Technology%20Strategy%20Assessment%20-](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Thermal%20Energy%20Storage.pdf)

[%20Thermal%20Energy%20Storage.pdf](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Thermal%20Energy%20Storage.pdf)

This document frames thermal storage for long-duration electricity use, highlighting system-level integration challenges (storage medium + heat transfer + power block) and innovation pathways needed for scale and cost reduction. It matters because it captures the ART’s “storage plant” idea where **hardware durability** and **conversion efficiency** dominate economics. [7]

6) **Title:** Technology Strategy Assessment – Bidirectional Hydrogen Storage (Findings from Storage Innovations 2030)

**Authors/organisation:** U.S. Department of Energy[1]

**Venue/type:** Government technology strategy assessment (technology roadmap)

**Publication date:** July 2023

**Link:** [https://www.energy.gov/sites/default/files/2023-](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Bidirectional%20Hydrogen%20Storage.pdf)

[07/Technology%20Strategy%20Assessment%20-](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Bidirectional%20Hydrogen%20Storage.pdf)

[%20Bidirectional%20Hydrogen%20Storage.pdf](https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Bidirectional%20Hydrogen%20Storage.pdf)

The assessment explicitly models bidirectional hydrogen storage as a **plant** (electricity → hydrogen → electricity) and compares cost/performance pathways for storage in different configurations (e.g., tanks vs salt caverns), clarifying why duration and utilisation strongly shape economics. It matters because chemical storage is the ART’s pathway to **multi-week/seasonal** storage, despite lower round-trip efficiency. [8]

7) **Title:** Long-Duration Energy Storage Grid Integration – Valuation Framework and Incentive Gaps

**Authors/organisation:** National Renewable Energy Laboratory[9]

**Venue/type:** National-lab technical report (system integration / valuation)

**Publication date:** September 2025

**Link:** <https://www.nrel.gov/docs/fy25osti/95548.pdf>

This report focuses on how LDES value is (and is not) monetised, providing a valuation framing and identifying incentive gaps that can block deployment even when engineering

feasibility exists. It matters because “maturity” for infrastructure-like storage depends heavily on **market design, valuation methods, and compensation structures**, not only hardware readiness. [10]

8) **Title:** Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and a High-Efficiency Power Cycle

**Authors/organisation:** National Renewable Energy Laboratory[9]

**Venue/type:** National-lab report (techno-economic analysis; ARPA-E DAYS program context)

**Publication date:** September 2023

**Link:** <https://www.nrel.gov/docs/fy23osti/87881.pdf>

This analysis evaluates a thermal-to-electric LDES architecture combining **low-cost thermal storage media** with a **high-efficiency power cycle**, directly addressing the ART’s claim that marginal cost per added hour becomes decisive for multi-day storage. It matters because it provides a quantitative-style techno-economic framing for one of the ART’s key non-battery pathways. [11]

9) **Title:** Reliability Guideline: Performance, Modeling, and Simulations of BPS-Connected Battery Energy Storage Systems and Hybrid Power Plants

**Authors/organisation:** North American Electric Reliability Corporation[12]

**Venue/type:** Grid reliability guideline (authoritative operational / modelling guidance)

**Publication date:** June 2023

**Link:**

[https://www.nerc.com/comm/PC\\_Reliability\\_Guidelines\\_DL/Reliability\\_Guideline\\_BPS\\_connected\\_BEES\\_HybridPlants.pdf](https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_BPS_connected_BEES_HybridPlants.pdf)

This guideline targets performance requirements and modelling practices for grid-connected BESS and hybrid inverter-based plants, helping establish what “grid-ready” means beyond a lab prototype. It matters because the ART’s maturity hinges on **predictable operation** and **system-level validation** (models, simulations, interconnection behaviour). [13]

10) **Title:** Demonstrating an Aqueous Air-Breathing Energy Storage System for Multi-Day Resilience

**Authors/organisation:** California Energy Commission[14] (authors: Annie Baldwin[15] et al.)

**Venue/type:** Government project report with independent measurement & verification and safety testing

**Publication date:** November 2025

**Link:** <https://www.energy.ca.gov/sites/default/files/2025-11/CEC-500-2025-045.pdf>

The report documents kW-scale prototype module validation for an iron–air-style multi-day system, reporting **zero safety events** and **short-circuit temperature rise ~0–5°C**, and cites **~140 MW / 14 GWh** in signed agreements plus a planned **1.5 MW / 150 MWh** deployment. It matters because it provides unusually concrete, quasi-pre-commercial evidence on **safety, verification**, and early **commercial traction** for multi-day aqueous metal–air. [16]

11) **Title:** Award Wednesdays | June 5, 2024 (LDES Demonstrations Program – Multiday Iron Air Demonstration)

**Authors/organisation:** U.S. Department of Energy[1]

**Venue/type:** Government programme award notice (deployment milestone)

**Publication date:** June 2024

**Link:** <https://www.energy.gov/oced/articles/award-wednesdays-june-5-2024>

This award notice describes a plan to deploy **two 10 MW, 100-hour** iron–air LDES systems at retiring coal sites, with >\$4.3M awarded initially and up to **\$70M** federal cost-share, signalling a move from prototypes into structured, phased project delivery. It matters because publicly financed demonstration programmes are a key maturity indicator for infrastructure technologies with long permitting/build cycles. [17]

12) **Title:** Clean Energy Technology Observatory: Novel Energy Storage in the European Union – 2024 Status Report

**Authors/organisation:** European Commission Joint Research Centre[18]

**Venue/type:** Authoritative EU roadmap/status report (TRL, markets, value chains)

**Publication date:** November 2024

**Link:** [https://setis.ec.europa.eu/document/download/b24bc3ac-4f0d-43dc-abca-2dabfaf44530\\_en](https://setis.ec.europa.eu/document/download/b24bc3ac-4f0d-43dc-abca-2dabfaf44530_en)

This report surveys mechanical, electromagnetic, and thermal storage classes, including TRL positioning and market/value-chain indicators, and explicitly notes that some technologies (e.g., certain CAES variants) are closer to wide implementation while others remain developmental. It matters as a second-region, policy-relevant evidence base showing how the ART’s “family of plants” is being monitored and prioritised at continental scale. [19]

13) **Title:** Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union – 2024 Status Report

**Authors/organisation:** European Commission Joint Research Centre[18]

**Venue/type:** Authoritative EU status report (mature long-duration mechanical storage)

**Publication date:** November 2024

**Link:** [https://setis.ec.europa.eu/document/download/67632c8c-a010-4e74-a8c1-8659b2246707\\_en](https://setis.ec.europa.eu/document/download/67632c8c-a010-4e74-a8c1-8659b2246707_en)

The report reiterates pumped storage hydropower’s role as the dominant deployed electricity storage form (with major system-service value but site/environment constraints), illustrating the ART’s point that some options are heavily **site dependent**. It matters because it anchors the upper end of maturity for long-duration storage and highlights constraints that drive interest in more modular alternatives. [20]

14) **Title:** Long duration electricity storage consultation: Designing a policy framework to enable investment in long duration electricity storage

**Authors/organisation:** Department for Energy Security and Net Zero[21]

**Venue/type:** Government consultation (financeability / market design)

**Publication date:** January 2024

**Link:**

<https://assets.publishing.service.gov.uk/media/659bde4dd7737c000ef3351a/long-duration-electricity-storage-policy-framework-consultation.pdf>

The consultation explicitly identifies barriers consistent with the ART description—**high upfront capex, long build times**, limited technology track record (FOAK), and **insufficient revenue certainty**—and discusses a cap-and-floor style approach. It matters because policy mechanisms are a gating maturity factor for multi-day storage plants whose economics are infrastructure-like. [22]

15) **Title:** Long Duration Electricity Storage: Technical Decision Document

**Authors/organisation:** Ofgem[23] (with UK government branding)

**Venue/type:** Regulator technical decision (implementation design for cap-and-floor)

**Publication date:** March 2025 (11 March 2025)

**Link:** <https://www.ofgem.gov.uk/sites/default/files/2025-03/Long%20Duration%20Electricity%20Storage%20Technical%20Decision%20Document.pdf>

This decision document confirms key design elements of a GB LDES cap-and-floor scheme (including operational details and readiness steps), moving beyond consultation into executable rules. It matters as a high-signal maturity indicator: **finance structures are being institutionalised**, which is often prerequisite to scaling FOAK storage plants. [24]

16) **Title:** Compressed Air Energy Storage: A Case Study

**Authors/organisation:** World Bank[25] / Energy Sector Management Assistance Program[26]

**Venue/type:** Authoritative case study / knowledge note (deployment evidence + economics framing)

**Publication date:** January 2026

**Link:**

<https://documents1.worldbank.org/curated/en/099741101222620522/pdf/IDU-e56b0f51-75c8-4de7-87b1-0eef28f82012.pdf>

The note reports the Yingcheng CAES project in China[27] operating at **300 MW** with **five-hour** discharge (**1,500 MWh**) and identifies it as the largest CAES project commissioned to date and the first of its kind operating **without supplemental fuels**, using repurposed salt caverns (~700,000 m<sup>3</sup>). It matters because it is a well-sourced, third-party documentation of a **utility-scale, non-battery** long-duration plant that has crossed into operations. [28]

17) **Title:** World's Largest Flow Battery Energy Storage Station Connected to Grid

**Authors/organisation:** Chinese Academy of Sciences[29]

**Venue/type:** National research institution technical news release (grid-connection milestone)

**Publication date:** October 2024 (31 Oct 2024 implied by URL path)

**Link:**

[https://english.cas.cn/Special\\_Reports/rd/2022/202410/t20241031\\_693355.shtml](https://english.cas.cn/Special_Reports/rd/2022/202410/t20241031_693355.shtml)

This release reports the grid connection of the Dalian vanadium flow-battery peak-shaving station, with **100 MW / 400 MWh** first phase and eventual scale **200 MW / 800 MWh**, citing national demonstration status and describing operational peak-shaving use. It matters because it provides a credible, non-company confirmation of **100-MW-class flow battery deployment**, placing at least one LDES electrochemical pathway firmly beyond pilot scale. [30]

18) **Title:** China Three Gorges' 200 MW / 1,000 MWh Vanadium Flow Battery Energy Storage Project in Xinjiang Achieves Full-Capacity Operation

**Authors/organisation:** Vanitec[31] (author: Yu Li[32])

**Venue/type:** Industry association technical news / project note

**Publication date:** January 2026 (01 Jan 2026)

**Link:** <https://vanitec.org/latest-from-vanitec/article/china-three-gorges-200-mw-1000-mwh-vanadium-flow-battery-energy-storage-project-in-xinjiang-achieves-full-capacity-operation>

The note describes **200 MW / 1,000 MWh** (five-hour) VFB full-capacity operation in Xinjiang[33] paired with **1 GW PV**, reporting **RMB 3.8B** investment and operational features like intelligent thermal management and a **digital-twin O&M platform**, plus a reported ~9%



**PV utilisation uplift** and ~220 million kWh additional renewable absorption annually. It matters because it evidences scaling of flow batteries into **GWh-class projects** with explicit digital operations tooling—matching the ART’s control-software claims. [34]

19) **Title:** Experimental Demonstration of a Solar Powered High Temperature Latent Heat Storage Prototype: Preliminary Results of an Experimental Validation Campaign

**Authors/organisation:** Asem Alemam[35] et al.

**Venue/type:** Peer-reviewed conference proceedings (SolarPACES 2023 proceedings) with prototype field validation data

**Publication date:** July 2024 (Published 24 Jul 2024)

**Link:** <https://doi.org/10.52825/solarpaces.v2i.968>

The authors report a full-scale electro-thermal storage prototype monitored continuously for 10 days, maintaining near-constant electricity output of **10.5 ± 1 kW** for **13 hours** discharge, with **average cycle efficiency ~23%** and **power block efficiency ~25%**. It matters because it provides measured, real-operation evidence for thermal-to-electric storage pathways and makes clear the efficiency trade-offs that shape maturity and market fit. [36]

20) **Title:** A low-cost all-iron hybrid redox flow batteries enabled by deep eutectic solvents

**Authors/organisation:** Xusheng Cheng[37] et al.

**Venue/type:** Peer-reviewed experimental paper (Chemical Engineering Journal)

**Publication date:** July 2024 (Volume 491, 1 July 2024)

**Link:** <https://doi.org/10.1016/j.cej.2024.151936>

This paper experimentally demonstrates a deep-eutectic all-iron hybrid flow battery achieving **>98% average coulombic efficiency** over a **360-hour charge–discharge cycle** (with reported energy efficiency approaching **~54%** at 10 mA/cm<sup>2</sup> and **~100%** coulombic efficiency in early cycles). It matters because it supports the plausibility of **iron-based, low-cost** electrochemical LDES variants while also evidencing today’s efficiency limitations versus incumbent systems. [38]

### **Maturity score and reasoning**

#### **A) Final maturity score: 6**

#### **B) Why this is at least level 6 (and not lower)**

Level 4 (PoC) and below are ruled out because the dossier includes multiple examples of **operational, grid-scale plants** and structured demonstration deployments, not merely lab prototypes. The World Bank case study documents a CAES facility operating at **300 MW / 1,500 MWh** with five-hour discharge and operating without supplemental fuels, which is beyond PoC and firmly in “real asset” territory. [28]

Likewise, flow-battery technology has crossed into **100-MW-class grid-connected** operation (first phase **100 MW / 400 MWh**) with ambitions to scale higher, as reported by a national research institution, and subsequent reporting indicates **200 MW / 1,000 MWh** operation with explicit operational tooling (thermal management, digital twin O&M). [39]

#### **C) Why this is not yet level 7 (what is still missing)**

A level 7 judgement would require that *competing* long-duration products are being delivered broadly, with demand rising across many regions and competition largely internally financed (i.e., a mature, self-sustaining market across most variants). The U.S. “Commercial Liftoff” report explicitly characterises the non-pumped-hydro LDES supply chain as **nascent (<1 GW**



**deployed as of 2022)** and argues that annual manufacturing/deployment capacity must grow sharply (order-of-magnitude increases) to meet projected needs—an indicator that many LDES segments do **not yet** have fully mature, scalable supply chains. [40]

Further, policy and revenue mechanisms are still being finalised in major markets (e.g., GB moving from consultation to technical decision and scheme design), implying that “bankable scaling” remains an active workstream rather than a settled, globally standardised condition. [41]

### Subcomponent maturity breakdown

#### Sub-component → maturity estimate → key supporting source(s)

- Pumped-storage hydropower (mature long-duration mechanical storage) → **7** → EU status reporting plus cross-technology benchmarks treating PSH as established infrastructure. [42]
- Compressed air energy storage at utility scale (CAES) → **6** → Documented operational 300-MW-class plant case study and market context. [28]
- Vanadium flow batteries at utility scale (VRFB) → **6** → 100-MW-class grid connection and subsequent 200 MW / 1,000 MWh full-output operation reporting. [39]
- Iron–air / aqueous air-breathing multi-day batteries → **5** → Independent module verification + safety testing + early commercial agreements and demonstration-funded deployments, but still early in volume delivery. [43]
- Thermal-to-electric storage (power-to-heat-to-power variants) → **4** → Prototype field validation shows functionality but also low round-trip efficiency; techno-economic reports indicate active optimisation rather than mass deployment. [44]
- Bidirectional hydrogen storage for grid applications → **4** → Roadmaps and plant-level modelling exist, but widespread power-sector seasonal storage deployment remains limited relative to mature options. [45]
- Low-cost iron-based flow battery chemistry improvements (lab-scale electrolyte/system advances) → **3–4** → Recent experimental evidence demonstrates cycling and efficiency metrics but not large-scale field deployment. [38]

#### Aggregation method → single score

Because the ART is explicitly a **bundle** of storage plant types (electrochemical + mechanical + thermal + chemical) serving broadly similar system functions but at different durations and with different siting constraints, the score is based on an **average-by-commercial-weight** approach rather than a maximum. Mature incumbents (notably PSH) pull the ceiling upward, while multi-day electrochemical and thermal/chemical pathways are still moving through demonstration and early bankability stages; taken together, the evidence best fits **level 6**: multiple technologies are being delivered and operated at meaningful scale, with strong institutional financing and policy mechanisms emerging, but not yet a universally mature, self-sustaining market across all variants. [46]

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## ART 08.061 Solid-State Batteries

### ART extraction

#### Primary capability the ART claims

- Replace today's flammable liquid electrolyte with a **solid ion-conducting electrolyte layer** to improve safety (reduced thermal-runaway/fire risk) while maintaining usable ion transport.
- Enable **higher energy density**—especially via **lithium-metal anodes** (instead of graphite) and tighter packaging—without sacrificing reliability under cycling.
- Deliver **practical, modular packs** (cells → modules → packs) whose operation is made predictable and safe via monitoring (temperature/pressure/impedance) and battery-management controls.

#### Key sub-components or variants

- **Solid electrolyte families:** sulfides (e.g., argyrodites), oxides/garnets (e.g., LLZO/LLZTO), halides (chloride/bromide systems), polymers, and hybrid “gel/solid-state” electrolytes. [1]
- **Interface engineering:** engineered interlayers/coatings, microstructure densification, and mechanically robust lamination/co-rolling to maintain intimate solid–solid contact and suppress dendrite/filament growth. [2]
- **Lithium-metal management approaches:** thin Li foils, Li-free/reservoir-free concepts, uniform plating/stripping protocols, and manufacturing routes for high-quality thin lithium films at scale. [3]
- **Cell engineering for scale:** pouch-cell architecture and “passive-mass dilution” via larger electrode areas / stack counts; robust thin electrolyte membranes; tolerable stack-pressure requirements. [4]
- **Manufacturing and QC:** dry-room/moisture handling, defect/void control, film handling, and process tolerance windows (yield, thickness uniformity, contamination control). [5]
- **System integration constraints:** pack-level thermal/pressure management, monitoring, and qualification/validation pathways (automotive-style A/B/C samples, demo vehicles). [6]

#### What maturity indicators would constitute evidence

- **Cell-level demonstrations** in relevant form factors (multi-layer pouch cells) with clearly stated **energy density, areal capacity, cycle life, and safety/abuse** behaviour. [7]
- **Evidence that key blockers are being reduced:** dendrite/short mitigation at higher current density; reduced stack-pressure dependence; stable interfaces over long cycling. [8]

- **Pilot-line / scale-up evidence:** credible manufacturing routes (dry-process films, roll-to-roll, densification) and techno-economic or process-capacity analyses tied to gigafactory-like throughput constraints. [5]
- **Customer/field validation:** shipments of prototype cells, automotive qualification steps, and (strongest) **vehicle integration trials**. [9]

Evidence (10–20 recent, reliable sources)

Peer-reviewed experimental and cell-engineering evidence

1) **A scalable and long-cycle-life 600 Wh kg<sup>-1</sup> solid-state lithium metal pouch cell**

- **Authors/org:** Xudong Peng[10] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** Nov 2025.
- **Link:** [11]
- **What and why:** Reports an **~11 Ah-class** Li-metal pouch cell achieving **~604 Wh/kg** (package-included) and **>100 cycles** with **~92.83% energy retention** under **lean electrolyte** conditions—direct evidence that very high specific energy can be reached in multi-layer, pouch-format designs (though still early-life by automotive standards). [12]

2) **High plating currents without dendrites at the interface between a lithium anode and solid electrolyte**

- **Authors/org:** Dominic L. R. Melvin[13] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** Sep 2025.
- **Link:** [14]
- **What and why:** Shows that densifying a sulfide solid electrolyte (Li<sub>6</sub>PS<sub>5</sub>Cl) to **~99% relative density** can raise the **critical current density** from ~1 to **~10 mA/cm<sup>2</sup>**, with **no dendritic cracks observed at 9 mA/cm<sup>2</sup>**, addressing one of the core feasibility blockers (dendrite-induced shorting) at higher plating rates. [15]

3) **Robust interface and reduced operation pressure enabled by co-rolling dry-process for stable all-solid-state batteries**

- **Authors/org:** Dong Ju Lee[16] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** May 2025.
- **Link:** [17]
- **What and why:** Demonstrates a **dry-process co-rolling** approach that improves film integrity and enables long-term cycling at **much lower stack pressure** (e.g., **~2 MPa**) while sustaining **high areal capacities (~3–4 mAh/cm<sup>2</sup>)** for **~500 cycles**; this directly targets pack-level practicality because maintaining high pressure is a major system-integration penalty. [18]

4) **Advanced parametrization for the production of high-energy solid-state lithium pouch cells containing polymer electrolytes**

- **Authors/org:** Wonmi Lee[19] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** Jul 2024.
- **Link:** [20]
- **What and why:** Reports practical pouch-cell builds, including an **~1 Ah** cell at **~280 Wh/kg**

and an **~0.5 Ah** cell at **~310 Wh/kg**, with explicit accounting for packaging and passive parts; also notes **third-party certification** of specific energy for a demonstrated pouch cell, strengthening credibility around “beyond-coin-cell” maturity. [21]

#### 5) A $\text{LaCl}_3$ -based lithium superionic conductor compatible with lithium metal

- **Authors/org:** Yi-Chen Yin[22] et al.
- **Venue/type:** Peer-reviewed journal article.
- **Publication date:** Apr 2023.
- **Link:** [23]
- **What and why:** Introduces a Ta-doped  $\text{LaCl}_3$ -based conductor with **~3.02 mS/cm conductivity at 30 °C** and reports **>5,000 h Li-Li symmetric cycling** ( $1 \text{ mAh/cm}^2$ ), plus **>100 cycles** in a full cell at **4.35 V cut-off** with **>1 mAh/cm<sup>2</sup> areal capacity**—strong evidence that halide SSEs can combine high conductivity with improved Li-metal compatibility. [23]

#### 6) Beneficial redox activity of halide solid electrolytes empowering high-performance anodes in all-solid-state batteries

- **Authors/org:** Zhu Cheng[24] et al.
- **Venue/type:** Peer-reviewed journal article.
- **Publication date:** Jul 2025.
- **Link:** [25]
- **What and why:** Reports “dynamic stability” in halide SSEs (e.g.,  $\text{Li}_3\text{YCl}_3\text{Br}_3$ ,  $\text{Li}_2\text{ZrCl}_6$ ), with demonstrations including **~7.65 mAh/cm<sup>2</sup> areal capacity** and **~70% retention after 1,000 cycles** for halide-based full cells, arguing that certain SSE redox activity can be reversible and performance-positive—relevant to plausibility of stable interfaces and high-loading electrodes. [26]

#### 7) Effect of pulse-current-based protocols on the lithium dendrite formation and evolution in all-solid-state batteries

- **Authors/org:** V. Reisecker[27] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** Apr 2023.
- **Link:** [28]
- **What and why:** Demonstrates that a MHz pulse-current protocol can enable all-solid-state Li-metal cells operating up to **~6.5 mA/cm<sup>2</sup>**, explicitly linking protocol design to dendrite risk (stress/fracture at defects) and showing that “software/control” approaches can complement materials solutions for fast charge. [28]

#### 8) An electron-blocking interface for garnet-based quasi-solid-state lithium-metal batteries to improve lifespan

- **Authors/org:** Chang Zhang[29] et al.
- **Venue/type:** Peer-reviewed open-access journal article.
- **Publication date:** Jun 2024.
- **Link:** [30]
- **What and why:** Uses a KF-derived interlayer (forming KF/LiF) on LLZTO to reduce electron leakage and inhibit dendrites; reports Li-symmetric cycling of **~3,000 h at 0.2 mA/cm<sup>2</sup>**, and full-cell cycling to **~3,500 cycles** (72.5% retention at 2C, 25 °C), illustrating meaningful progress on garnet-interface durability. [31]

#### Manufacturing, scale-up, and cost/throughput analyses



### 9) **Scaling up high-energy-density sulfidic solid-state batteries: A lab-to-pilot perspective**

- **Authors/org:** Darren H. S. Tan[\[32\]](#) et al.
- **Venue/type:** Peer-reviewed perspective (manufacturing scale-up).
- **Publication date:** Aug 2022.
- **Link:** [\[33\]](#)
- **What and why:** Consolidates practical scale-up constraints (moisture handling, dry processing, cell assembly and the implications of stack pressure) and argues that many published ASSB results remain tied to impractical lab form factors—directly supporting the ART’s manufacturing-cleanliness/contact requirements as key maturity bottlenecks. [\[34\]](#)

### 10) **Techno-economic assessment of thin lithium metal anodes for solid-state batteries**

- **Authors/org:** Matthew Burton[\[35\]](#) et al.
- **Venue/type:** Peer-reviewed open-access analysis.
- **Publication date:** Dec 2024.
- **Link:** [\[36\]](#)
- **What and why:** Evaluates scalable routes for producing thin lithium films compatible with gigafactory volumes and identifies **thermal evaporation** as a potentially cost-effective approach; provides quantified throughput framing (e.g., area-per-year equivalents) and highlights defect/thickness control as a QC priority—directly tied to whether Li-metal-based solid-state cells can reach cost/scale. [\[36\]](#)

### 11) **A Roadmap for Solid-State Batteries**

- **Authors/org:** Thomas Schmaltz[\[37\]](#) et al.
- **Venue/type:** Peer-reviewed open-access perspective/roadmap.
- **Publication date:** Oct 2023 (first published).
- **Link:** [\[38\]](#)
- **What and why:** Synthesises materials choices, hybrid concepts, production routes, and the long qualification cycles typical in automotive deployment; it explicitly frames cost, safety, and production uncertainty as gating factors, aligning with the ART’s claims that maturity is as much a manufacturing/interfaces challenge as a materials one. [\[39\]](#)

### 12) **Development perspectives for lithium-ion battery cell formats**

- **Authors/org:** Fraunhofer ISI[\[40\]](#) (report team).
- **Venue/type:** Authoritative research institute report.
- **Publication date:** Nov 2022.
- **Link:** [\[41\]](#)
- **What and why:** Provides a structured industry-facing discussion of future cell formats and explicitly identifies **polymers, oxide-based, and sulfide-based solid electrolytes** as key classes, noting the requirement for chemical/mechanical stability against Li-metal and dendrite growth—useful as a neutral framing of design trade-offs and manufacturability. [\[42\]](#)

### 13) **A Review on Solid State Batteries: Life Cycle Perspectives**

- **Authors/org:** Ramsharan Pandey[\[43\]](#) et al., via OSTI.gov[\[44\]](#) record.
- **Venue/type:** National-lab technical report (life-cycle and manufacturing hotspot review).
- **Publication date:** Sep 2024.
- **Link:** [\[45\]](#)
- **What and why:** Summarises SSB advantages and highlights that **interface stability** is a primary commercialization barrier; from an LCA framing, it notes solid-electrolyte manufacturing as a major hotspot and that production routes can diverge from conventional

Li-ion—relevant to the ART claim that bottlenecks shift toward QC, materials supply, and recycling pathways. [45]

#### Industry scale-up signals and prototype/field evidence

##### 14) Idemitsu and Toyota Announce Beginning of Cooperation toward Mass Production of All-Solid-State Batteries for BEVs

- **Authors/org:** Toyota Motor Corporation[46] and Idemitsu Kosan Co.,Ltd.[47] (joint announcement).
- **Venue/type:** Industry programme announcement (pilot facility + launch planning).
- **Publication date:** Oct 2023.
- **Link:** [48]
- **What and why:** Describes phased work on **sulfide solid electrolytes**, preparation and construction of a **large pilot facility**, and a target to launch BEVs with all-solid-state batteries in **2027–28**—credible evidence of industrial commitment and an explicit scaling timeline, albeit not proof of volume delivery yet. [48]

##### 15) BMW Group and Solid Power are testing all-solid-state battery cells in a BMW i7

- **Authors/org:** BMW Group[49] (author: Bernhard Ederer[50]).
- **Venue/type:** OEM press release describing in-vehicle testing programme.
- **Publication date:** May 2025.
- **Link:** [51]
- **What and why:** States that large-format all-solid-state cells are integrated into a test vehicle operated in the Munich[52] area, with investigations into cell expansion management, operating pressure, and temperature control—strong maturity evidence that pack integration and vehicle-relevant validation have begun. [53]

##### 16) Q1 Fiscal 2024 Letter to Shareholders

- **Authors/org:** QuantumScape[54] (corporate letter; no individual authors listed).
- **Venue/type:** Company technical update / investor document (prototype metrics; company-tested).
- **Publication date:** Apr 2024.
- **Link:** [55]
- **What and why:** Reports prototype-sample progression (including shipment of earlier prototype cells to automotive customers at end-2022) and presents in-house test metrics such as **10–80% fast charge in <15 minutes** under specified conditions and a stated target of **>800 Wh/L** for the planned design—useful maturity evidence of iterative sample delivery, while still requiring independent validation and long-duration qualification. [56]

##### 17) ProLogium Unveils Solid-state Battery Creation Process, Plans to Start Mass Production in 2023

- **Authors/org:** ProLogium Technology[57] (press release).
- **Venue/type:** Company manufacturing/scale announcement (treat as self-reported).
- **Publication date:** Jun 2022.
- **Link:** [58]
- **What and why:** Claims roll-to-roll pilot-line operation, a planned **3 GWh** plant ramp, and self-reported manufacturing KPIs (e.g., **99.9% single-layer yield**) and shipment figures (including large-format **~50–60 Ah EV cells**)—helpful as a market-actor signal but should be treated cautiously because figures are not independently audited in the release. [59]

## Maturity score (1–7) and reasoning

### Final maturity score: 5

[60]

### Evidence-to-rubric mapping

#### Why level 5 (and not lower):

- Levels **2–3** are exceeded because multiple peer-reviewed works demonstrate not only lab principles but **integrated cell prototypes** addressing previously blocking issues (e.g., dendrite suppression at higher current density via microstructural densification, and reduced-pressure operation via co-rolled dry-process interfaces). [61]
- Level **4 (PoC)** is exceeded because the technology is being demonstrated in **commercially relevant form factors** (Ah-class pouch cells with quantified specific energy) and is beginning **system/vehicle integration work** (an OEM road test programme), which is beyond a purely scientific PoC. [62]
- Level **5** is supported by clear evidence of **multiple well-capitalised actors** executing pilot-facility plans and prototype-sample programmes, including explicit timelines to launch (2027–28 target in a major automotive programme) and iterative automotive sample shipments reported by a major developer. [63]

#### What is still missing for level 6:

- Level **6** requires convincing evidence that solid-state battery products are being **delivered to customers in increasing amounts**, with scaling that credibly implies learning-curve cost reductions and expanding applications. The strongest public evidence in this dossier is still dominated by **prototype/pilot** status: advanced pouch-cell demonstrations often remain at **hundreds of cycles (not thousands in EV-relevant conditions)**, and some require **elevated temperature and/or stack pressure**, signalling remaining pack-integration complexity. [64]
- A level-6 case would likely need: (i) sustained, independently verified automotive qualification results, (ii) production-line yields and throughput data showing consistent large-format manufacturing, and (iii) credible cost-down trajectories versus incumbent Li-ion—none of which are yet demonstrated conclusively in the open literature and documents cited here. [65]

### Sub-component maturity notes and aggregation

Because the ART description is centred on **high-energy, safer, scalable solid-state cells (often Li-metal)** and their integration into packs, the variants below are treated as a single functional family; maturity is therefore taken as the **maximum consistent level supported across the strongest evidence**, rather than averaging across unrelated niche applications.

- **Interface/dendrite suppression in inorganic SSE systems** → **~4–5** (lab-to-prototype maturity): demonstrated improvements such as **CCD ~10 mA/cm<sup>2</sup>** in densified sulfide SSE and long-cycle strategies at reduced pressure, but still with significant engineering constraints. [61]
- **Ah-class pouch-cell engineering (polymer/hybrid and all-solid variants)** → **~4–5**: repeated evidence of pouch-scale specific energy in the **~280–310 Wh/kg** class and even extreme **~600 Wh/kg** demonstrations, but cycle-life and conditions remain short of mass-market automotive requirements. [66]

- **Industrial pilot/qualification efforts** → ~5: explicit pilot-facility and automotive launch planning, plus early vehicle integration testing and reported sample shipment pipelines. [67]

**Aggregation to one score:** The overall ART maturity is set to **5** because the clearest, most recent evidence shows **post-PoC competition and pilot/qualification acceleration**, while evidence for **broad, growing customer deliveries and scaled economics** (level 6) is not yet demonstrated publicly. [68]

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## ART 08.062 Green Hydrogen & Power-to-X

### ART extraction

#### A) Primary capability claimed (core “what it does”)

- Convert low-carbon electricity and water into **hydrogen**, and optionally combine hydrogen with **captured CO<sub>2</sub>** to make storable/transportable “Power-to-X” molecules (e.g., ammonia-like carriers, methanol, synthetic hydrocarbons). [1]
- Operate **flexibly and dynamically** (load-following variable renewables / price signals), rather than only at steady baseload conditions. [2]

- Run as **modular plants** (containerised up to 100-MW-class standard plant designs) with increasing use of automation, monitoring, and model-based/predictive maintenance. [3]

#### B) Key sub-components / variants (technology bundle threads)

- **Electrolysis stacks:** alkaline water electrolysis (AWE), proton exchange membrane (PEM), anion exchange membrane (AEM), and high-temperature electrolysis variants including solid oxide / proton-conducting ceramics (SOEC/PCEC). [4]
- **Balance of plant (BoP):** power electronics/rectifiers, thermal management, water purification, gas–liquid separation, compression and drying/purification. [5]
- **Power-to-X synthesis modules:** reactors to convert  $H_2 + CO_2$  (e.g., methanol) and/or  $H_2 + N_2$  (ammonia), plus conditioning, storage, and export interfaces. [6]
- **Digital control and assurance layer:** sensors, control architectures (including safety instrumented functions), monitoring/diagnostics, digital twins, and certification frameworks for “renewable hydrogen / RFNBO” claims. [7]
- **Supply-chain and materials constraints:** catalysts (notably iridium for PEM anodes), membranes/MEAs, coatings and metal components, recycling pathways, and manufacturing throughput. [8]

#### C) Maturity indicators that would count as strong evidence

- **Industrial-scale deployments** (MW-class systems) operating on realistic duty cycles (start/stop, ramping, turndown), not only lab steady-state tests. [9]
- **Market signals of scaling:** installed capacity growth, evidence of sales/manufacturing capacity expansion, standardised plant offerings, and multiple competing vendors. [10]
- **Durability and materials progress:** quantified lifetime/degradation under dynamic operation; credible pathways for scarce/critical inputs (e.g., iridium loading + recycling) and improved membranes. [11]
- **Integration progress for PtX:** pilot or demonstration coupling of electrolysis with downstream synthesis and  $CO_2$  handling, plus techno-economic studies that explicitly cover scale-up. [6]
- **Regulatory/safety/certification readiness:** operational safety guidance and enforceable “renewable hydrogen” rules (additionality + temporal/geographic correlation), enabling tradable origin claims. [12]

## 2. Evidence (10–20 recent, reliable sources)

### System-level deployment and scaling evidence

#### 1) Hydrogen production — Global Hydrogen Review 2024 (Hydrogen production page)

- **Organisation:** International Energy Agency [13] (IEA)
- **Venue/type:** authoritative annual tracking report (webpage section)
- **Publication date:** Oct 2024 (report edition)
- **Link:** <https://www.iea.org/reports/global-hydrogen-review-2024/hydrogen-production>
- **Why it matters:** Reports installed water electrolyser capacity reaching **1.4 GW by end-2023**, a possible **5 GW by end-2024**, and notes that “announced” capacity could be far



larger but only about **4%** has reached **FID or construction**—direct maturity evidence on real deployment vs. pipeline optimism. [14]

## 2) The European hydrogen market landscape (November 2024)

- **Organisation:** European Hydrogen Observatory[15]
- **Venue/type:** authoritative market/industrial landscape report (PDF)
- **Publication date:** Nov 2024
- **Link:** [https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape\\_November%202024.pdf](https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape_November%202024.pdf)
- **Why it matters:** Provides manufacturing/scaling signals, including **5.4 GW/year operational electrolyser manufacturing capacity** in Europe (as of May 2024), expected **8.8 GW/year by end-2024**, and **~65 MW electrolyser sales by European manufacturers in 2023**—useful for assessing “products delivered” vs. early-stage R&D. [16]

## Regulation, certification, and safety readiness

### 3) Renewable hydrogen — EU definition, additionality, temporal & geographic correlation; certification via voluntary schemes

- **Organisation:** European Commission[17]
- **Venue/type:** authoritative policy/implementation guidance page
- **Publication date:** page reflects delegated acts adopted June 2023; includes transition timing (noted on the page)
- **Link:** [https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/renewable-hydrogen\\_en](https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/renewable-hydrogen_en)
- **Why it matters:** Specifies the EU’s renewable hydrogen criteria: **additionality** (new RES capacity via PPAs), and **temporal/geographic correlation** to avoid driving fossil generation; also confirms certification relies on recognised third-party “voluntary schemes.” This directly supports plausibility of embedded traceability/certification data flows in PtX commerce. [18]

### 4) Factsheet — Commission Delegated Regulation (EU) 2023/1184 (RFNBO production rules)

- **Organisation:** European Free Trade Association[19]
- **Venue/type:** standards/legal indexing factsheet
- **Publication date:** adoption **10 Feb 2023**; Official Journal listed **20 Jun 2023**
- **Link:** <https://www.efta.int/eea-lex/32023r1184>
- **Why it matters:** Provides verifiable dates and identifiers for the key EU delegated act governing “renewable fuels of non-biological origin” (renewable hydrogen and derivatives), a prerequisite for scalable certification and trade. [20]

### 5) EHSP Guidance on Hydrogen Safety Engineering — Guidance Document

- **Organisation:** Clean Hydrogen Partnership[21] (Clean Hydrogen JU / partnership)
- **Venue/type:** authoritative safety engineering guidance (PDF)
- **Publication date:** 01 May 2023
- **Link:** <https://www.clean-hydrogen.europa.eu/system/files/2023-05/EHSP%20Guidance%20on%20Hydrogen%20Safety%20Engineering%20-%20v1-Final.pdf>
- **Why it matters:** Demonstrates maturing **siting/permitting and hazard analysis** practice (consequence modelling, prevention/mitigation, and navigation of

regulations/codes/standards), which is essential for scaling real electrolyser + storage facilities. [22]

#### Electrolyser dynamic operation and control (plausibility of load-following)

##### 6) Dynamic operation of water electrolyzers: A review for applications in photovoltaic systems integration

- **Organisation/authors:** academic authors (peer-reviewed)
- **Venue/type:** peer-reviewed review article (Renewable & Sustainable Energy Reviews)
- **Publication date:** 2023 (available online/published in 2023 on ScienceDirect page)
- **Link:** <https://www.sciencedirect.com/science/article/pii/S1364032123002642>
- **Why it matters:** Summarises dynamic behaviour of low-temperature electrolyzers and identifies limiting variables (e.g., **temperature/pressure** rather than electrical response), directly supporting feasibility of “dynamic setpoint” operation under variable renewables.

[23]

##### 7) Dynamic operation of proton exchange membrane electrolyzers — Critical review

- **Organisation/authors:** academic authors (peer-reviewed)
- **Venue/type:** peer-reviewed review article (Renewable & Sustainable Energy Reviews)
- **Publication date:** Jan 2024
- **Link:** <https://research.aalto.fi/en/publications/dynamic-operation-of-proton-exchange-membrane-electrolyzerscritic/>
- **Why it matters:** Focuses on PEM electrolysis under dynamic operation and explicitly links dynamic behaviour to **degradation, safety, efficiency, and electricity-market participation**, clarifying what must be solved for reliable commercial load-following.

[24]

##### 8) Experimental studies on dynamic performance of 250-kW alkaline electrolytic system

- **Organisation/authors:** academic + industrial-scale experimental work (peer-reviewed)
- **Venue/type:** peer-reviewed experimental paper (Journal of Power Sources)
- **Publication date:** 01 Feb 2024
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S037877532301296X>
- **Why it matters:** Reports dynamic tests on a **250 kW industrial alkaline system**; shows start-stop response on **hourly** timescales (temperature-limited) and load-step response with behaviour from **minutes to seconds**, providing concrete evidence that MW-class-relevant alkaline systems can be characterised (and improved) for renewable-following control strategies.

[25]

#### Digitalisation, monitoring, and predictive maintenance enablers

##### 9) How to build a Digital Twin for operating PEM-Electrolyser system — A reference approach

- **Organisation/authors:** academic authors (peer-reviewed)
- **Venue/type:** peer-reviewed “vision”/methods article (Annual Reviews in Control)
- **Publication date:** 2024
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S1367578824000129>
- **Why it matters:** Describes Digital Twin architecture for electrolyser systems, explicitly tying real-time **sensor data** to optimisation, fault detection/diagnosis, and prediction—directly aligned with the ART claim of software-updated control and predictive maintenance.

[26]

#### 10) Fault diagnosis of cells in PEM electrolyzer stack under fluctuating power source

- **Organisation/authors:** academic authors (peer-reviewed)
- **Venue/type:** peer-reviewed methods paper (International Journal of Hydrogen Energy)
- **Publication date:** 06 Jan 2025
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S0360319924051152>
- **Why it matters:** Proposes and validates a diagnostic method to separate **sensor faults vs stack faults** (via interleaved voltage detection and signal processing) under fluctuating input power—evidence that monitoring/automation for safe dynamic operation is technically tractable. [27]

#### Key constraints: membranes, catalysts, and supply chain

#### 11) Durable and conductive anion exchange membranes ... for water electrolysis

- **Organisation/authors:** academic authors (peer-reviewed)
- **Venue/type:** peer-reviewed materials + single-cell performance paper (International Journal of Hydrogen Energy)
- **Publication date:** 08 Mar 2024
- **Link:**  
<https://www.sciencedirect.com/science/article/abs/pii/S0360319924001836>
- **Why it matters:** Reports an AEM with **136 mS/cm conductivity at 80 °C**, <10% conductivity loss after **>1000 h** in 1 M NaOH at 80 °C, and an AEMWE single-cell achieving **3.2 A/cm<sup>2</sup> at 2 V** and operation for **>800 h**—evidence that non-PEM membrane routes are advancing toward durability targets relevant to scale-up. [28]

#### 12) Perspectives on current and future iridium demand and iridium oxide catalysts for PEM water electrolysis

- **Organisation/authors:** academic authors (peer-reviewed; open access)
- **Venue/type:** peer-reviewed analysis + catalyst constraints paper (Catalysis Today)
- **Publication date:** 01 Aug 2023
- **Link:** <https://www.sciencedirect.com/science/article/pii/S0920586123001645>
- **Why it matters:** Quantifies PEM's key scaling bottleneck (iridium) and identifies specific technical targets (e.g., **~0.1 mgIr/cm<sup>2</sup>** MEA loading and recycling) needed to avoid iridium-limited deployment; directly supports the ART's supply-chain constraint framing and what "credible scale" requires. [29]

#### 13) Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers

- **Organisation:** National Renewable Energy Laboratory[30] (NREL)
- **Venue/type:** national lab techno-economic manufacturing cost report (technical report)
- **Publication date:** Feb 2024
- **Link:** <https://docs.nrel.gov/docs/fy24osti/87625.pdf>
- **Why it matters:** Provides a detailed manufactured-cost model including manufacturing pathways (e.g., conventional spray coating vs higher-throughput **roll-to-roll/slot-die** approaches for catalyst-coated membranes/MEAs), directly informing maturity of electrolyser manufacturability and expected economies of scale. [31]

#### 14) Water Electrolyzers and Fuel Cells Supply Chain — Supply Chain Deep Dive Assessment

- **Organisation:** U.S. Department of Energy[32]
- **Venue/type:** government supply-chain assessment (report responding to Executive Order 14017)
- **Publication date:** 24 Feb 2022
- **Link:** <https://www.energy.gov/sites/default/files/2024-12/Fuel%2520Cells%2520%26%2520Electrolyzers%2520Supply%2520Chain%2520Report%2520-%2520Final%5B1%5D.pdf>
- **Why it matters:** Maps supply chains and vulnerabilities (materials + manufacturing) for electrolyzers and fuel cells at system level—direct evidence that scale-up constraints are being treated as national industrial-base issues, not just lab challenges. [33]

#### **Siting, water, and permitting constraints (non-optional for scale)**

##### **15) Green Hydrogen: A Briefing for Land Managers**

- **Organisation:** NREL (see prior entry; organisation not repeated here)
- **Venue/type:** national lab applied briefing (technical note)
- **Publication date:** May 2023
- **Link:** <https://docs.nrel.gov/docs/fy23osti/83885.pdf>
- **Why it matters:** Provides concrete water/land/permitting considerations, including that while stoichiometric water is **9 kg water/kg H<sub>2</sub>**, real electrolysis projects often consume **~18–24 kg water/kg H<sub>2</sub>** due to demineralisation and balance-of-plant needs—directly matching the ART’s water-access and siting constraints. [34]

#### **High-temperature electrolysis and PtX integration evidence (beyond “H<sub>2</sub> only”)**

##### **16) Next Level Solid Oxide Electrolysis — upscaling potential and techno-economic evaluation for industrial use cases**

- **Organisation:** Institute for Sustainable Process Technology[35]
- **Venue/type:** research consortium / industry-linked public report (PDF)
- **Publication date:** 2023 (public report)
- **Link:** [https://ispt.eu/media/2023-SOE-public-report\\_ISPT.pdf](https://ispt.eu/media/2023-SOE-public-report_ISPT.pdf)
- **Why it matters:** Evaluates SOEC integration into real industrial contexts (ammonia, syngas/e-fuels, CO production) and quantifies efficiency framing (e.g., indicative **~33 kWh/kg H<sub>2</sub>** for SOEC vs **~48 kWh/kg H<sub>2</sub>** for low-temperature electrolysis at stack level), plus an upscaling path toward **multi-MW modules**—direct evidence supporting PtX feasibility and what remains to be validated (dynamic performance, degradation, feedstock quality). [36]

##### **17) Intermediate Temperature Proton-Conducting Solid Oxide Electrolysis Cells with Improved Performance and Durability**

- **Organisation:** West Virginia University[37] (recipient on the report)
- **Venue/type:** DOE-funded technical report (OSTI-hosted)
- **Publication date:** 30 Apr 2023
- **Link:** <https://www.osti.gov/servlets/purl/2567526>
- **Why it matters:** Demonstrates high-current operation (reported **1.46 A/cm<sup>2</sup> at 600 °C and 1.3 V**) with **5,000-hour** operation at low degradation (reported **~1 mV/kh**), strengthening plausibility for high-temperature electrolysis variants while highlighting the gap between cell achievements and commercial system deployment. [38]

##### **18) PROMET-H2 Deliverable D6.3 — Techno-economical report including potential upscaling for PROMET-H2**

- **Organisation:** PROMET-H2 consortium[\[39\]](#)
- **Venue/type:** public–private consortium deliverable (technical report / project deliverable)
- **Publication date:** Mar 2023 (Ares reference date 25/03/2023)
- **Link:** <https://promet-h2.eu/wp-content/uploads/d63.pdf>
- **Why it matters:** Describes a pressurised **25 kW PEMWE** system intended to couple to a pilot plant producing **methanol from CO<sub>2</sub>**, and frames targeted stack cost ranges (e.g., **€500–750/kW** cited as an aspiration in the deliverable) alongside scale-up cost modelling—direct PtX integration evidence, but still at pilot/demonstration maturity. [\[40\]](#)

#### Commercial product / vendor technical documentation (measurable operating envelopes)

##### 19) MC Series Modular Plants — PEM Electrolyser Systems (specification sheet)

- **Organisation:** Nel Hydrogen[\[41\]](#)
- **Venue/type:** vendor technical doc (product specification PDF)
- **Publication date:** Oct 2025 (from file path /2025/10/ and document revision shown)
- **Link:** <https://nelhydrogen.com/wp-content/uploads/2025/10/MC-Series-Modular-Plants-PD-0600-0145-Rev-A-1.pdf>
- **Why it matters:** Provides concrete “containerised modular plant” metrics: e.g., a unit producing **984 Nm<sup>3</sup>/h**, **turndown 20–100% (automatic)**, **ramp-up <15 s** (min→full), and start-up from standby **<8 min**, supporting the ART’s claim that modular plants can dynamically follow available power. [\[42\]](#)

##### 20) Industrial-Scale Water Electrolysis for Green Hydrogen Production (scalum® + automation & monitoring)

- **Organisation:** thyssenkrupp nucera[\[43\]](#)
- **Venue/type:** vendor technical doc (brochure with operational/automation claims)
- **Publication date:** Oct 2024 (from file path /2024/10/ and document filename tag)
- **Link:** [https://www.thyssenkrupp-nucera.com/wp-content/uploads/2024/10/thyssenkrupp-nucera\\_green-hydrogen\\_brochure\\_A4\\_241029\\_RZ\\_WEB.pdf](https://www.thyssenkrupp-nucera.com/wp-content/uploads/2024/10/thyssenkrupp-nucera_green-hydrogen_brochure_A4_241029_RZ_WEB.pdf)
- **Why it matters:** Claims operational flexibility (operation down to **~10% load profiles**) and describes specific automation/safety concepts (DCS + separate SIS, automated gas measurement, single-cell monitoring, and condition monitoring for predictive maintenance), aligning with the ART’s “digital control + safety + predictive maintenance” maturity storyline. [\[44\]](#)

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 5

#### B) Why this score fits the rubric

##### What rules out lower levels (1–4):

- The ART is far beyond “principle only” or “lab-only” for major components: there is clearly documented **GW-scale installed electrolyser capacity** globally (1.4 GW end-2023) and continuing growth, which indicates operating deployments rather than only prototypes. [\[14\]](#)
- Commercial suppliers publish concrete, measurable operating envelopes for modular/containerised systems (e.g., turndown ranges, ramp rates, start-up times), which is consistent with genuine productisation rather than purely academic PoCs. [\[45\]](#)
- Multi-hundreds-kW experimental systems show real dynamic constraints (temperature-

limited start/stop, H<sub>2</sub>-in-O<sub>2</sub> response inertia, etc.), demonstrating that the dynamic-operation problem is being solved at industrially relevant scales and that remaining issues are engineering optimisation rather than unknown science. [25]

#### **Why it does not yet justify the next higher level (6) for the ART as a whole:**

- While electrolyzers as products are clearly commercially delivered, the ART description explicitly includes **integrated, reconfigurable Power-to-X plants** (switching outputs among H<sub>2</sub> / carriers / synthetic hydrocarbons under market signals). For this integrated “plant-as-a-system” scope, the evidence shows **pilot/demonstration and early deployment**, but also that only a small fraction of announced capacity reaches **FID or construction**—a sign that scaling to widespread repeatable builds is still constrained by economics, offtake, siting, and supply chain. [46]
- Core bottlenecks highlighted in the ART description remain active constraints in the literature and roadmaps: scarce catalyst supply (iridium), manufacturability of MEAs/stacks, and durability under dynamic duty cycles. These are being addressed with quantified targets and manufacturing process improvements, but the need for order-of-magnitude improvements and high recycling rates indicates the scale-up path is not yet “routine.” [47]
- PtX beyond “H<sub>2</sub> only” is advancing, but evidence is still weighted toward **techno-economic reports and multi-MW integration roadmaps** rather than broad, repetitive commercial roll-out. For example, the SOEC/PCEC evidence shows impressive cell durability (thousands of hours) but is not yet equivalent to high-volume delivered commercial plants. [48]

#### **Rubric match for 5:**

Score **5** best matches the observed state: multiple well-capitalised actors and consortia are advancing production prototypes and standard plant offerings, but (for the full green-hydrogen-plus-PtX integrated system functionality) the evidence still points to “post-PoC, scaling underway but not yet routine,” with materially limiting constraints (electricity price, permitting/safety, materials supply, and project bankability). [49]

#### **C) Bundle sub-score breakdown and aggregation**

Because “Green Hydrogen & Power-to-X” spans multiple sub-technologies with different commercial readiness, an average-based score is appropriate.

- **Low-temperature electrolysis systems (AWE/PEM) as modular products → 6**  
Evidence: commercial product specs and operating ranges (fast ramping, turndown), plus real market manufacturing capacity/sales indicators. [50]
- **Dynamic operation + diagnostics/digital control layer → 5**  
Evidence: peer-reviewed literature on dynamic-operation impacts and actionable diagnostic/control approaches (Digital Twin guidance; fault diagnosis under fluctuating power), plus vendor descriptions of plant automation and monitoring. [51]
- **Power-to-X integration (e.g., H<sub>2</sub> + captured CO<sub>2</sub> to methanol; multi-process integration) → 4–5**  
Evidence: consortium deliverable describing a 25 kW PEMWE system intended to be coupled to a methanol-from-CO<sub>2</sub> pilot plant and explicit scale-up cost modelling; still largely “demonstration/pilot” rather than widespread delivered plants. [52]
- **High-temperature electrolysis variants (SOEC / proton-conducting ceramics) for PtX coupling → 3–4**



Evidence: multi-MW integration roadmapping and industrial use cases, plus long-duration cell/prototype validation (5,000 h) — strong technical plausibility but earlier commercial maturity than low-temperature electrolysis. [53]

**Aggregation to one score:** averaging these sub-estimates ( $\approx 6, 5, 4.5, 3.5$ ) yields  $\sim 4.75$ , rounded to **5** to reflect strong commercialisation in electrolysis hardware but incomplete maturity for “fully integrated, reconfigurable Power-to-X plants” at scale. [54]

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## ART 08.063 High-Efficiency Wind Turbines

### ART extraction

### A) Primary capability claimed (what the ART enables)

- Higher **annual energy capture per unit of installed hardware** by enlarging swept area (very large rotors/blades) while keeping structures light, fatigue-resistant, and scalable to manufacture and install.
- Improved **availability and lifetime energy yield** by shifting turbines toward **cyber-physical operation**: dense sensing + models + closed-loop control to stay near aerodynamic optimum while limiting fatigue/wear.
- Expanded siting options for high-efficiency generation via **alternative wind-harvesting architectures** (e.g., vertical-axis and airborne wind energy) that can exploit turbulent or higher-altitude winds.

### B) Key sub-components / variants (sub-threads)

- Ultra-large horizontal-axis turbines (HAWTs), especially offshore: **>100 m blades**, 12–15 MW class, large rotors, high capacity factor.
- Advanced sensing & control: **preview wind sensing (LiDAR)**, feedforward pitch/yaw, model-based control, and optimisation across changing winds.
- Condition monitoring / digital twins (cyber-physical): strain/vibration/loads inference, fatigue estimation, anomaly detection, remote updates.
- Blade materials & manufacturability: **advanced composites**, longer blades, modular/segmented blades for transport and assembly, and advanced manufacturing methods.
- Durability and performance retention in harsh climates: leading-edge erosion mitigation, coatings, repair strategies, and reliability data.
- Alternative form factors: **vertical-axis wind turbines (VAWTs)** (including floating concepts) and **airborne wind energy (AWE)** systems (kites/drones/wings with tethers and ground stations).
- Permitting/standards and operational constraints: aviation/safety (AWE), noise/wake interactions, storm survivability, offshore installation logistics.

### C) Maturity indicators that would constitute evidence

- Independent **type certification** (or equivalent) and documented **prototype → commercial** transition for large turbines.
- Evidence of **at-sea commissioning / commercial installation counts**, manufacturing ramp-up, and service contracts at scale.
- Peer-reviewed results showing **quantified performance improvements** (AEP/capacity factor, load reductions, fatigue impact, wake recovery) and validated models/field tests.
- Demonstrated pathways for **manufacturing/transport/installation** of very large blades (segmentation, novel tooling, repair approaches).
- Authoritative standards/roadmaps and funded programmes addressing **erosion**, reliability, and **certification/airspace integration** (AWE).
- For VAWT/AWE specifically: **TRL statements**, funded demonstrators, operating test sites, and credible techno-economic/system-integration studies.

### Evidence (10–20 recent, reliable sources)

#### Large-rotor turbines and scaling evidence

##### 1) Vestas Annual Report 2025

**Organisation:** Vestas Wind Systems A/S[1]

**Type:** Company annual report (audited corporate report)

**Publication date:** 5 Feb 2026 (management sign-off date in report)

**Link:** <https://mb.cision.com/Main/18886/4302973/3918542.pdf>

**What it shows / why it matters:** Reports the first commercial milestones of the V236 platform, including first power at the He Dreiht offshore wind farm[2] and **52 V236-15.0 MW turbines installed during 2025**, indicating real customer delivery and ramp-up evidence beyond PoC. [3]

## 2) Vestas Annual Report 2023

**Organisation:** Vestas Wind Systems A/S

**Type:** Company annual report (audited corporate report)

**Publication date:** Feb 2024 (auditor signature dated 7 Feb 2024)

**Link:** <https://www.vestas.com/content/dam/vestas-com/global/en/investor/reports-and-presentations/financial/2023/2023-annual-report/Annual%20Report%202023.pdf.coredownload.inline.pdf>

**What it shows / why it matters:** States that the V236-15.0 MW prototype set a **363 MWh / 24h** production record and that the platform received **DNV type certification in Nov 2023**, supporting maturity of 15 MW-class hardware entering serial production. [4]

## 3) Vestas press release: “V236-15.0 MW prototype wind turbine produces first kWh”

**Organisation:** Vestas Wind Systems A/S

**Type:** Manufacturer technical press release (prototype + measurable specs)

**Publication date:** 30 Dec 2022

**Link:** <https://www.vestas.com/en/media/company-news/2022/vestas--v236-15-0-mw-prototype-wind-turbine-produces-fi-c3691167>

**What it shows / why it matters:** Documents full prototype installation at Østerild National test centre for large wind turbines[5], including **115.5 m blades**, **>43,000 m<sup>2</sup> swept area**, “around **80 GWh/year**” energy production claim (site-dependent), and a reported **capacity factor >60% (site-dependent)**—direct evidence for plausibility and industrialisation of very long blades. [6]

## 4) GE Vernova press release: “Haliade-X 14.7 MW-220 obtains full DNV type certificate”

**Organisation:** GE Vernova[7] (press release) with DNV[8] certification referenced

**Type:** Manufacturer technical press release (certification milestone)

**Publication date:** 15 Dec 2022

**Link:** <https://www.ge.com/news/press-releases/ge-renewable-energys-haliade-x-147-mw-220-obtains-full-dnv-type>

**What it shows / why it matters:** Reports independent **full type certification** for a **14.7 MW, 220 m rotor** platform and positions it for deployment at utility-scale projects, demonstrating that very large turbine classes are certified for commercial builds. [9]

## 5) Offshore Wind Market Report: 2024 Edition

**Authors/Org:** Angel McCoy[10] et al.; National Renewable Energy Laboratory (NREL) / U.S. Department of Energy[11]

**Type:** Authoritative national-lab market + technology trends report

**Publication date:** Aug 2024

**Link:** <https://docs.nrel.gov/docs/fy24osti/90897.pdf>

**What it shows / why it matters:** Quantifies global offshore turbine upscaling: 2023 global installations had capacity-weighted-average **turbine rating 9.7 MW** and **rotor diameter**

**183.4 m**, and notes the market beginning to adopt **12–15 MW** platforms; it also outlines typical **~3-year** prototype-to-commercial project timeline for Western OEMs. [12]

#### **Sensing, control, and cyber-physical operation**

##### **6) “A digital twin solution for estimating wind turbine loads and fatigue validated by a full-scale prototype”**

**Authors/Org:** Y. Koukoura[13] et al.; National Renewable Energy Laboratory

**Type:** Peer-reviewed journal article (full-scale validation)

**Publication date:** 8 Jan 2024

**Link:** <https://www.nrel.gov/docs/fy24osti/86243.pdf>

**What it shows / why it matters:** Demonstrates a digital-twin approach (using standard turbine measurements + estimation) validated on a full-scale prototype, directly supporting the ART’s “cyber-physical platform” claim for load/fatigue-aware optimisation and condition-based operation. [14]

##### **7) “LiDAR-assisted feedforward individual pitch control of a 15 MW floating offshore wind turbine”**

**Authors/Org:** A. J. Russell[15] et al.; University of Strathclyde[16] (paper repository copy)

**Type:** Peer-reviewed journal article (control + simulation methodology)

**Publication date:** 2024 (journal volume year; accepted Dec 2023)

**Link:** <https://strathprints.strath.ac.uk/88862/7/Russell-et-al-WE-2024-LIDAR-assisted-feedforward-individual-pitch-control-of-a-15-MW-floating-offshore-wind-turbine.pdf>

**What it shows / why it matters:** Reports simulation results where LiDAR-assisted feedforward IPC yields up to **54% reductions** in variability metrics for key turbine parameters under turbulent inflow, and notes that LiDAR simulation modifications were accepted into OpenFAST releases (v3.5+), supporting feasibility and toolchain readiness for advanced control in very large machines. [17]

##### **8) “Analysis and evaluation of two reference LiDAR-assisted control designs for wind turbines”**

**Authors/Org:** Cedric D. Steinmann Perez[18] et al.; Technical University of Denmark[19]

**Type:** Peer-reviewed conference article in Journal of Physics: Conference Series (TORQUE 2024)

**Publication date:** 2024 (JPCS volume year)

**Link:**

[https://backend.orbit.dtu.dk/ws/files/363468423/Steinmann\\_Perez\\_2024\\_J.\\_Phys.\\_Conf.\\_Ser.\\_2767\\_032048.pdf](https://backend.orbit.dtu.dk/ws/files/363468423/Steinmann_Perez_2024_J._Phys._Conf._Ser._2767_032048.pdf)

**What it shows / why it matters:** Evaluates practical limitations of fixed-beam commercial LiDAR for large turbines (e.g., coherence degradation with scale) and compares control architectures (Schlipf vs Bossanyi), giving engineering-relevant constraints on how close “near-optimal” cyber-physical control can be in real hardware. [20]

#### **Blades, manufacturability, and durability**

##### **9) “CFAR – Literature review: Wind turbine blades design and manufacturing”**

**Organisation:** ORE Catapult[21] (Carbon Fibre in Wind Turbine Blade at Scale programme)

**Type:** Authoritative applied R&D literature review (blade scaling constraints)

**Publication date:** 31 Mar 2022

**Link:** <https://ore.catapult.org.uk/app/uploads/2022/03/CFAR-Blade-design-and-manufacturing-Literature-Review-Final-1.pdf>

**What it shows / why it matters:** Reviews blade scaling constraints and highlights segmented-blade manufacturing/transport as a pathway: reporting an example where segmented blade “main box” assembly could be **~4 hours**, and discussing cost trade-offs (e.g., potential blade cost reduction vs added joint manufacturing cost). [22]

#### 10) “Toward the Advanced Manufacturing of Land-Based Wind Turbine Blades: Preprint”

**Authors/Org:** Pietro Bortolotti[23] et al.; National Renewable Energy Laboratory + GE research collaborators

**Type:** National-lab conference paper (preprint; manufacturing concepts)

**Publication date:** Dec 2022

**Link:** <https://docs.nrel.gov/docs/fy23osti/84397.pdf>

**What it shows / why it matters:** Identifies blade manufacturing innovation routes (including advanced/additive manufacturing concepts and modularisation focus areas) intended to lower cost, improve throughput, and support continued rotor upsizing—key for plausibility of very large blade production at scale. [24]

#### 11) ZEBRA consortium press release: “Second recyclable wind turbine blade”

**Organisation:** IRT Jules Verne[25] (with industry consortium partners)

**Type:** Consortium technical press release (full-scale blade build)

**Publication date:** 14 Dec 2023

**Link:** <https://www.irt-jules-verne.fr/wp-content/uploads/08-irt-jules-verne-cp-zebra-ven-14122023.pdf>

**What it shows / why it matters:** Reports a **77 m** recyclable thermoplastic blade manufactured at industrial blade-plant scale and describes use of advanced resin/adhesive concepts (including recycled resin use), supporting the manufacturability and circularity sub-claims for scaling high-performance blades. [26]

#### 12) “Aerodynamic effects of leading-edge erosion in wind farm flow modeling”

**Authors/Org:** Visbech et al. (DTU Wind)

**Type:** Peer-reviewed journal article (Wind Energy Science)

**Publication date:** 10 Sep 2024

**Link:** <https://wes.copernicus.org/articles/9/1811/2024/>

**What it shows / why it matters:** Provides quantified AEP impact of leading-edge erosion (LEE) via coupled erosion–aero–farm modelling (Horns Rev 1 case), reporting up to **2.9% annual AEP loss** for a turbine late in life and demonstrating that wake interactions can change farm-level loss estimates—directly relevant to maintaining “high efficiency” over operating life. [27]

#### 13) IEA Wind TCP Task 46: Erosion final report

**Organisation:** International Energy Agency[28] Wind TCP Task 46

**Type:** Authoritative international task final report (R&D synthesis / roadmap)

**Publication date:** 13 Mar 2025

**Link:** [https://eudp.dk/files/media/document/Slutrapport%20IEA-Task46-Erosion\\_1\\_13032025\\_0944.pdf](https://eudp.dk/files/media/document/Slutrapport%20IEA-Task46-Erosion_1_13032025_0944.pdf)

**What it shows / why it matters:** Frames blade leading-edge erosion as a multidisciplinary reliability and performance bottleneck and consolidates mitigation/testing directions—



evidence that durability constraints are actively being standardised and engineered (a maturity marker for long-life high-output turbines). [29]

#### **Alternative form factors: VAWT and airborne wind**

##### **14) “Large-eddy simulations of turbulent flows in arrays of helical- and straight-bladed vertical-axis wind turbines”**

**Authors/Org:** Masoumeh Gharaati[30] et al.

**Type:** Peer-reviewed journal article (Journal of Renewable and Sustainable Energy); indexed via OSTI

**Publication date:** 13 Dec 2023

**Link:** <https://www.osti.gov/pages/biblio/2282549>

**What it shows / why it matters:** Uses LES to compare array performance and reports mean power production improvements of **~4.94%–7.33%** for helical-bladed VAWTs versus straight-bladed cases in fully developed array regions, plus **~47.6%–60.1%** reduction in temporal power fluctuations—direct evidence for “turbulence-tolerant / different packing” plausibility. [31]

##### **15) “Effect of background turbulence on the wakes of horizontal-axis and vertical-axis wind turbines”**

**Authors/Org:** van der Deijl et al.

**Type:** Peer-reviewed journal article (Journal of Wind Engineering & Industrial Aerodynamics; wind-tunnel study)

**Publication date:** 2024 (month not shown on abstract page)

**Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S016761052400240X>

**What it shows / why it matters:** Wind-tunnel experiments show VAWT wakes recover faster than HAWT wakes under **low-turbulence inflow**, but under moderately turbulent inflow the wake shapes become similar—important realism for claims that VAWTs can improve site packing/energy density in specific turbulence regimes. [32]

##### **16) EU CORDIS project fact sheet: VERTI-GO (floating vertical-axis offshore demonstrator)**

**Organisation:** European Commission[33] (CORDIS/Horizon)

**Type:** Authoritative programme record (Horizon Europe innovation action)

**Publication date:** EC signature date 29 Aug 2025 (project start 1 Oct 2025)

**Link:** <https://cordis.europa.eu/project/id/101235735>

**What it shows / why it matters:** States the project has already reached **TRL5 with a 30 kW demonstrator** and aims to scale to a **2 MW floating VAWT demonstrator** tested in real conditions for ~15 months, with ~€15M EU contribution—clear “field-demo funding + scaling plan” maturity evidence for floating VAWT variants. [34]

##### **17) “System design and scaling trends in airborne wind energy demonstrated for a ground-generation concept”**

**Authors/Org:** Rishikesh Joshi[35] et al.

**Type:** Peer-reviewed journal article (Wind Energy Science)

**Publication date:** 14 Apr 2025

**Link:** <https://wes.copernicus.org/articles/10/695/2025/>

**What it shows / why it matters:** Develops an integrated MDAO framework for AWE system

sizing and reports that LCoE-driven optima fall in roughly **100–1000 kW** rated power under model assumptions, identifying key cost drivers (e.g., kite mass, storage, tether replacement)—evidence for engineering plausibility and scaling constraints. [36]

#### 18) “Standardisation and Certification of Airborne Wind Energy”

**Organisation:** ORE Catapult

**Type:** Applied standards/certification report

**Publication date:** 23 Oct 2024

**Link:** <https://airbornewindeurope.org/wp-content/uploads/2024/10/Standardisation-and-Certification-of-Wind-Energy.pdf>

**What it shows / why it matters:** Lays out pathways and gaps for AWE certification and standards, including mapping against the IEC 61400 ecosystem—evidence of maturing “market infrastructure” (certification/permitting) needed before broad deployment. [37]

#### 19) RWE press release: “RWE and Kitepower deliver new test site for Airborne Wind in Ireland”

**Organisation:** RWE[38] with Kitepower[39]

**Type:** Field-trial announcement (industry test infrastructure)

**Publication date:** 25 Sep 2023

**Link:** <https://ie.rwe.com/press-and-news/2023-09-25-rwe-and-kitepower-deliver-new-test-site-for-airborne-wind-in-ireland/>

**What it shows / why it matters:** Documents an operational AWE test facility enabling maiden flight/testing at Bangor Erris (County Mayo), supporting the claim that airborne systems are moving beyond lab-only work into continuous test operations tied to industrial players. [40]

#### Maturity score (1–7) and reasoning

##### Final maturity score

6

##### Evidence-to-rubric mapping

##### What rules out lower levels (≤4):

- The dossier includes multiple examples of **independently type-certified, very large (14–15 MW class) turbine platforms** (e.g., GE Haliade-X and V236 certification references), and evidence of **commercial installation and commissioning** (e.g., dozens of V236 units installed in 2025 with first at-sea commissioning). This goes well beyond lab prototypes and PoCs. [41]
- National-lab reporting shows the offshore sector has already begun adopting **12–15 MW platform classes**, with quantified increases in capacity-weighted turbine rating and rotor diameter in recent global installations—evidence that upscaling is not only plausible but actively entering the market. [42]

##### Why this is at level 6 (not merely level 5):

- Level 6 requires **products delivered to customers in increasing amounts** and clear production expansion. The V236 platform shows installation ramp-up (installed turbine counts), and corporate reporting indicates ongoing production launch and operational scaling—matching the “delivered and increasing amounts / expansion financed” pattern. [3]

- Complementary engineering maturity is visible in adjacent enabling technologies: validated digital-twin load/fatigue estimation on a full-scale prototype and peer-reviewed demonstrations of LiDAR-assisted control benefits for very large turbine models and toolchains. [\[43\]](#)

#### **What is still missing to justify level 7 for the ART as a whole:**

- Several “alternative form factors” included in the ART description remain **pre-commercial** even if technically plausible: floating VAWT is moving through funded demonstrators (e.g., 2 MW planned, TRL5 claim from prior 30 kW) rather than broad commercial delivery. [\[44\]](#)
- Airborne wind energy has strong modelling and emerging standards work, plus test sites, but lacks evidence in this window of **multi-customer product delivery at scale** comparable to conventional turbines (i.e., deployments with broad, recurring customer demand and multiple competing shipped products). [\[45\]](#)
- Blade durability constraints (e.g., leading-edge erosion) have quantified impacts and active task-level roadmapping, but the dossier evidence emphasises continuing mitigation work rather than a fully “solved” reliability envelope for all high-tip-speed, long-life operations across regions. [\[46\]](#)

#### **Sub-component breakdown and aggregation**

Because the ART bundles **(i) mainstream ultra-large HAWTs** with **(ii) materially different architectures (VAWT, AWE)** that serve partly different sites/regulatory regimes, an average-style aggregation is more appropriate than taking the maximum.

- **Ultra-large offshore HAWTs (12–15 MW class, >100 m blades): 7** — Commercially delivered platforms with type certification and increasing installations. Key sources: Vestas Annual Report 2025; Vestas prototype/metrics release; NREL Offshore Wind Market Report 2024. [\[47\]](#)
- **Cyber-physical sensing/control & digital operation: 5–6** — Validated digital twin on a full-scale prototype and quantified load/variability reductions from LiDAR-assisted control in peer-reviewed studies, but broad “near-optimal” adaptive control as standard practice across fleets is still uneven. Key sources: NREL digital twin; Russell et al.; Steinmann Perez et al. [\[43\]](#)
- **Manufacturability innovations (segmented/advanced manufacturing, recyclable composite blades): 4–5** — Concrete prototypes and industrial-scale blade builds exist (e.g., 77 m recyclable blade), and segmentation is documented as feasible, but these approaches are not yet evidenced here as dominant, standardised mass production paths for all >100 m blades globally. Key sources: ORE Catapult CFAR review; NREL manufacturing preprint; ZEBRA press release. [\[48\]](#)
- **Durability/performance retention (erosion, repair optimisation): 6** — Measured farm-level AEP impacts, plus IEA task roadmapping and mitigation work indicate mature recognition and industrial response, though still a live bottleneck area. Key sources: Visbech et al. 2024; IEA Wind Task 46 final report. [\[46\]](#)
- **Floating VAWT: 5** — EU-funded 2 MW demonstrator programme (with stated TRL5 predecessor) indicates late-stage prototype-to-demo maturity, but not broad product delivery. Key source: EU CORDIS VERTI-GO. [\[44\]](#)
- **Airborne wind energy (AWE): 4** — Demonstrated modelling frameworks, emerging certification work, and operational test sites show functional prototypes and growing

ecosystem readiness, but not scaled product delivery. Key sources: Joshi et al. 2025; ORE AWE certification report; RWE/Kitepower test site announcement. [45]

**Aggregation to one score:** Taking a simple midpoint of the above (weighted toward the already-commercial mainstream HAWT pathway because it dominates near-term market impact and installation volume) yields an overall **6**: delivered systems scaling now, with clear remaining gaps centred on the alternative architectures and some next-generation blade/material approaches. [49]

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## ART 08.064 Wireless & Space-Based Power Transfer

### 1. ART extraction

**A) Primary capability (what the ART claims)** - Deliver *usable electrical power* without cables by converting electricity into a steerable electromagnetic beam (microwave or laser) and converting it back to electricity at a receiver. [1]

- Extend that capability to *space-based solar power* (SBSP): collect solar energy in orbit (often GEO), convert to RF/optical beams, transmit to Earth receiving sites as a quasi-dispatchable generation asset. [2]

- Evolve into modular networks of transmitter nodes (ground/airborne/orbital) and receiver arrays (small mobile receivers → large rectenna fields) with closed-loop beam control and monitoring interfaces. [3]

**B) Key sub-components / variants (technology bundle)** - SBSP system architecture: orbital collectors, on-orbit DC→RF (or DC→laser) conversion, beamforming/transmission, and ground rectenna + grid interconnection. [4]

- Microwave power transmission (MPT): phased-array beamforming, beam steering, retrodirective / pilot-signal tracking, and RF→DC rectenna arrays. [5]

- Optical/laser wireless power transmission (OWPT): high-power lasers, beam shaping/homogenisation, atmospheric-turbulence tolerance, and PV (or hybrid) receivers. [6]

- Receiver and conversion hardware: high-power rectennas (RF→DC), laser PV receivers (photoelectric conversion), plus thermal management (e.g., PV-TEG hybrids). [7]

- Control, safety, and verification: pointing accuracy, beam-locked operation, misalignment safety logic, and standards/regulatory compliance (spectrum, orbital slots, safety). [8]

- Scaling enablers: mass manufacturing, launch cadence, in-space assembly/manufacturing (ISAM), and cost-reduction pathways. [9]

### **C) Maturity indicators that would constitute strong evidence - End-to-end**

**demonstrations:** beam → receiver → delivered electric power into a real load, at materially relevant ranges (km) and powers (100s W → kW), with quantified efficiency and safety procedures. [10]

- **In-space demonstrations:** power beaming performed on-orbit (even at low power), and/or space-to-ground detection that validates pointing/control and link budget in realistic conditions. [11]

- **Receiver performance:** reproducible RF→DC efficiencies and/or laser photoelectric conversion efficiencies, plus evidence of thermal stability under sustained exposure. [7]

- **Credible scaling pathways:** authoritative pre-Phase A / roadmap documents with quantified system sizing (rectenna fields, mass, launch cadence) and explicit blockers. [12]

- **Multiple well-resourced actors:** government programmes and major industrial labs conducting repeatable trials (and publishing technical details), suggesting sustained development rather than one-off stunts. [13]

### 2. Evidence (10–20 recent, reliable sources)

#### 1) Space-Based Solar Power (OTPS report)

- **Authors/Org:** NASA[14] Office of Technology, Policy, and Strategy (OTPS)

- **Venue/type:** Authoritative government report



- **Publication date:** Jan 2024 (11 Jan 2024)
- **Link:** <https://www.nasa.gov/wp-content/uploads/2024/01/otps-sbsp-report-final-tagged-approved-1-8-24-tagged-v2.pdf>
- **Why it matters:** Quantifies an end-to-end SBSP efficiency chain (e.g., DC→RF ~0.7, rectenna reception ~0.78) and estimates delivered power (~2 GW) while highlighting blockers including spectrum allocation, orbital-slot competition, debris and security/safety of power beaming—directly addressing plausibility and maturity constraints. [15]

## 2) Potential Activities for the Space Based Solar Power Specific Area in GSTP Element 1

- **Authors/Org:** European Space Agency[16] (ESA), GSTP documentation
- **Venue/type:** Government programme planning / technology roadmap document
- **Publication date:** Dec 2022 (19 Dec 2022)
- **Link:**  
<https://indico.esa.int/event/453/attachments/5098/8056/Potential%20Activities%20for%20the%20Space-based%20Solar%20Power%20Specific%20Area%20in%20GSTP%20Element%201%2022Dec22.pdf>
- **Why it matters:** Explicitly states that SBSP WPT needs substantially higher DC→RF efficiencies (targeting >70%) and describes the scale problem (phasing thousands of antennas across km-scale arrays) plus a proposed path via an MW-scale in-orbit demonstrator (with >30 m deployable antenna) by ~2030—strong maturity-signalling roadmap detail. [17]

## 3) Request for Information: Research Activities in support of Space-Based Solar Power for terrestrial needs

- **Authors/Org:** ESA SOLARIS team (ESA)
- **Venue/type:** Government RFI / research-plan scoping document
- **Publication date:** Feb 2023 (26 Feb 2023)
- **Link:**  
<https://indico.esa.int/event/453/attachments/5098/8054/Request%20for%20Information%20-%20Research%20Activities%20for%20Space-Based%20Solar%20Power.pdf>
- **Why it matters:** Shows an active, time-bounded institutional decision process (aiming to inform a 2025 decision including a first in-orbit demonstrator) and centres research uncertainties around RF power beaming in Earth's environment—evidence of “programme maturity” but also that key feasibility questions remain open. [18]

## 4) SBSP Pre-Phase A System Study – Final Report

- **Authors/Org:** Thales Alenia Space[19] (under ESA contract)
- **Venue/type:** Authoritative industrial pre-Phase A system study report (agency-contracted)
- **Publication date:** Dec 2023 (20 Dec 2023)
- **Link:**  
[https://nebula.esa.int/sites/default/files/neb\\_study/3136/FR\\_Final%20Report\\_v4\\_E-Sgn.pdf](https://nebula.esa.int/sites/default/files/neb_study/3136/FR_Final%20Report_v4_E-Sgn.pdf)
- **Why it matters:** Provides quantified commercial-scale system assumptions (e.g., 1 GW grid-power baseline; ground receiver field ~34 km<sup>2</sup> and ~70,000-ton receiver mass estimate; misalignment/safety-logic simulation) that indicate SBSP is still at “architecture and sizing” maturity rather than product maturity. [20]

### 5) Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs – Final Report

- **Authors/Org:** Frazer-Nash Consultancy[21] (in partnership with London Economics[22])
- **Venue/type:** ESA-commissioned cost/tech feasibility report (system breakdown + economics)
- **Publication date:** Jul 2022
- **Link:** <https://www.fnc.co.uk/media/fi4pvbgv/space-based-solar-power-final-report.pdf>
- **Why it matters:** Puts concrete scale/cost numbers behind SBSP (e.g., 1.44 GW FOAK scenario; Capex and Opex ranges; LCOE range; total spacelift mass ~2,491 tonnes for one system), making clear that launch mass/cadence and industrialisation dominate readiness and time-to-market. [23]

### 6) The Caltech Space Solar Power Project: Design, Progress, and Future Direction

- **Authors/Org:** A. Fikes et al.; California Institute of Technology[24]
- **Venue/type:** Peer-reviewed conference paper (IEEE EuCAP)
- **Publication date:** Mar 2022
- **Link:** [https://www.researchgate.net/publication/364304401\\_The\\_Caltech\\_Space\\_Solar\\_Power\\_Project\\_Design\\_Progress\\_and\\_Future\\_Direction](https://www.researchgate.net/publication/364304401_The_Caltech_Space_Solar_Power_Project_Design_Progress_and_Future_Direction)
- **Why it matters:** Describes a modular “sandwich” SBSP architecture using lightweight IC-driven phased-array RF transmission and flexible PV/structure packaging (e.g., discussing nominally ~60 m × 60 m deployed structures and module scaling), supporting plausibility of modular kilometre-scale concepts while implicitly signalling early-stage maturity. [25]

### 7) The Caltech Space Solar Power Demonstration One Mission

- **Authors/Org:** A. Fikes et al.
- **Venue/type:** IEEE-style technical paper describing a space demo payload (technical documentation with mission engineering detail)
- **Publication date:** 2022 (paper text references Nov 2022 launch schedule; month-of-publication not stated in document)
- **Link:** <https://www.its.caltech.edu/~sslabor/PUBLICATIONS/2022%20IEEE%20Paper%20%231570826333.pdf>
- **Why it matters:** Specifies a multi-experiment in-space demonstrator (SSPD-1) including a microwave WPT experiment (MAPLE) and a deployable-structure experiment (DOLCE at ~1.7 m × 1.7 m scale), providing concrete prototype scope and integration approach consistent with TRL-advancing space tests. [26]

### 8) Wireless power transfer in space using flexible, lightweight, coherent arrays

- **Authors/Org:** Ayling et al.
- **Venue/type:** Peer-reviewed research paper (Acta Astronautica)
- **Publication date:** Nov 2024 (Volume 224)
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S009457652400434X>
- **Why it matters:** Reports (to the authors’ knowledge) the first documented WPT demonstration in space using lightweight flexible phased arrays driven by custom RFICs, operated/tested over months in LEO and including pointing the beam toward Earth and

ground detection—strong plausibility evidence for orbital transmitter modules but still at small experimental scale. [27]

#### 9) First In-Space Laser Power Beaming Experiment Surpasses 100 Days of Successful On-Orbit Operations

- **Authors/Org:** U.S. Naval Research Laboratory[28]
- **Venue/type:** Government lab experiment report (official lab news release with technical metrics)
- **Publication date:** Jul 2023 (13 Jul 2023)
- **Link:** <https://www.nrl.navy.mil/Media/News/Article/3457014/first-in-space-laser-power-beaming-experiment-surpasses-100-days-of-successful-on-orbit-operations/>
- **Why it matters:** Documents on-orbit laser power beaming (SWELL) with quantified performance ( $\approx 1.5$  W receiver output,  $\approx 11\%$  end-to-end efficiency,  $\approx 1.45$  m link), demonstrating the principle in space beyond theory while underscoring that orbital power levels are still far from grid-material transfer. [29]

#### 10) POWER Program Selects Teams to Design Power Beaming Relays

- **Authors/Org:** [2]entity[2] ["organization", "DARPA", "us defense r&d agency"] [2]
- **Venue/type:** Government programme milestone announcement (named teams; programme goals)
- **Publication date:** Sep 2023 (7 Sep 2023)
- **Link:** <https://www.darpa.mil/news/2023/power-beaming-relay>
- **Why it matters:** Signals multi-team, funded competition to build airborne optical power relays (an “energy web”), indicating that power beaming is transitioning from isolated demos to system concepts with multiple well-capitalised engineering efforts. [30]

#### 11) DARPA program sets distance record for power beaming

- **Authors/Org:** DARPA (POWER / PRAD tests)
- **Venue/type:** Government test report / programme results announcement with quantitative performance
- **Publication date:** May 2025 (16 May 2025)
- **Link:** <https://www.darpa.mil/news/2025/darpa-program-distance-record-power-beaming>
- **Why it matters:** Reports delivery of  $>800$  W over 8.6 km for 30 seconds (and  $>1$  megajoule transferred over the campaign), a key maturity datapoint for long-range optical power beaming at meaningful power levels (though still not a commercial deployment). [31]

#### 12) Long Range WPT Flight Demonstration (Dec. 2024) – First Report

- **Authors/Org:** Japan Space Systems[32]
- **Venue/type:** Field-trial technical report / demonstration results (slides with measurement plots)
- **Publication date:** Dec 2024 (12 Dec 2024)
- **Link:** [https://www.jspacesystems.or.jp/jss/wp-content/uploads/2025/01/1stTestReport\\_2024.12.24en-1.pdf](https://www.jspacesystems.or.jp/jss/wp-content/uploads/2025/01/1stTestReport_2024.12.24en-1.pdf)
- **Why it matters:** Describes a phased-array microwave WPT flight demo using 5.8 GHz beaming from a high-speed aircraft to ground, reporting  $>5$  km vertical WPT, beam formation and directional control, and multiple flight/experiment repetitions—evidence that beam control works outside the lab and on moving platforms. [33]

### 13) Ground Receiving System and Antenna Pattern Reconstruction Method for SPS Demonstration Satellite

- **Authors/Org:** Yoshiyuki Fujino et al. (incl. JAXA[34] and Toyo University[35] affiliations in paper)

- **Venue/type:** Peer-reviewed journal article (Journal of Evolving Space Activities, open access)

- **Publication date:** 2024 (Vol. 2, Article No. 166)

- **Link:** [https://www.jstage.jst.go.jp/article/jesa/2/0/2\\_166/\\_article/-char/en](https://www.jstage.jst.go.jp/article/jesa/2/0/2_166/_article/-char/en)

- **Why it matters:** Details a proposed LEO microwave WPT demonstration framework (ground receiving station layouts for antenna-pattern reconstruction and tracking), including explicit transmitter assumptions (e.g., 5.8 GHz active phased-array concept and an 810 W transmit-power assumption), which is the kind of engineering work needed to move from concept to on-orbit tests. [36]

### 14) Demonstration of 15% Efficient Optical Wireless Power Transmission Over 1 km With Atmospheric Turbulence

- **Authors/Org:** Ochiai et al. (NTT + Mitsubishi Heavy Industries)

- **Venue/type:** Peer-reviewed experimental paper (Electronics Letters; open access)

- **Publication date:** Aug 2025

- **Link:**

[https://www.researchgate.net/publication/394319253\\_Demonstration\\_of\\_15\\_Efficient\\_Optical\\_Wireless\\_Power\\_Transmission\\_Over\\_1\\_km\\_With\\_Atmospheric\\_Turbulence](https://www.researchgate.net/publication/394319253_Demonstration_of_15_Efficient_Optical_Wireless_Power_Transmission_Over_1_km_With_Atmospheric_Turbulence)

- **Why it matters:** Reports a 1 km OWPT field experiment under strong turbulence with measured 1035 W optical transmitted and 152 W electric received (15% efficiency), using diffractive beam shaping + homogenisation + current-smoothing, and explicitly noting laser safety measures (IEC 60825-1 Class 4)—a strong PoC for practical optical links. [37]

### 15) A Compact and High-Power Rectenna Array for Wireless Power Transmission Applications

- **Authors/Org:** Huang et al.

- **Venue/type:** Peer-reviewed experimental paper (Energies; open access)

- **Publication date:** Nov 2024 (Published 29 Nov 2024)

- **Link:** <https://www.mdpi.com/1996-1073/17/23/6008>

- **Why it matters:** Demonstrates a rectenna array for MWPT with reported efficiency (47.6%) and volumetric output DC power density ( $117.6 \text{ mW/cm}^3$ ) and a verification demo powering a 12 W-rated LCD screen—direct evidence that receiver-side hardware can deliver “usable electricity” to loads in lab/benchtop demos. [38]

### 16) Enhanced laser wireless power transmission efficiency with a novel PV-TEG hybrid receiver: dual thermal management and energy recovery

- **Authors/Org:** Xian-long et al.

- **Venue/type:** Peer-reviewed experimental + simulation paper (Scientific Reports; open access)

- **Publication date:** Oct 2025 (Published 13 Oct 2025)

- **Link:** <https://www.nature.com/articles/s41598-025-14275-7>

- **Why it matters:** Shows receiver-side progress for laser WPT: a PV-TEG hybrid receiver reduces PV temperature (up to 31.94 K), improves output (reported overall improvement

25.81% over PV-only), and reports PV photoelectric conversion stabilising around ~48%—directly addressing thermal/efficiency bottlenecks highlighted in the ART. [39]

### 17) The high power electricity generation and WPT demonstration mission — Proposed first step to develop space solar power

- **Authors/Org:** Xinbin Hou et al.
- **Venue/type:** Peer-reviewed open-access paper (Space Solar Power and Wireless Transmission, Elsevier/KeAi)
- **Publication date:** Jun 2025
- **Link:** <https://www.sciencedirect.com/science/article/pii/S2950104025000276>
- **Why it matters:** Proposes a stepwise space-solar roadmap with a first mission explicitly targeting kW-level microwave WPT from LEO to ground and kW-level laser power transmission, plus validating beam control precision—evidence that the next maturity step is being engineered but is not yet demonstrated. [40]

## 3. Maturity score (1–7) and reasoning

### A) Final maturity score: 3

### B) Why this score fits the rubric (explicit evidence → rubric mapping)

**What rules out levels 1–2 (the tech is beyond theory and basic lab validation):** - There is **peer-reviewed on-orbit WPT evidence:** a space demonstration of wireless power transfer using a flexible coherent RF array operated in LEO for months and including beam-to-Earth pointing with ground detection, which exceeds “lab-only verification”. [27]

- There is **documented in-space laser power beaming** with quantified output power and efficiency over >100 days, showing that the basic laser power-beaming principle works in orbit (even if at low power and short range). [29]

- There are **high-power, long-distance terrestrial demonstrations:** optical power beaming delivering >800 W over 8.6 km (programme test) and independent peer-reviewed OWPT delivering 152 W over 1 km at 15% efficiency under strong atmospheric turbulence. [41]

Together, these directly satisfy rubric level 3’s expectation that a laboratory/prototype demonstration exists and that key functionality (beam generation, propagation, pointing, and reconversion) has been achieved in recent work.

**What is still missing to justify level 4 (PoC “meeting commercialisation requirements”) -**

**Scale gap to utility relevance:** The most credible in-space demonstrations are still **very low power** (e.g., ~1.5 W output for an orbital laser-beaming demo) or **very small experimental scale** for space-to-ground detection; none demonstrate sustained **kW–MW class space-to-ground delivered electrical power** into an operational grid interface. [42]

- **System-level readiness and operations:** Authoritative SBSP assessments highlight unresolved system blockers: spectrum/orbital-slot coordination, debris vulnerability, security, and the extreme scale of manufacturing/launch cadence required for commercial SBSP. These are not “minor engineering details”; they are front-and-centre feasibility constraints. [43]

- **Commercial-scale receiver/site build-out remains conceptual:** Pre-Phase A studies quantify very large rectenna/receiver infrastructure (e.g., tens of km<sup>2</sup> for ~1 GW-class

concepts) and still discuss safety logic for misalignment—evidence that commercial deployment sits beyond current PoC. [44]

### C) Sub-component maturity breakdown and aggregation

- **Terrestrial optical power beaming (laser → PV electricity): ~4**
- Evidence: 1 km, 1035 W optical transmitted / 152 W electric received (15%) with explicit beam-shaping and safety protocol; plus >800 W delivered at 8.6 km in programme tests. [45]
- Rationale: This is beyond lab-only; it is a functional field PoC at meaningful power. Still not at “product shipments” scale.
- **Terrestrial/airborne microwave beaming (phased array → rectenna): ~4**
- Evidence: >5 km flight demonstration of 5.8 GHz microwave WPT with beamforming and directional control on a high-speed aircraft-to-ground link; receiver hardware work showing delivery into real loads (e.g., 12 W LCD demo). [46]
- Rationale: Functional prototype in realistic geometry (moving transmitter; vertical link) exists, but not yet packaged as a commercial product with standardised deployments.
- **In-space power beaming (orbital demonstrations): ~3**
- Evidence: on-orbit laser power beaming with measured output/efficiency; peer-reviewed space WPT array demonstration with beam-to-Earth pointing/detection. [11]
- Rationale: Demonstrated prototype functionality in space, but far from high-power and far from operationalised deployment.
- **Commercial-scale SBSP delivering grid power: ~2**
- Evidence: multiple authoritative studies and roadmaps quantify system scale, economics, and blockers (launch mass/cadence; huge receivers; regulatory/security issues), indicating the concept is feasible enough to warrant pre-Phase A work but not yet demonstrated at a scaled technical level. [47]

**Aggregation to one score:** The ART as written is dominated by **space-based and utility-relevant power delivery**, not just terrestrial niche WPT. Taking a conservative average across the above ( $\approx (4 + 4 + 3 + 2) / 4 \approx 3.25$ ) and weighting toward the SBSP elements that govern the overall claim, the appropriate single score is **3** rather than 4. [48]

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<https://www.nasa.gov/wp-content/uploads/2024/01/otps-sbsp-report-final-tagged-approved-1-8-24-tagged-v2.pdf>

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<https://indico.esa.int/event/453/attachments/5098/8056/Potential%20Activities%20for%20the%20Space-based%20Solar%20Power%20Specific%20Area%20in%20GSTP%20Element%201%2022Dec22.pdf>

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[https://www.jspacesystems.or.jp/jss/wp-content/uploads/2025/01/1stTestReport\\_2024.12.24en-1.pdf](https://www.jspacesystems.or.jp/jss/wp-content/uploads/2025/01/1stTestReport_2024.12.24en-1.pdf)

[36] [https://www.jstage.jst.go.jp/article/jesa/2/0/2\\_166/\\_pdf/-char/ja](https://www.jstage.jst.go.jp/article/jesa/2/0/2_166/_pdf/-char/ja)

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[39] <https://www.nature.com/articles/s41598-025-14275-7>

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<https://www.sciencedirect.com/science/article/pii/S2950104025000276>

## ART 08.065 Advanced geothermal technology

### 1. ART extraction

- **Primary capability claimed**
- Engineer geothermal heat extraction in many more locations than conventional hydrothermal geothermal by **drilling deeper ( $\approx 5\text{--}10\text{+ km}$ ) into hotter rock** and **creating predictable heat-transfer pathways** (engineered circulation or closed-loop heat exchangers).
- Deliver **round-the-clock** high-grade heat and/or electricity using standard surface conversion equipment (e.g., binary cycles/ORC, steam cycles where temperatures allow) with modular scale-up from single well-pairs to multi-well “heat fields”.
- Reduce reliance on naturally permeable reservoirs via **reservoir engineering + high-temperature well construction + continuous sensing/control**.
- **Key sub-components / variants**
- **Engineered Geothermal Systems (EGS):** horizontal/deviated wells + stimulation (hydraulic fracturing/hydroshearing) to create permeable pathways between injector/producer wells.
- **Closed-loop geothermal systems (CLGS):** sealed wellbore loops (coaxial, U-tube, multi-lateral “radiator” geometries) extracting heat largely by conduction (and sometimes leveraging groundwater convection).

- **Superhot / supercritical geothermal:** targeting  $>\sim 374\text{ }^{\circ}\text{C}$  (often cited as “superhot rock”) to increase energy density per well, but requiring new tool/material envelopes.
- **High-temperature drilling & completion:** faster hard-rock drilling, temperature-tolerant bits, drilling fluids, and directional tools; plus casing/liners rated for extreme temperatures and stresses.
- **Well integrity materials:** corrosion-resistant casing alloys, high-temperature cement systems and zonal isolation under thermal cycling, aggressive fluids, and long duration.
- **Downhole sensing & telemetry:** fibre-optic/distributed sensing, pressure/temperature gauges, microseismic monitoring, and survivable cabling/packaging.
- **Closed-loop + surface integration:** heat exchangers, pumping/thermosiphon management, ORC/steam cycle matching, and supervisory control/digital models for thermal drawdown forecasting.
- **Risk governance:** induced seismicity management (traffic-light systems, probabilistic hazard updates), permitting pathways, and community risk acceptance.
- **What “maturity evidence” looks like for this ART**
- **Field-scale pilots** showing sustained circulation and usable heat/power output (not just lab validation).
- **Repeatable multi-well drilling and completion campaigns** with documented learning curves (reduced drilling days, cost/ft, fewer failures).
- Demonstrated **monitoring-and-control in harsh wells** (multi-well microseismic, pressure/temperature control loops; anomaly detection) with quantified performance.
- **High-temperature well integrity demonstrations** (cement/casing materials surviving months-long exposure at  $\geq 300\text{ }^{\circ}\text{C}$  and/or supercritical conditions).
- Clear **induced-seismicity risk frameworks** demonstrated in practice (adaptive traffic lights, probabilistic hazard updates).
- **Commercial pull:** PPAs/heat off-take agreements, project-finance milestones, and multiple well-capitalised actors pursuing scale projects.
- For superhot/deep variants specifically: **drilling + completion toolchains proven at  $>374\text{ }^{\circ}\text{C}$**  and at multi-km depths with credible cost trajectories.

## 2. Evidence (10–20 recent, reliable sources)

### 1) Pathways to Commercial Liftoff: Next-Generation Geothermal Power

**Authors/Org:** U.S. Department of Energy<sup>[1]</sup> (multiple DOE offices)

**Type:** Authoritative roadmap/report (government programme)

**Date:** March 2024

**Link:** <https://cdn.catf.us/wp-content/uploads/2025/06/09154348/doe-liftoff-nextgen-geothermal.pdf>

**Why it matters:** Quantifies the near-term state of “next-generation geothermal” (EGS + closed-loop), explicitly citing field-scale pilots and commercial timelines, and frames the key scaling bottlenecks: drilling cost, operability risk, and societal licence (including induced seismicity). <sup>[2]</sup>

## 2) **2025 U.S. Geothermal Market Report** (web summary + embedded figures)

**Authors/Org:** National Laboratory of the Rockies[3]

**Type:** Market monitoring / authoritative report summary (national-lab publication)

**Date:** Last updated Feb 2026

**Link:** <https://www.nlr.gov/geothermal/2025-us-geothermal-market-report>

**Why it matters:** Provides concrete, recent maturity signals: growth in U.S. geothermal nameplate capacity, a count of newly signed PPAs, documented drilling-time reductions at Utah FORGE[4] (e.g., drilling time reductions from 2020 to 2023), and named progress of next-generation projects—useful for “how close to market and scaling” assessment. [5]

## 3) **Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office**

**Authors/Org:** Chad Augustine[6] et al., National Renewable Energy Laboratory[7]

**Type:** Authoritative techno-economic analysis / national lab technical report

**Date:** January 2023

**Link:** <https://docs.nrel.gov/docs/fy23osti/84822.pdf>

**Why it matters:** Establishes quantitative cost/performance targets (e.g., the Earthshot framing of \$/MWh by 2035) and documents the modelling assumptions needed for EGS to scale (flow/productivity, drilling cost reductions, plant sizing), directly supporting plausibility checks for the ART’s economics. [8]

## 4) **The Future of Enhanced Geothermal Systems in the United States**

**Authors/Org:** Lauren Boyd[9], Geothermal Technologies Office[10]

**Type:** Government programme briefing/report (authoritative)

**Date:** September 2023

**Link:** [https://www.energy.gov/sites/default/files/2023-](https://www.energy.gov/sites/default/files/2023-10/The%20Future%20of%20Enhanced%20Geothermal%20Systems%20in%20the%20United%20States.pdf)

[10/The%20Future%20of%20Enhanced%20Geothermal%20Systems%20in%20the%20United%20States.pdf](https://www.energy.gov/sites/default/files/2023-10/The%20Future%20of%20Enhanced%20Geothermal%20Systems%20in%20the%20United%20States.pdf)

**Why it matters:** Lays out the U.S. programme structure and near-term demonstration categories (including superhot/supercritical EGS), clarifying which components are treated as “demonstration-ready” vs “still R&D,” which is directly relevant to maturity scoring. [11]

## 5) **2025 Geothermal Drilling Cost Curves Update**

**Authors/Org:** Dayo Akindipe[12] and Erik Witter[13]

**Type:** Technical conference proceedings (Stanford Geothermal Workshop)

**Date:** February 2025

**Link:** <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2025/Akindipe.pdf>

**Why it matters:** Uses field drilling campaigns and publicly available commercial data to revise geothermal drilling cost curves, including tabulated drilling performance and cost/ft values—direct evidence that drilling is moving along a learning curve (a core maturity constraint for advanced geothermal). [14]

## 6) **Microseismic Monitoring of a Horizontal EGS System: Case Study and State of the Art**

**Authors/Org:** Sireesh Dadi[15] et al. (Fervo Energy[16]; includes Jack Norbeck[17])

**Type:** Technical conference proceedings (Stanford Geothermal Workshop)

**Date:** February 2024

**Link:** <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Dadi.pdf>

**Why it matters:** Reports operational monitoring at a horizontal EGS site using multi-well fibre-optic microseismic acquisition detecting ~50,000 events over ~3 months, with traffic-

light thresholds not exceeded, and documents practical issues (e.g., fibre loss in poorly cemented areas)—strong evidence for real-world sensing/control maturity. [18]

#### 7) **Assessment of two recent hot dry rock thermal energy production projects: Utah FORGE and Blue Mountain EGS (Project Red)**

**Authors/Org:** B. Mindygaliyeva[19] et al.

**Type:** Peer-reviewed paper (Geothermics)

**Date:** 2024 (month not captured in accessible metadata)

**Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0375650524001408>

**Why it matters:** Compares two contemporary HDR/EGS field efforts in a single peer-reviewed analysis, grounding plausibility claims (depth/temperature ranges, reservoir-engineering approach) and highlighting what has and has not been demonstrated in recent “modern EGS” campaigns. [20]

#### 8) **Numerical investigation of closed-loop geothermal systems in deep geothermal reservoirs**

**Authors/Org:** Mark White[21] et al.

**Type:** Peer-reviewed journal article (Geothermics; indexed via DOE/OSTI)

**Date:** January 2024

**Link:** <https://www.osti.gov/pages/biblio/2205271>

**Why it matters:** Provides a quantified design-space study (including techno-economics) showing closed-loop systems can reach competitive *heat* costs but *electricity* economics remain drilling-cost-limited—directly informing plausibility and maturity for the “sealed/closed-loop” branch of the ART. [22]

#### 9) **Numerical modelling of a deep closed-loop geothermal system: evaluating the Eavor-Loop**

**Authors/Org:** Joseph J. Kelly[23] and Christopher I. McDermott[24]; University of Edinburgh[25]

**Type:** Peer-reviewed paper (AIMS Geosciences)

**Date:** February 2022

**Link:** <https://www.aimspress.com/article/doi/10.3934/geosci.2022011>

**Why it matters:** An independent modelling-based plausibility check of deep closed-loop designs, finding headline outputs plausible under certain thermal assumptions while flagging sensitivity to subsurface conditions—useful for assessing how close CLGS variants are to robust, generalisable deployment. [26]

#### 10) **Iceland Deep Drilling Project: a Review of the Main Challenges and Implications of Drilling the Well IDDP-1**

**Authors/Org:** Agustin Garbino[27]

**Type:** Technical conference paper (GRC Transactions; superhot drilling lessons)

**Date:** October 2023

**Link:**

[https://www.researchgate.net/publication/379220950\\_Iceland\\_Deep\\_Drilling\\_Project\\_a\\_Review\\_of\\_the\\_Main\\_Challenges\\_and\\_Implications\\_of\\_Drilling\\_the\\_Well\\_IDDP-1](https://www.researchgate.net/publication/379220950_Iceland_Deep_Drilling_Project_a_Review_of_the_Main_Challenges_and_Implications_of_Drilling_the_Well_IDDP-1)

**Why it matters:** Summarises real drilling/production experience from a “magma / superhot” context (including reported ~450 °C discharge and very high enthalpy), providing hard evidence that superhot wells are physically feasible while emphasising why tool/material envelopes and corrosive fluids remain central maturity blockers. [28]

### 11) **Drilling for superhot geothermal energy: A technology gap analysis (Version 1.0)**

**Authors/Org:** Clean Air Task Force[29] and Cascade Institute[30]

**Type:** Technical report / gap analysis

**Date:** 2024

**Link:** <https://cascadeinstitute.org/wp-content/uploads/2024/09/REPORT-Drilling-for-Superhot-Geothermal-Energy-v1.0-1.pdf>

**Why it matters:** Decomposes the “superdeep + superhot” claim into specific engineering gaps (HPHT tools, bits, casing/cement, drilling fluids, well construction practices) and assigns readiness levels—directly supporting a maturity judgement for the 5–15 km, >374 °C regime. [31]

### 12) **Superhot Rock Methodology Report**

**Authors/Org:** Clean Air Task Force (methodology team)

**Type:** Technical report (resource mapping methodology; superhot rock definition and depth bins)

**Date:** June 2025 (from document path/timestamp)

**Link:** <https://cdn.catf.us/wp-content/uploads/2025/06/25170717/shr-heat-mapping-methodology.pdf>

**Why it matters:** Defines “superhot rock” operationally ( $\geq 374$  °C), separates nearer-term ( $\approx 4$ –8 km) vs medium-term ( $\approx 8$ –12 km) depth bands, and provides a repeatable mapping method—useful for evaluating the “how widespread is the resource if drilling improves?” claim. [32]

### 13) **Aluminum-Rich Cements for High Temperature Geothermal Wells**

**Authors/Org:** Tatiana Pyatina[33] and Toshifumi Sugama[34]; Brookhaven National Laboratory[35]

**Type:** Technical conference proceedings (Stanford Geothermal Workshop)

**Date:** February 2024

**Link:** <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Pyatina.pdf>

**Why it matters:** Reports lab and long-duration exposure tests (including months-long supercritical CO<sub>2</sub> environments) where aluminium-rich cements retain performance relative to OPC/silica degradation—directly supporting the feasibility of well integrity materials required for hotter/deeper geothermal. [36]

### 14) **Assessment of Cementitious Composites for High-Temperature Geothermal Wells**

**Authors/Org:** Pyatina et al.

**Type:** Peer-reviewed paper (Materials)

**Date:** 2024 (month not reliably extractable from the non-JS page view)

**Link:** <https://www.mdpi.com/1996-1944/17/6/1320>

**Why it matters:** Combines cyclic pressure-function testing with field exposure in a 300–350 °C geothermal well, reporting that calcium–aluminate systems outperform OPC/silica and that OPC/silica can lose mechanical properties over months—direct evidence for the durability constraint highlighted in the ART. [37]

### 15) **Updating induced seismic hazard assessments during hydraulic stimulation experiments in underground laboratories: workflow and limitations**

**Authors/Org:** Valentin Gischig[38] et al.; ETH Zürich[39] is referenced in the paper history/context

**Type:** Peer-reviewed paper (Solid Earth, Copernicus)



**Date:** 2025

**Link:** <https://se.copernicus.org/articles/16/1153/2025/>

**Why it matters:** Demonstrates an operationally relevant workflow for near-real-time induced-seismic hazard updating (including adaptive traffic-light framing), which is one of the major non-technical (but engineering-governed) scaling constraints for EGS-style reservoir creation. [40]

#### 16) Managing induced seismicity risks from enhanced geothermal systems: A good practice guideline

**Authors/Org:** Wenqin Zhou[41] et al.

**Type:** Peer-reviewed synthesis / guideline (Reviews of Geophysics)

**Date:** 2024

**Link:** <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024RG000849>

**Why it matters:** Consolidates best-practice risk management for induced seismicity (a leading cause of project delay/moratoria), strengthening the plausibility of large-scale deployment *if* such governance is implemented systematically. [42]

#### 17) Forecasting induced seismicity in enhanced geothermal systems with machine learning

**Authors/Org:** S. Karimpouli[43] et al.

**Type:** Peer-reviewed paper (Geophysical Journal International)

**Date:** 2025

**Link:** <https://academic.oup.com/gji/article/242/2/ggaf155/8169887>

**Why it matters:** Provides evidence that data-driven forecasting of induced seismic response during injection is technically feasible, directly supporting the ART's claim that automated diagnostics and model-updating control loops can shift operations toward remote supervision. [44]

#### 18) Insights Into Seismicity Associated With Flexibly Operating Enhanced Geothermal System From Real-Time Distributed Acoustic Sensing

**Authors/Org:** (multi-institution team; includes industry + lab participants)

**Type:** Peer-reviewed paper (JGR: Solid Earth)

**Date:** July 2025

**Link:** <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025JB031634?af=R>

**Why it matters:** Reports field evidence for real-time distributed sensing applied to a flexibly operated EGS context, directly connected to the “continuous regulation + anomaly flagging” maturity indicators described in the ART. [45]

### 3. Maturity score (1–7) and reasoning

**Final maturity score: 4**

#### Why this score rules out lower levels (1–3)

- **Field-scale and commercially oriented prototypes exist**, not just theory or lab-only demonstrations: DOE's liftoff report explicitly identifies next-generation geothermal pilots and frames a pathway to commercial scale. [2]

- The ecosystem has **repeatable drilling + reservoir-creation practice advancing beyond lab**, evidenced by documented improvements in drilling time and multi-well campaigns reported in the 2025 U.S. market tracking, and by drilling cost-curve updates grounded in recent field drilling datasets. [46]

- Operational monitoring/control elements that the ART claims (continuous sensing, anomaly detection hooks, traffic-light governance) are demonstrated in practice via multi-well fibre-optic microseismic monitoring and formalised induced-seismic hazard workflows. [47]

These collectively exceed “scientific principle + lab verification” and justify at least “PoC functional prototype” (level 4).

### Why the evidence is still insufficient for level 5 (and above)

- The ART’s defining leap—**routine superdeep (≈5–10+ km) access into >374 °C superhot rock with durable downhole toolchains**—is not yet shown as a repeatable, scalable, cost-bounded capability. The superhot drilling gap analysis catalogues multiple low-to-mid-TRL bottlenecks (HPHT drilling tools, well integrity, fluids, and long-duration survivability), implying the “superhot/superdeep” core remains pre-scale. [31]

- Closed-loop geothermal (a key ART variant) is still **economically and performance constrained for electricity** in many settings: peer-reviewed modelling finds competitive heat costs plausible but indicates electricity competitiveness requires major drilling cost reductions, and independent modelling highlights strong sensitivity to subsurface assumptions. [48]

- While EGS and monitoring/control are advancing rapidly, **industry-wide product delivery at increasing volumes** (levels 6–7) is not yet the norm across the “advanced geothermal” bundle; market evidence points to momentum and financing mechanisms, but scaling is still in the “prove repeatability + drive costs down” stage. [49]

### Sub-component maturity breakdown and aggregation approach

Because the ART description bundles variants with meaningfully different operating envelopes (especially the >374 °C superhot regime vs ~150–250 °C EGS/CLGS), an **average-based score** is most defensible.

- **Modern near-term EGS (horizontal drilling + multi-stage stimulation + monitoring/traffic-light governance) → ~5**
- Supported by evidence of commercial-facing pilots and rapid learning in drilling/monitoring practices (market tracking + drilling cost curve updates + field microseismic monitoring). [50]
- **Closed-loop geothermal systems (sealed loops, multi-lateral/pipe-in-pipe variants) → ~3–4**
- Strong plausibility and parameterised performance/economic modelling exist, but electricity competitiveness remains drilling-cost limited and deployment evidence is still comparatively sparse. [48]
- **Superhot / supercritical deep geothermal (>374 °C, multi-km drilling into extreme conditions) → ~2–3**
- Real-world superhot lessons exist (IDDP-1 retrospective) but the “routine superhot” toolchain is not yet mature; the primary evidence base emphasises gaps rather than reproducible commercial operations. [51]
- **High-temperature well integrity materials (cements/corrosion resistance) → ~3**

- Credible materials testing and field exposure evidence exists at 300–350 °C and under supercritical CO<sub>2</sub> environments, but system-level qualification across full well lifetimes in superhot wells is not yet established. [52]

### Aggregation to a single ART score

- Taking the above as a bundle with divergent maturity, the centre-of-mass falls at **4**: there is **clear PoC/early-commercial functionality** for the EGS branch and meaningful enabling-progress (monitoring, drilling learning curves, cement systems), but **the superdeep/superhot generalisation and broad scaling** needed for a level-5 “production prototype race” across the whole ART is not yet evidenced. [53]

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[1] [36] [52] <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Pyatina.pdf>

<https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Pyatina.pdf>

[2] [6] [10] [34] [39] [53] <https://cdn.catf.us/wp-content/uploads/2025/06/09154348/doe-liftoff-nextgen-geothermal.pdf>

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[https://www.researchgate.net/publication/379220950\\_Iceland\\_Deep\\_Drilling\\_Project\\_a\\_Review\\_of\\_the\\_Main\\_Challenges\\_and\\_Implications\\_of\\_Drilling\\_the\\_Well\\_IDDP-1](https://www.researchgate.net/publication/379220950_Iceland_Deep_Drilling_Project_a_Review_of_the_Main_Challenges_and_Implications_of_Drilling_the_Well_IDDP-1)

[https://www.researchgate.net/publication/379220950\\_Iceland\\_Deep\\_Drilling\\_Project\\_a\\_Review\\_of\\_the\\_Main\\_Challenges\\_and\\_Implications\\_of\\_Drilling\\_the\\_Well\\_IDDP-1](https://www.researchgate.net/publication/379220950_Iceland_Deep_Drilling_Project_a_Review_of_the_Main_Challenges_and_Implications_of_Drilling_the_Well_IDDP-1)

[4] [31] [38] [43] <https://cascadeinstitute.org/wp-content/uploads/2024/09/REPORT-Drilling-for-Superhot-Geothermal-Energy-v1.0-1.pdf>

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<https://www.nrel.gov/geothermal/2025-us-geothermal-market-report>

[7] [18] [47] <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Dadi.pdf>

<https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Dadi.pdf>

[8] <https://docs.nrel.gov/docs/fy23osti/84822.pdf>

<https://docs.nrel.gov/docs/fy23osti/84822.pdf>

[9] [44] <https://academic.oup.com/gji/article/242/2/ggaf155/8169887>

<https://academic.oup.com/gji/article/242/2/ggaf155/8169887>

[11] <https://www.energy.gov/sites/default/files/2023-10/The%20Future%20of%20Enhanced%20Geothermal%20Systems%20in%20the%20United%20States.pdf>

<https://www.energy.gov/sites/default/files/2023-10/The%20Future%20of%20Enhanced%20Geothermal%20Systems%20in%20the%20United%20States.pdf>

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<https://www.osti.gov/pages/biblio/2205271>

[14] <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2025/Akindipe.pdf>

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[20] <https://www.sciencedirect.com/science/article/abs/pii/S0375650524001408>

<https://www.sciencedirect.com/science/article/abs/pii/S0375650524001408>

[21] [42] <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024RG000849>

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[30] [40] <https://se.copernicus.org/articles/16/1153/2025/>

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[37] <https://www.mdpi.com/1996-1944/17/6/1320>

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[45] <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025JB031634?af=R>

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025JB031634?af=R>

## ART 08.066 Resilient microgrids

### ART extraction

- **Primary capability claimed**
- Maintain electricity supply to a defined local area during wider-grid outages or stress by operating as an islandable “local grid” that can disconnect and later resynchronise/reconnect, with minimal interruption. [1]

- Coordinate distributed energy resources (DER)—renewables, engines/gensets, and batteries—via power electronics and control software to balance supply/demand and sustain critical loads (including some black-start capability). [2]
- Improve resilience and power quality via monitoring, fast control actions, protection coordination, and operational automation—while managing constraints such as permitting/interconnection, cybersecurity, and maintenance. [3]
- **Key sub-components / sub-threads**
- **DER stack:** PV/wind + dispatchable generation + battery energy storage systems (BESS) integrated through inverters (grid-forming and grid-following). [4]
- **Microgrid controller / energy management system:** dispatch, load shedding, islanding transitions, secondary voltage/frequency control, reconnection synchronisation, and black-start sequencing. [5]
- **Sensing and data infrastructure:** SCADA/telemetry, time-synchronised measurements (e.g., event records/oscillography), and historians for operations and root-cause analysis. [6]
- **Protection & interconnection engineering:** anti-islanding measures, protection relay coordination for inverter-limited fault currents, sync-check functions, and coordination with upstream distribution equipment. [7]
- **Cybersecurity of control interfaces and smart inverters:** secure configuration, patching, interface hardening, and device/installer guidance. [8]
- **Operational readiness:** O&M, testing/commissioning practices, endurance targets, and regulatory/programme structures that enable deployment. [9]
- **Maturity indicators that would constitute strong evidence**
- **Fielded deployments** (especially critical infrastructure / community microgrids) demonstrating islanding, sustained islanded operation, and reconnection. [10]
- **Procurement-grade specifications and design criteria** that require black start, “blinkless” transitions, data logging, and secure/standardised communications. [11]
- **Independent test plans and HIL/PHIL validation** of controller functions (black start, island constraints, secondary control, reconnection). [12]
- **Standardisation/consortium performance requirements** for grid-forming inverter behaviour relevant to islanding and restoration. [13]
- **Demonstrated handling of known blockers:** inverter fault-current limitations affecting protection; cybersecurity hardening and governance; and operational procedures for maintenance and endurance. [14]

#### Evidence (10–20 recent, reliable sources)

##### 1) Microgrid Controller Survey Report: 2024 Update

- **Organisation:** Oak Ridge National Laboratory [15]
- **Venue/type:** National-lab technical report
- **Publication date:** April 2024
- **Link:** <https://info.ornl.gov/sites/publications/Files/Pub214751.pdf>
- **Why it matters:** Reviews the state of commercial microgrid controller functionality and

identifies gaps/trends, which directly informs how mature islanding/reconnection/dispatch capabilities are in real products—not just in theory. [16]

## 2) Utility Microgrid Controller Test Plan: Evaluation Method for Utility Microgrid Controllers

- **Organisation:** Electric Power Research Institute[17]
- **Venue/type:** Industry R&D technical update (test methodology)
- **Publication date:** December 2023
- **Link:** <https://restservice.epri.com/publicdownload/000000003002028385/0/Product>
- **Why it matters:** Defines concrete test cases and performance metrics for controller functions including island operations, **black start**, and **synchronised reconnection**, indicating that controller evaluation is moving into repeatable, deployment-oriented practice. [18]

## 3) Controller Hardware-in-the-Loop Evaluation of a Microgrid Controller for a Microgrid System with Multiple Grid-Forming Inverters (Preprint)

- **Organisation:** National Renewable Energy Laboratory[19]
- **Venue/type:** National-lab conference paper / preprint (controller-HIL validation)
- **Publication date:** September 2024 (conference presentation noted for October 2024)
- **Link:** <https://docs.nrel.gov/docs/fy24osti/89074.pdf>
- **Why it matters:** Demonstrates controller-managed islanded operation using multiple DER types and explicitly exercises a **black-start sequence** (BESS energisation and staged load/DER bring-up), providing technical evidence that advanced microgrid control functions can be validated in HIL environments. [20]

## 4) Unified Facilities Criteria: Resilient Installation Microgrid Design (UFC 3-550-04)

- **Organisation:** United States Department of Defense[21]
- **Venue/type:** Authoritative engineering/design criteria (military facilities)
- **Publication date:** March 2024
- **Link:** [https://www.wbdg.org/FFC/DOD/UFC/ufc\\_3\\_550\\_04\\_2024.pdf](https://www.wbdg.org/FFC/DOD/UFC/ufc_3_550_04_2024.pdf)
- **Why it matters:** Treats resilient microgrids as a procurement-ready capability; explicitly states that installation microgrids **must be capable of black start** and discusses islanding formation and operational requirements—strong evidence of real-world engineering feasibility and institutional adoption. [22]

## 5) UFGS 26 37 13: Microgrid Control System

- **Organisation:** (U.S. federal facilities guide specification; issued via WBDG)
- **Venue/type:** Procurement specification for microgrid control systems
- **Publication date:** February 2024
- **Link:** <https://www.wbdg.org/FFC/DOD/UFGS/UFGS%2026%2037%2013.pdf>
- **Why it matters:** Specifies implementation-level requirements for alarms, health status, metering, historian data, dispatch modes (including resiliency dispatch), and reconnection/black-start test scenarios—evidence that “dense sensing + control dashboards + automation” is being concretely required in procurements. [23]

## 6) UNIFI Specifications for Grid-Forming Inverter-Based Resources: Version 2 (UNIFI-2024-2-1)

- **Organisation:** UNIFI Consortium[24]



- **Venue/type:** Research consortium specification / requirements document
- **Publication date:** March 2024 (release date 21 March 2024)
- **Link:** <https://www.nrel.gov/docs/fy24osti/89269.pdf>
- **Why it matters:** Codifies vendor-agnostic performance requirements for grid-forming inverter-based resources, including sections explicitly addressing **intentional islanding** and **black start/system restoration**, supporting the plausibility of inverter-enabled resilient microgrids and signalling accelerating standardisation. [25]

#### 7) White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems

- **Organisation:** North American Electric Reliability Corporation[26]
- **Venue/type:** Reliability/standards-adjacent white paper
- **Publication date:** September 2023
- **Link:** [https://www.nerc.com/globalassets/our-work/reports/white-papers/white\\_paper\\_gfm\\_functional\\_specification.pdf](https://www.nerc.com/globalassets/our-work/reports/white-papers/white_paper_gfm_functional_specification.pdf)
- **Why it matters:** Provides functional performance framing and verification approaches for grid-forming BESS, noting that some smaller islanded systems already face these challenges and detailing verification tests—relevant to microgrid stability, fault response expectations, and reconnection readiness. [27]

#### 8) Protection of 100% Inverter-dominated Power Systems with Grid-Forming Inverters and Protection Relays – Gap Analysis and Expert Interviews (SAND2024-04848)

- **Organisation:** Sandia National Laboratories[28]
- **Venue/type:** National-lab technical report (gap analysis + expert interviews; public copy available)
- **Publication date:** April 2024
- **Link:** [https://www.researchgate.net/publication/379952862\\_Protection\\_of\\_100\\_Inverter-dominated\\_Power\\_Systems\\_with\\_Grid-Forming\\_Inverters\\_and\\_Protection\\_Relays\\_-\\_Gap\\_Analysis\\_and\\_Expert\\_Interviews](https://www.researchgate.net/publication/379952862_Protection_of_100_Inverter-dominated_Power_Systems_with_Grid-Forming_Inverters_and_Protection_Relays_-_Gap_Analysis_and_Expert_Interviews)
- **Why it matters:** Directly addresses one of the ART's hardest constraints—**protection coordination** under grid-forming inverter fault behaviour—by documenting gaps and priority issues (e.g., relay response to inverter-limited currents), indicating where maturity is still bounded. [29]

#### 9) Anti-Islanding Techniques for Integration of Inverter-Based Distributed Energy Resources to the Electric Power System

- **Authors:** Ênio Costa Resende[30] et al.
- **Venue/type:** Peer-reviewed paper (IEEE Access)
- **Publication date:** January 2024 (published 23 January 2024; current version 6 February 2024)
- **Link:** <https://osuva.uwasa.fi/bitstreams/4e7124e5-7227-4081-b5a3-30cd6a47a399/download>
- **Why it matters:** Surveys practical anti-islanding approaches (passive/active/remote/hybrid/ML) and highlights risks such as out-of-phase reconnection—direct evidence that engineering methods exist but must be selected/tuned to enable safe intentional islanding in resilient microgrids. [31]

#### 10) Reconnection of MV Microgrid with Universal Grid-forming Inverter-based Resources (Accepted Manuscript; IET Conference Proceedings / MEDPOWER 2024)

- **Authors:** Hannu Laaksonen[32]; Nikos Hatziaargyriou[33]
- **Venue/type:** Peer-reviewed conference proceedings (postprint/accepted manuscript)
- **Publication date:** 2025 (conference proceedings volume 2024)
- **Link:** <https://osuva.uwasa.fi/bitstreams/61fee869-6e8c-4957-8a4d-74e97dc1ef9d/download>
- **Why it matters:** Provides concrete reconnection stability findings for a medium-voltage microgrid using a specific synchronisation method (U-FLL), reporting stable reconnection under large phase-angle differences ( $\pm 140\text{--}180^\circ$  depending on case) in PSCAD studies—relevant to the “reconnection with minimal interruption” claim. [34]

#### 11) Fiscal Year 2021 Isolated Grids and Grid-Connected Turbine Reference Systems; Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL)

- **Organisation:** United States Department of Energy[35] national-lab programme report (multi-lab)
- **Venue/type:** National-lab technical report
- **Publication date:** July 2022
- **Link:** <https://docs.nrel.gov/docs/fy22osti/81792.pdf>
- **Why it matters:** Discusses microgrid resilience services and explicitly describes how black start can be provided by renewables through a **grid-forming inverter plus integrated battery storage**, supporting engineering plausibility for black-start capable microgrids beyond diesel-only designs. [36]

#### 12) Cybersecurity for Smart Inverters: Guidelines for Residential and Light Commercial Solar Energy Systems (NIST IR 8498)

- **Organisation:** National Institute of Standards and Technology[37]
- **Venue/type:** Government technical guidance with device testing
- **Publication date:** December 2024
- **Link:** <https://nvlpubs.nist.gov/nistpubs/ir/2024/NIST.IR.8498.pdf>
- **Why it matters:** Provides seven cybersecurity guidelines and reports testing of **five** example smart inverters, while recommending manufacturer capabilities to support secure installation/operation—directly relevant to the ART’s cybersecurity constraint around inverter/control interfaces. [38]

#### 13) Cybersecurity of distributed energy resource systems in the smart grid: A survey

- **Authors:** Juanwei Chen[39] et al.
- **Venue/type:** Peer-reviewed survey (Applied Energy, open access)
- **Publication date:** April 2025 (Volume 383, 1 April 2025)
- **Link:** <https://www.sciencedirect.com/science/article/pii/S0306261925000947>
- **Why it matters:** Synthesises DER cybersecurity requirements/standards and defence strategies (prevention/detection/mitigation) and maps research gaps—evidence that scaling resilient microgrids requires systematic cyber risk management across multi-stakeholder DER coordination. [40]

#### 14) Microgrid Handbook for Army Resilience: A Technical Review (PNNL-38494)

- **Organisation:** Pacific Northwest National Laboratory[41]
- **Venue/type:** National-lab technical review / handbook
- **Publication date:** October 2025

- **Link:** <https://www.osti.gov/servlets/purl/2997694>
- **Why it matters:** Provides an end-to-end technical view of microgrid components, monitoring/control, O&M, and explicitly treats microgrid cybersecurity (including processes such as security authorisation), reinforcing that resilience is as much operations and governance as hardware capability. [42]

#### 15) State Microgrid Policy, Programmatic, and Regulatory Framework

- **Organisations:** National Association of Regulatory Utility Commissioners[43]; National Association of State Energy Officials[44]
- **Venue/type:** Multi-stakeholder policy/regulatory framework (with DOE support)
- **Publication date:** August 2023
- **Link:** <https://www.naseo.org/data/sites/1/documents/publications/Final%20Microgrid%20Framework.pdf>
- **Why it matters:** Documents how state agencies and regulators are actively creating programmes/rules for microgrid deployment and interconnection, reflecting real-world maturation drivers and constraints (safety, reliability, market structure, regulatory approvals). [45]

#### 16) Black start from renewable energy resources: Review and a case study of Great Britain

- **Authors:** Zhongmei Pan[46] et al.
- **Venue/type:** Peer-reviewed review + case study (Renewable and Sustainable Energy Reviews, open access)
- **Publication date:** March 2025 (Volume 209)
- **Link:** <https://www.sciencedirect.com/science/article/pii/S1364032124008694>
- **Why it matters:** Reviews black-start control/planning with renewables and discusses “multiple power islands” restoration concepts using findings from innovation projects in the United Kingdom[47]—highly relevant to microgrids’ black-start and restoration plausibility beyond conventional generators. [48]

#### 17) Enhancing resilience: Climate-proofing power infrastructure

- **Organisation:** International Renewable Energy Agency[49]
- **Venue/type:** International agency technical report
- **Publication date:** December 2025
- **Link:** [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Dec/IRENA\\_TEC\\_Enhancing\\_resilience\\_power\\_infrastructure\\_2025.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Dec/IRENA_TEC_Enhancing_resilience_power_infrastructure_2025.pdf)
- **Why it matters:** Summarises how grid-forming inverters plus storage can support standalone operation and provide black-start services, while noting ongoing international trials—useful corroboration that enabling technologies for resilient microgrids are seen as deployable resilience tools globally. [50]

#### 18) MICROGRIDS: Benefits, metrics, applications, and state-level programmes (SAND2025-15190PE)

- **Organisation:** United States[51] national laboratory presentation (Sandia)
- **Venue/type:** National-lab technical briefing / slide deck
- **Publication date:** November 2025 (dated 14 November 2025)
- **Link:**

[https://www.sandia.gov/app/uploads/sites/273/2025/12/Microgrids\\_Reliability\\_StatePrograms\\_12012025.pdf](https://www.sandia.gov/app/uploads/sites/273/2025/12/Microgrids_Reliability_StatePrograms_12012025.pdf)

- **Why it matters:** Cites a microgrid installation database count (461 installations) and provides deployment-oriented discussion of outage duration, endurance targets (including a DoD 30-day endurance target), and cost scaling—direct maturity evidence that microgrids are deployed and operationally framed as reliability/resilience infrastructure. [52]

### **Maturity score (1–7) and reasoning**

#### **Final maturity score: 6**

Resilient microgrids (as a system bundle) best fit level **6**: deployments and products exist and are expanding, but scaling remains constrained by site-specific engineering, protection/cybersecurity maturity limits, and regulatory complexity.

#### **Why the evidence rules out lower maturity levels (≤5)**

- The technology is not just laboratory or single-site prototype work: procurement-grade criteria explicitly require core resilience functions (e.g., black start and islanding formation) and specify microgrid control system capabilities, data collection, and operational functions—strong evidence of deployable, repeatable engineering practice rather than PoC. [53]

- Independent test/evaluation methods exist for commercial/utility microgrid controllers (including black start and reconnection test plans), indicating post-PoC operational validation and readiness activities. [54]

- Controller/HIL studies explicitly exercise black-start sequencing and islanded operation in structured test settings, which is typical of late-stage validation before/alongside field roll-out. [55]

- Deployment-maturity signals appear in compiled deployment counts and operational framing (e.g., hundreds of installations referenced and state-level programmes targeting resilience outcomes). [10]

#### **What is still missing to justify the next higher level (7)**

- Level 7 implies broad, rising demand with strongly self-sustaining growth and “competing products” scaling across wide customer segments. While deployments are real and growing, the evidence here still shows that major parts of the system are **integration-heavy and bespoke** (procurement specs emphasise extensive data/historian requirements, protection studies, and endurance/dispatch configuration), which tends to slow industrial-scale commoditisation. [56]

- Key blockers remain active research/standardisation topics—especially **protection coordination in inverter-dominated fault conditions** and **DER/microgrid cybersecurity governance**—suggesting that “fully mature resilient microgrids” with uniformly high automation and assured safety/security across contexts are not yet a solved, standardised product category. [57]

### **Evidence-to-rubric mapping**

- **Score-anchoring evidence for level 6 (delivered systems + expanding applications)**
- Procurement/design standards requiring black start and defining islanding/reconnection architectures: UFC 3-550-04 and UFGS 26 37 13. [11]

- Utility/industry evaluation methodology for microgrid controllers and HIL validation of black-start/island operation: EPRI test plans and NREL controller-HIL paper. [12]
- Deployment-scale indicators: national-lab briefing citing hundreds of installations and ongoing state programmes. [10]
- **Sub-component maturity snapshot (bundle-aware)**
- **Microgrid controller / EMS functions (islanding, dispatch, reconnection, basic black start sequencing) → ~6** (commercial + test-plan standardisation + HIL validation). Key sources: EPRI controller test plan; NREL controller-HIL; ORNL controller survey. [58]
- **Grid-forming inverter capability enabling stable islanded operation / restoration → ~5–6** (formalised performance requirements and major standardisation push; still evolving). Key sources: UNIFI specifications; NERC functional specs; IRENA resilience report. [59]
- **Protection coordination in inverter-dominated microgrids (self-healing, relay behaviour under limited fault current) → ~4–5** (clear gaps and ongoing work; still a maturity limiter). Key source: Sandia gap analysis report. [29]
- **Cybersecurity of inverters and microgrid/DER interfaces → ~4–5** (actionable guidelines and testing exist, but sector-wide assurance/certification and implementation consistency remain a bottleneck). Key sources: NIST IR 8498; Applied Energy DER cybersecurity survey; PNNL microgrid handbook. [8]

**Aggregation logic:** The overall ART score is set to **6** (not the maximum of subcomponents) because resilient microgrids are system-of-systems deployments; the operational value depends on the weakest links (protection coordination, cybersecurity governance, and site-specific interconnection engineering). [60]

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[1] [2] [11] [22] [41] [46] [53] [https://www.wbdg.org/FFC/DOD/UFC/ufc\\_3\\_550\\_04\\_2024.pdf](https://www.wbdg.org/FFC/DOD/UFC/ufc_3_550_04_2024.pdf)

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[3] [6] [19] [23] [47] [56]

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[https://www.researchgate.net/publication/379952862\\_Protection\\_of\\_100\\_Inverter-dominated\\_Power\\_Systems\\_with\\_Grid-Forming\\_Inverters\\_and\\_Protection\\_Relays\\_-\\_Gap\\_Analysis\\_and\\_Expert\\_Interviews](https://www.researchgate.net/publication/379952862_Protection_of_100_Inverter-dominated_Power_Systems_with_Grid-Forming_Inverters_and_Protection_Relays_-_Gap_Analysis_and_Expert_Interviews)

[https://www.researchgate.net/publication/379952862\\_Protection\\_of\\_100\\_Inverter-dominated\\_Power\\_Systems\\_with\\_Grid-Forming\\_Inverters\\_and\\_Protection\\_Relays\\_-\\_Gap\\_Analysis\\_and\\_Expert\\_Interviews](https://www.researchgate.net/publication/379952862_Protection_of_100_Inverter-dominated_Power_Systems_with_Grid-Forming_Inverters_and_Protection_Relays_-_Gap_Analysis_and_Expert_Interviews)

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## Group 9 - Bio-engineering & Life-Science Technologies

### ART 09.067 Next-Generation Gene Editing

#### ART extraction

#### Primary capability claimed by the ART

- Programmable “molecular repair tools” that can change DNA (and sometimes RNA) with tighter control over **where**, **what**, and **how** edits occur, reducing unintended edits and improving reliability across cell types. [1]
- A broader editing menu than “cut-and-replace”: single-nucleotide corrections, small indels, gene switching (up/down regulation without sequence rewrite), and multiplex edits coordinated across multiple genomic sites. [2]
- A software-like design-and-validate loop supported by measurement standards: predictable performance, sequencing-based verification, standardised off-target/quality metrics, and transient “payloads” that degrade after editing to reduce risk. [3]

#### Key sub-components / variants implied by the ART

- **Precision editors** for “small” changes: base editors and prime editors (nuclease-independent or reduced-break approaches) intended to reduce by-products from double-strand breaks. [4]
- **Large-insert / gene-sized writing tools** (e.g., CRISPR-directed integrases; CRISPR-associated transposases) for targeted, kilobase-to-gene scale insertion without relying on classical HDR. [5]
- **Gene switching / epigenome editing** (durable silencing or reversible control) via targeted chromatin/DNA methylation changes rather than sequence edits. [6]
- **Delivery engineering** tailored to tissue/context (e.g., LNPs, AAV, engineered virus-like particles), with an emphasis on transient expression/forms (RNPs, mRNA) to reduce integration and long-term exposure. [7]

- **Off-target and QC metrology:** sensitive, unbiased off-target mapping methods; inter-lab studies, reference materials, and regulator expectations for safety/quality documentation. [8]
- **Clinical translation & governance:** regulatory guidance for genome-editing products, and real-world approvals for genome-editing medicines that demonstrate manufacturability, clinical monitoring, and post-market obligations. [9]

#### What maturity indicators would count as strong evidence

- Robust **in vivo editing** in therapeutically relevant tissues at clinically meaningful levels, with quantified safety signals (off-target, toxicity, immune effects) and durability where relevant. [10]
- Demonstrations of **new editing modalities** (e.g., gene-sized insertion without DSBs) achieving workable efficiencies in human cells and/or animals. [11]
- **Standardised measurement** activity: regulator guidance defining expected safety/quality packages; inter-lab studies; reference materials; methods that are demonstrably sensitive and reproducible. [12]
- Clear **translation signals:** IND-enabling packages, first-in-human treatments, and/or formal product authorisations by multiple regulators/regions. [13]

#### 2. Evidence (10–20 recent, reliable sources)

##### Large-insert and “gene-sized” editing modalities

##### 1) Drag-and-drop genome insertion of large sequences without double-strand DNA cleavage using CRISPR-directed integrases (PASTE)

- Authors/Org: M.T.N. Yarnall et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Nov 2022** (24 Nov 2022)
- Link: <https://www.nature.com/articles/s41587-022-01527-4> [14]
- Why it matters: Demonstrates targeted integration of payloads up to ~36 kb in human cell lines, primary T cells, and non-dividing primary human hepatocytes using a Cas9 nickase–RT–serine integrase fusion, supporting plausibility of “repair-tool” style gene insertion without DSB reliance. [15]

##### 2) Targeted DNA integration in human cells without double-strand breaks using CRISPR-associated transposases (Type I-F CASTs)

- Authors/Org: G.D. Lampe et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Mar 2023** (29 Mar 2023)
- Link: <https://www.nature.com/articles/s41587-023-01748-1> [16]
- Why it matters: Reconstitutes multi-component CAST machinery in human cells and reports large-DNA integration without DSBs, including “orders of magnitude” enhancement from bacterial ClpX, indicating rapid engineering progress but still research-stage complexity. [16]

##### 3) Programmable gene insertion in human cells with a laboratory-evolved CRISPR-associated transposase (evoCAST)

- Authors/Org: I.P. Witte et al.
- Venue/type: Science (peer-reviewed experimental paper; PubMed abstract accessible)
- Publication date: **May 2025** (15 May 2025)

- Link: <https://pubmed.ncbi.nlm.nih.gov/40373119/> [17]
- Why it matters: Uses continuous evolution (PACE) to create CAST variants with **>200×** improved integration activity and reports **~10–30%** integration efficiencies of kilobase cargoes across 14 genomic target sites in human cells, a major maturity signal for gene-sized “writing” tools. [17]

#### **Precision editing of small variants and reliability improvements**

#### **4) High-fidelity PAMless base editing of hematopoietic stem cells to treat chronic granulomatous disease**

- Authors/Org: V. Bzhilyanskaya et al.
- Venue/type: Science Translational Medicine (peer-reviewed experimental/translation paper; PMC full text)
- Publication date: **Oct 2024** (16 Oct 2024)
- Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11753194/> [18]
- Why it matters: Shows PAMless ABE8e-SpRY achieves **up to 70% correction** of a prototypical CGD mutation in human HSPCs with “minimal off-target or bystander edits,” persistence post-transplant in mice, and states IND-enabling work supporting a first-in-human clinical trial. [18]

#### **5) Patient-Specific In Vivo Gene Editing to Treat a Rare Genetic Disease**

- Authors/Org: K. Musunuru et al.
- Venue/type: The New England Journal of Medicine (peer-reviewed case report; PubMed abstract accessible)
- Publication date: **May/Jun 2025** (Epub 15 May 2025; issue 12 Jun 2025)
- Link: <https://pubmed.ncbi.nlm.nih.gov/40373211/> [19]
- Why it matters: Reports an individually customised, LNP-delivered base-editing therapy given to a patient (two infusions at ~7 and 8 months) with no serious adverse events in early follow-up—strong evidence that “bespoke, high-end” next-gen editing workflows can reach real clinical use under regulatory oversight. [19]

#### **6) Engineered base editors with reduced bystander editing through directed evolution**

- Authors/Org: R.M. Perrotta et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Dec 2025** (18 Dec 2025)
- Link: <https://www.nature.com/articles/s41587-025-02937-w> [20]
- Why it matters: Integrates gRNA engineering, directed evolution, and protein-language-model design to reduce bystander editing while maintaining efficiency—directly aligned with the ART’s “tighter control” and incremental engineering pathway. [21]

#### **Delivery modalities and transient “payloads”**

#### **7) Lung and liver editing by lipid nanoparticle delivery of a stable CRISPR–Cas9 ribonucleoprotein**

- Authors/Org: K. Chen et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Oct 2024** (16 Oct 2024)
- Link: <https://www.nature.com/articles/s41587-024-02437-3> [22]
- Why it matters: Reports tissue-selective LNP formulations delivering a thermostable Cas9 RNP achieving **16–37%** editing in liver/lung after a single IV injection in reporter mice and

~19% editing of a disease gene in lung, supporting plausible scaling of transient, non-viral delivery beyond liver. [22]

### **8) Safer and efficient base editing and prime editing via ribonucleoproteins delivered through optimized lipid-nanoparticle formulations**

- Authors/Org: R. Hołubowicz et al.
- Venue/type: Nature Biomedical Engineering (peer-reviewed experimental paper)
- Publication date: **Nov 2024** (28 Nov 2024)
- Link: <https://www.nature.com/articles/s41551-024-01296-2> [23]
- Why it matters: Shows microfluidically mixed, chemically defined LNPs encapsulating base/prime editor RNPs can yield >300× in vivo editing-efficiency improvements over naked RNP delivery and reports “no detectable off-target edits,” directly addressing reliability + delivery bottlenecks. [24]

### **9) Engineered virus-like particles for transient delivery of prime editor ribonucleoprotein complexes in vivo**

- Authors/Org: M. An et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Jan 2024** (08 Jan 2024)
- Link: <https://www.nature.com/articles/s41587-023-02078-y> [25]
- Why it matters: Develops prime editor eVLPs delivering prime editor proteins + guide RNAs as transient RNPs, with **65–170×** higher editing than prior constructs and functional rescue signals in mouse retinal disease models—evidence of maturing transient payload packaging beyond LNPs. [25]

### **10) Efficient prime editing in mouse brain, liver and heart with dual AAVs**

- Authors/Org: J.R. Davis et al.
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **May 2023** (04 May 2023)
- Link: <https://www.nature.com/articles/s41587-023-01758-z> [26]
- Why it matters: Reports dual-AAV prime editor systems achieving up to **42%** editing in cortex, **46%** in liver, and **11%** in heart in mice, with “no detectable off-target effects” in tested contexts—strong plausibility evidence that prime editing can reach hard-to-edit tissues with clinically familiar vectors. [26]

### **Editing optimisation, design rules, and outcome prediction**

### **11) Systematic optimization of prime editing for the efficient functional correction of CFTR F508del in human airway epithelial cells**

- Authors/Org: A.A. Sousa et al.
- Venue/type: Nature Biomedical Engineering (peer-reviewed experimental/engineering paper)
- Publication date: **Jul 2024** (10 Jul 2024)
- Link: <https://www.nature.com/articles/s41551-024-01233-3> [27]
- Why it matters: Combines multiple engineering levers (e.g., PEmax/PE6 variants, engineered guides, transient mismatch-repair modulation) to raise F508del correction from <**0.5%** to **58%** in immortalised bronchial cells and **25%** in patient-derived airway cells, with edit-to-indel ratios exceeding nuclease HDR by ~3.5× and functional rescue to >50% of WT—clear PoC-level performance progress. [28]

## 12) Multimodal scanning of genetic variants with base and prime editing

- Authors/Org: (first author not shown in excerpt)
- Venue/type: Nature Biotechnology (peer-reviewed experimental paper)
- Publication date: **Nov 2024** (20 Nov 2024)
- Link: <https://www.nature.com/articles/s41587-024-02439-1> [29]
- Why it matters: Uses pooled base- and prime-editing guide libraries to install “tens of thousands” of variants across EGFR in multiple cell lines, demonstrating the high-throughput design→test→learn loop implied by the ART (software-like iteration backed by sequencing readouts). [29]

### Gene switching via epigenome editing (durable, reversible control)

## 13) Durable and efficient gene silencing in vivo by hit-and-run epigenome editing

- Authors/Org: M.A. Cappelluti et al.
- Venue/type: Nature (peer-reviewed experimental paper)
- Publication date: **Feb 2024** (28 Feb 2024)
- Link: <https://www.nature.com/articles/s41586-024-07087-8> [30]
- Why it matters: Demonstrates transient delivery of epigenome editors via LNP mRNA can produce long-lived gene silencing in vivo (PCSK9 nearly 1 year; persistence through liver regeneration), underpinning the ART’s “gene switching without rewriting sequence” pathway. [30]

## 14) A potent epigenetic editor targeting human PCSK9 for durable reduction of low-density lipoprotein cholesterol levels

- Authors/Org: F. Tremblay et al.
- Venue/type: Nature Medicine (peer-reviewed preclinical paper)
- Publication date: **Feb 2025** (10 Feb 2025)
- Link: <https://www.nature.com/articles/s41591-025-03508-x> [31]
- Why it matters: Reports a single dose of LNP mRNA encoding an epigenetic editor drives near-complete PCSK9 silencing in mice for ≥1 year and, in cynomolgus monkeys, ~90% PCSK9 protein reduction with ~70% LDL-C reduction—high-value maturity signal for scalable, non-sequence “switch-off” therapeutics (still preclinical). [31]

## 15) Programmable epigenome editing by transient delivery of CRISPR epigenome editor ribonucleoproteins (RENDER)

- Authors/Org: D. Xu et al.
- Venue/type: Nature Communications (peer-reviewed experimental paper)
- Publication date: **Aug 2025** (26 Aug 2025)
- Link: <https://www.nature.com/articles/s41467-025-63167-x> [32]
- Why it matters: Presents an eVLP-based platform for transient delivery of large epigenome-editor RNPs (CRISPRi/CRISPRoff and others) with durable silencing across human cell types including primary T cells, supporting the feasibility of transient, controllable gene-regulation payloads. [32]

### Off-target detection, QC, standards, and governance

## 16) Sensitive and unbiased genome-wide profiling of base-editor-induced off-target activity using CHANGE-seq-BE

- Authors/Org: C.R. Lazzarotto et al.
- Venue/type: Nature Biotechnology (peer-reviewed methods/experimental paper)

- Publication date: **Jan 2026** (02 Jan 2026)
- Link: <https://www.nature.com/articles/s41587-025-02948-7> [33]
- Why it matters: Introduces a sensitive, unbiased off-target discovery workflow for base editors and reports base-editor off-target profiles can differ substantially from nuclease methods (e.g., **98.8%** of validated off-target sites unique to ABE8e vs Cas9 nuclease in one comparison), illustrating why next-gen editors need editor-specific safety metrology to mature. [34]

### **17) Human Gene Therapy Products Incorporating Human Genome Editing: Guidance for Industry**

- Authors/Org: U.S. Food and Drug Administration[35] (CBER)
- Venue/type: Regulator guidance (authoritative report)
- Publication date: **Jan 2024**
- Link: <https://www.fda.gov/media/156894/download> [36]
- Why it matters: Sets explicit expectations for IND packages spanning product design, manufacturing/testing, nonclinical safety, and clinical trial design, and highlights risks such as off-target editing and unintended on-target consequences—evidence of governance maturity and a clearer translation pathway for new editors. [37]

### **18) Measurement solutions and standards for advanced therapy (meeting report)**

- Authors/Org: L. Wang et al.; National Institute of Standards and Technology[38]
- Venue/type: Meeting report in Molecular Therapy: Methods & Clinical Development (authoritative standards/roadmap evidence)
- Publication date: **Mar 2024** (published 01 Mar 2024)
- Link: [https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=957436](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=957436) [39]
- Why it matters: Documents inter-laboratory studies, working groups, and cross-sector workshops (including gene-delivery system metrology and genome-editing measurement efforts), signalling an emerging standardisation infrastructure needed for scalable, auditable editing. [39]

### **19) Variability in genome-engineering source materials: consider your starting point**

- Authors/Org: S. Patange et al.; National Institute of Standards and Technology[38]
- Venue/type: Synthetic Biology (peer-reviewed perspective with engineering framework)
- Publication date: **Mar 2023** (advance access 10 Mar 2023)
- Link: [https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=933768](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933768) [40]
- Why it matters: Identifies how genotype/phenotype variability and cell heterogeneity can confound genome engineering outcomes and provides a cause-and-effect framework—directly relevant to the ART's emphasis on repeatability, QC, and predictable outcomes across cell states. [41]

### **Market and regulatory maturity signals (cross-region)**

### **20) CASGEVY product approval information (FDA biologics page)**

- Authors/Org: U.S. Food and Drug Administration[35]; manufacturer listed as Vertex Pharmaceuticals[42]
- Venue/type: Regulator product page (authoritative product/regulatory evidence)
- Publication date: Page content current **Feb 2024** (content current as of 21 Feb 2024)
- Link: <https://www.fda.gov/vaccines-blood-biologics/casgev> [43]
- Why it matters: Confirms an approved genome-editing medicine exists with defined



indications, manufacturer, and regulatory documentation—evidence that genome editing has crossed into delivered products (even if “next-gen” modalities vary in maturity). [43]

## **21) MHRA authorisation announcement for Casgevy (world-first gene-editing therapy) with interim trial readouts**

- Authors/Org: Medicines and Healthcare products Regulatory Agency[44]
- Venue/type: Regulator press release with trial outcomes (authoritative)
- Publication date: **Nov 2023** (16 Nov 2023)
- Link: <https://www.gov.uk/government/news/mhra-authorises-world-first-gene-therapy-that-aims-to-cure-sickle-cell-disease-and-transfusion-dependent-thalassemia> [45]
- Why it matters: Provides regulator-published interim efficacy figures (e.g., **97%** free of severe pain crises for  $\geq 12$  months in eligible SCD participants; **93%** transfusion-independent for  $\geq 12$  months in eligible TDT participants) and confirms post-authorisation monitoring expectations—strong maturity signal for clinical adoption of genome editing. [45]

## **22) Casgevy EPAR (EU) indicating conditional marketing authorisation date**

- Authors/Org: European Medicines Agency[46]
- Venue/type: Regulator EPAR (authoritative)
- Publication date: **Feb 2024** (conditional marketing authorisation valid throughout EU on 9 Feb 2024; EPAR first published 28 Feb 2024)
- Link: <https://www.ema.europa.eu/en/medicines/human/EPAR/casgevy> [47]
- Why it matters: Independent regional authorisation confirms multi-jurisdiction regulatory acceptance for genome-editing therapeutics, supporting plausibility of future approvals for newer editor classes once safety/CMC evidence is adequate. [47]

## **3. Maturity score (1–7) and reasoning**

### **Final maturity score: 5**

The ART sits at **level 5** because (i) genome editing is already clearly beyond purely academic demonstrations (ruling out levels 1–3), and (ii) multiple editor classes and enabling technologies have crossed strong PoC thresholds with rapid iteration and translation signals, but (iii) the specific “next-generation” modalities (base/prime/epigenome editing and gene-sized insertions) are not yet broadly commercialised as routine, scaled products across many indications (so level 6 is not yet justified). [48]

### **Evidence-to-rubric mapping**

#### **What evidence rules out lower levels (why it is $\geq 4$ ):**

- There are multiple peer-reviewed in vivo demonstrations showing therapeutically relevant editing magnitudes and/or durable functional effects (e.g., prime editing in mouse cortex/liver/heart up to 42%/46%/11%; LNP-delivered stable Cas9 RNP achieving 16–37% organ editing; epigenetic editing producing near-year durability in vivo). [49]
- Several “previously blocking” bottlenecks highlighted in the ART—especially delivery and control—have direct experimental responses: transient RNP delivery via eVLPs (prime editing) and chemically defined LNP formulations that boost potency dramatically while emphasising low/no detectable off-target edits in stated assays. [50]
- For base editing, translation maturity is strongly signalled by IND-enabling work with quantitative correction in patient-relevant cell types (up to 70% mutation correction in HSPCs

with minimal off-target/bystander edits) and a published patient-specific in vivo base-editing intervention under regulatory approval. [51]

Together, these exceed “lab prototype only” (level 3) and meet PoC-style functional demonstrations (level 4). [52]

#### **Why level 5 (and not just level 4):**

- Rapidly improving capabilities for gene-sized insertion and DSB-free integration now reach ~10–30% efficiencies in human cells for kilobase cargoes (evoCAST), and PASTE demonstrates ~36 kb targeted integration across multiple human contexts—evidence of fast-paced post-PoC engineering with a credible path toward therapeutic/industrial prototypes. [53]

- The ecosystem is moving into scaling disciplines: regulator guidance targeted specifically at genome-editing products (manufacturing/testing, safety, clinical design) and government metrology/standards programmes documenting inter-lab studies and standardisation for gene delivery and editing measurement. [54]

- Cross-region authorisations of a genome-editing medicine (evidence of delivery to real patients under formal regulatory regimes) demonstrate that at least some genome-editing modalities have cleared major commercialisation gates, and those pathways can be re-used by next-generation editors as they mature. [55]

#### **What is still missing to justify level 6:**

- Broad, routine delivery of **next-generation editors** (base/prime/epigenome editors and gene-sized insertion tools) as marketed products with increasing volumes, not just in isolated cases or preclinical models; today’s strongest “delivered product” evidence is an approved nuclease-based genome-editing therapy rather than widespread approvals of base/prime/epigenome tools. [56]

- More public evidence of industrial-scale manufacturing expansion, consistent multi-site clinical trial outcomes for the newer editor classes, and mature reference standards/qualification frameworks widely adopted for editor-specific off-target and long-term safety. [57]

#### **Sub-score breakdown (bundle) and aggregation**

- **Approved, clinically delivered genome editing (nuclease CRISPR ex vivo) → 6**
- Support: regulatory product evidence and authorisations in multiple regions. [55]
- **Base editing (precision single-base repair; emerging in vivo use) → 5**
- Support: IND-enabling ex vivo HSPC correction up to 70% with minimal off-target/bystander edits; published patient-specific in vivo base-editing case under regulatory approval. [51]
- **Prime editing (versatile small edits; delivery still a key constraint) → 4**
- Support: high-efficiency in vivo mouse editing with dual AAV (up to 42% cortex, 46% liver); transient prime editor RNP delivery via engineered VLPs; but still largely preclinical. [58]
- **Gene-sized insertion / large payload writing (PASTE, CAST/evoCAST) → 4**
- Support: PASTE (~36 kb insertion across multiple human contexts) and evoCAST (~10–30% integration of kb cargoes across 14 loci) represent strong lab-to-prototype progress; still early for in vivo therapeutic deployment. [11]

- **Gene switching via epigenome editing (durable, reversible control without sequence rewrite) → 4**
- Support: durable in vivo silencing nearly 1 year after transient delivery; NHP reductions in PCSK9 (~90%) and LDL-C (~70%) with reversibility demonstration in mice; still preclinical. [6]
- **Measurement/QC/standards infrastructure (off-target discovery + inter-lab standards) → 4–5**
- Support: editor-specific, sensitive off-target profiling method (CHANGE-seq-BE) and active standards/ILS programmes; full standard adoption and universal qualification pathways still evolving. [59]

**Aggregation to one score:** Because these subthreads share a common value proposition (“more predictable, auditable, programmable edits”) but are at different translation stages, the overall ART score is best represented as an **average weighted by therapeutic maturity signals**, yielding **5** (with one sub-area already at 6, several at 4–5, and a clear metrology/regulatory ramp). [60]

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[1] [5] [11] [14] [15] <https://www.nature.com/articles/s41587-022-01527-4>

<https://www.nature.com/articles/s41587-022-01527-4>

[2] [13] [18] [51] [52] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11753194/>

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[3] [8] [33] [34] [46] [59] <https://www.nature.com/articles/s41587-025-02948-7>

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[4] [26] [38] [49] [58] <https://www.nature.com/articles/s41587-023-01758-z>

<https://www.nature.com/articles/s41587-023-01758-z>

[6] [30] <https://www.nature.com/articles/s41586-024-07087-8>

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[7] [10] [22] <https://www.nature.com/articles/s41587-024-02437-3>

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[9] [12] [36] [37] [54] <https://www.fda.gov/media/156894/download>

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[17] [53] <https://pubmed.ncbi.nlm.nih.gov/40373119/>

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[23] [24] <https://www.nature.com/articles/s41551-024-01296-2>

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[25] [50] <https://www.nature.com/articles/s41587-023-02078-y>

<https://www.nature.com/articles/s41587-023-02078-y>

[27] [28] <https://www.nature.com/articles/s41551-024-01233-3>

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[29] <https://www.nature.com/articles/s41587-024-02439-1>

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[31] [35] <https://www.nature.com/articles/s41591-025-03508-x>

<https://www.nature.com/articles/s41591-025-03508-x>

[32] <https://www.nature.com/articles/s41467-025-63167-x>

<https://www.nature.com/articles/s41467-025-63167-x>

[39] [57] [https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=957436](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=957436)

[https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=957436](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=957436)

[40] [41] [https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=933768](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933768)

[https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=933768](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933768)

[42] [43] [48] [55] [56] [60] <https://www.fda.gov/vaccines-blood-biologics/casgevy>

<https://www.fda.gov/vaccines-blood-biologics/casgevy>

[45] <https://www.gov.uk/government/news/mhra-authorises-world-first-gene-therapy-that-aims-to-cure-sickle-cell-disease-and-transfusion-dependent-thalassemia>

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[47] <https://www.ema.europa.eu/en/medicines/human/EPAR/casgevy>

<https://www.ema.europa.eu/en/medicines/human/EPAR/casgevy>

## ART 09.068 mRNA Therapies & Vaccines

### ART extraction

### Primary capability the ART claims

- A reconfigurable “software-defined” biopharmaceutical platform where changing the **mRNA sequence** changes the therapeutic or vaccine antigen/protein, while much of the synthesis, formulation, and QC workflow remains reusable across products. [1]
- Rapid design-to-manufacture iteration (including strain/variant updates) by leveraging platform manufacturing and prior clinical/quality knowledge, rather than rebuilding a bespoke process for each new target. [2]
- In vivo delivery of short-lived mRNA “instructions” via engineered carriers (predominantly lipid nanoparticles), enabling temporary protein expression in specific tissues for prophylaxis (vaccines) and therapy (e.g., protein replacement; immune priming; gene-editing payload delivery). [3]

### Key sub-components and variants

- **mRNA design layer:** sequence/UTRs/capping/poly(A) and nucleoside modification choices; for personalised products, per-patient sequence generation and tracking. [4]
- **Delivery carriers:** lipid nanoparticles (LNPs) and “tunable” LNP chemistries (ionisable/degradable lipids; supplementary components); alternative delivery systems (e.g., polymers) are explicitly contemplated by regulators. [5]
- **Targeting / biodistribution control:** organ- or tissue-selective LNP design approaches (e.g., selective organ targeting; formulation rules that bias delivery beyond the liver). [6]
- **Form-factor and stability innovations:** lyophilised mRNA-LNP powders; prefilled syringes; microneedle patch formats aimed at reducing cold-chain dependence and simplifying administration. [7]
- **Manufacturing & QC infrastructure:** scalable mixing/formulation methods (microfluidic mixing modules, scale-up workflows); validated analytics for identity, integrity, potency, encapsulation, lipid composition, and nanoparticles size/PDI; development of reference materials to standardise measurement. [8]
- **Safety constraints & monitoring:** innate immune activation / inflammatory adverse events (notably rare myocarditis/pericarditis signals for COVID-19 mRNA vaccines; infusion-related reactions in IV LNP-mRNA therapeutics), requiring surveillance, risk management, and in some cases premedication. [9]

### Maturity indicators that would count as strong evidence

- **Licensed / approved products** in multiple indications (not only pandemic COVID-19) and in multiple jurisdictions, with clear labelled storage/packaging and validated CMC. [10]
- **Large-scale lot/batch release and consistency** measured by regulators or national control labs across many batches, with trending and comparability evidence. [11]
- **Peer-reviewed human clinical efficacy/safety results** for non-vaccine therapeutics (protein replacement, personalised cancer vaccines, in vivo gene editing using LNP-delivered mRNA components). [12]
- **Delivery targeting improvements** demonstrated with reproducible in vivo data (e.g., organ-selective delivery, reduced off-target uptake, improved therapeutic index). [13]

- **Operational advances reducing deployment friction:** thermostability beyond ultra-cold storage; alternative administration formats (patches); scalable manufacturing equipment and workflows; emerging standards and reference materials. [14]

#### Evidence (10–20 recent, reliable sources)

##### 1) **Efficacy and Safety of an mRNA-Based RSV PreF Vaccine in Older Adults**

Authors/organisation: Eleanor Wilson[15] et al.

Venue/type: The New England Journal of Medicine[16] (peer-reviewed phase 2–3 randomised trial; PubMed record)

Publication date: Dec 2023

Link: <https://pubmed.ncbi.nlm.nih.gov/38091530/>

Concrete progress: Vaccine efficacy reported as 83.7% against RSV-associated LRTD with  $\geq 2$  signs/symptoms and 82.4% with  $\geq 3$  signs/symptoms in adults  $\geq 60$ , demonstrating a non-COVID mRNA vaccine can reach late-stage efficacy endpoints in a large trial. [17]

##### 2) **Summary Basis for Regulatory Action — MRESVIA (Respiratory Syncytial Virus Vaccine)**

Authors/organisation: U.S. Food and Drug Administration[18]

Venue/type: Regulatory approval dossier (CMC + clinical summary)

Publication date: May 2024

Link: <https://www.fda.gov/media/179634/download>

Concrete progress: Describes an approved mRNA-LNP RSV vaccine with defined composition (50  $\mu$ g nucleoside-modified mRNA; 4-lipid LNP), **prefilled syringe** presentations, and labelled storage/expiry (including allowance for limited 2–8°C storage), evidencing mature product packaging and regulated cold-chain parameters. [19]

##### 3) **mRESVIA EPAR Public Assessment Report**

Authors/organisation: European Medicines Agency[20]

Venue/type: Regulatory assessment report (quality + nonclinical + clinical)

Publication date: 2024 (report year on dossier; month not reliably extractable from captured lines)

Link: [https://www.ema.europa.eu/en/documents/assessment-report/mresvia-epar-public-assessment-report\\_en.pdf](https://www.ema.europa.eu/en/documents/assessment-report/mresvia-epar-public-assessment-report_en.pdf)

Concrete progress: Documents manufacturing-site GMP compliance, identifies the 4-lipid LNP composition, and discusses process validation/PPQ lots and lot comparability (including reliance on platform learnings from an existing mRNA product where LNP composition and equipment are shared), supporting “platform reuse” maturity claims. [21]

##### 4) **EUA Decision Memorandum for Moderna COVID-19 Vaccine (2024–2025 Formula)**

Authors/organisation: ModernaTX, Inc.[22] / U.S. Food and Drug Administration[18]

Venue/type: Regulatory decision memorandum (EUA amendment; includes CMC and safety rationale)

Publication date: Aug 2024

Link: <https://www.fda.gov/media/167306/download>

Concrete progress: Explicitly bases authorisation of an updated strain formulation on prior clinical and postmarketing evidence “manufactured using the same process,” and notes CMC information for a **pre-filled syringe presentation**, illustrating how rapid updates can leverage platform manufacturing and accumulated safety data. [23]



### 5) **Quality assurance and control — test results of COVID-19 mRNA vaccines from Pfizer and Moderna**

Authors/organisation: Therapeutic Goods Administration[24]

Venue/type: National control laboratory / regulator report on batch release testing

Publication date: Aug 2025

Link: <https://www.tga.gov.au/resources/publication/tga-laboratory-testing-reports/quality-assurance-and-control-test-results-covid-19-mrna-vaccines-pfizer-and-moderna>

Concrete progress: Reports testing of 167 batches supplied in Australia (RNA identity/content/integrity/potency; encapsulation; lipid identity/content; LNP size/PDI; endotoxin) with all batches passing specifications and showing high comparability; this is direct evidence of industrial-scale QC and consistent manufacture. [25]

### 6) **Progress reports — Strengthening local production of medicines and health technologies (includes mRNA technology transfer hub update)**

Authors/organisation: World Health Organization[26]

Venue/type: Authoritative multilateral programme report (World Health Assembly document)

Publication date: May 2025

Link: [https://apps.who.int/gb/ebwha/pdf\\_files/WHA78/A78\\_34Rev1-en.pdf](https://apps.who.int/gb/ebwha/pdf_files/WHA78/A78_34Rev1-en.pdf)

Concrete progress: States that the mRNA technology transfer hub developed an effective COVID-19 mRNA construct and is transferring it to 15 partners across six WHO regions, evidencing ecosystem-building for distributed manufacturing capacity (a precursor to platform scaling beyond a few originator firms). [27]

### 7) **Individualised neoantigen therapy mRNA-4157 (V940) plus pembrolizumab versus pembrolizumab monotherapy in resected melanoma (KEYNOTE-942)**

Authors/organisation: Jeffrey S Weber[28] et al.

Venue/type: The Lancet[29] (peer-reviewed randomised phase 2b study)

Publication date: Feb 2024

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S0140673623022687>

Concrete progress: Reports improved recurrence-free survival signals for a **personalised mRNA neoantigen** product combined with checkpoint blockade (HR for recurrence/death 0.561; 18-month RFS 79% vs 62%), demonstrating feasibility and clinical traction of per-patient mRNA “recipes” beyond prophylactic vaccines. [30]

### 8) **Interim analyses of a first-in-human phase 1/2 mRNA trial for propionic acidemia**

Authors/organisation: Dwight Koeberl[31] et al.

Venue/type: Nature[32] (peer-reviewed first-in-human therapeutic trial)

Publication date: Apr 2024

Link: <https://www.nature.com/articles/s41586-024-07266-7>

Concrete progress: In a first-in-human study of IV LNP-delivered dual mRNA (PCCA/PCCB), 346 doses over 15.69 person-years with no dose-limiting toxicities were reported, alongside a preliminary 70% reduction in risk of metabolic decompensation events in participants who had events pre-treatment—strong evidence that repeat-dose therapeutic mRNA is clinically plausible and measurable with biomarkers. [33]

### 9) **CRISPR-Based Therapy for Hereditary Angioedema (NTLA-2002)**

Authors/organisation: Intellia Therapeutics[34] (sponsor; trial paper authors include

academic and industry clinicians)

Venue/type: Peer-reviewed randomised clinical trial (via PubMed abstract record)

Publication date: 2024 (year from PubMed record; month not reliably extractable from captured lines)

Link: <https://pubmed.ncbi.nlm.nih.gov/39445704/>

Concrete progress: A single dose of an in vivo CRISPR therapy showed large reductions in hereditary angioedema monthly attack rates vs placebo ( $\approx 75$ – $77\%$  lower mean attack rate;  $40$ – $73\%$  attack-free in treated groups) with pharmacodynamic lowering of plasma kallikrein, illustrating that LNP delivery of mRNA gene-editing components can support clinically meaningful endpoints. [35]

#### 10) **Nexiguran ziclumeran gene editing in hereditary ATTR with polyneuropathy**

Authors/organisation: Julian D Gillmore[36] et al.; funded by Intellia Therapeutics[34] and Regeneron Pharmaceuticals[37]

Venue/type: Peer-reviewed clinical trial (via PubMed record)

Publication date: Sep 2025 (Epub)

Link: <https://pubmed.ncbi.nlm.nih.gov/41002250/>

Concrete progress: Reports that a single administration was associated with rapid, deep, and durable reductions in serum transthyretin levels with follow-up functional measures reported at month 24—evidence that LNP-mediated delivery of mRNA-based gene-editing payloads is moving beyond early proof-of-principle into longer-term human outcome tracking. [38]

#### 11) **Preparation of selective organ-targeting (SORT) lipid nanoparticles (LNPs) for tissue-specific mRNA delivery**

Authors/organisation: Xu Wang[39] et al.

Venue/type: Nature Protocols[40] (peer-reviewed protocol with in vivo evaluation workflow)

Publication date: Oct 2022

Link: <https://www.nature.com/articles/s41596-022-00755-x>

Concrete progress: Provides a reproducible, modular workflow for creating organ-targeted LNPs (including microfluidic mixing options) and outlines timelines for synthesis/formulation/characterisation/in vivo evaluation, supporting plausibility of “tunable delivery” as an engineering discipline rather than bespoke art. [41]

#### 12) **Artificial intelligence-driven rational design of ionizable lipids for mRNA delivery**

Authors/organisation: Wang Wang[42] et al.

Venue/type: Nature Communications[43] (peer-reviewed; data-driven delivery-material discovery)

Publication date: Dec 2024

Link: <https://www.nature.com/articles/s41467-024-55072-6>

Concrete progress: Uses AI/virtual screening to predict key LNP properties and accelerate ionisable lipid design, directly supporting the ART’s claim that delivery carriers can become more reliable and “engineering-optimised” (potentially reducing the iteration cost of new mRNA products). [44]

#### 13) **Fast and facile synthesis of amidine-incorporated degradable lipids for versatile mRNA delivery in vivo**

Authors/organisation: Xuexiang Han[45] et al.

Venue/type: Nature Chemistry[46] (peer-reviewed experimental paper)

Publication date: Jul 2024 (Epub; accepted May 2024 in PDF)

Link: <https://mitchell-lab.seas.upenn.edu/wp-content/uploads/2024/07/s41557-024-01557-2.pdf>

Concrete progress: Demonstrates a one-pot reaction enabling ~1-hour room-temperature synthesis of a 100-lipid library and shows a lead degradable lipid that supports systemic mRNA delivery and can redirect tropism (e.g., lung/spleen targeting by formulation adjustment), addressing the ART bottleneck of precise targeting without off-target uptake.

[47]

#### 14) **Morphological Characterization of Self-Amplifying mRNA Lipid Nanoparticles**

Authors/organisation: Jacob Thelen[48] et al.; published via ACS Nano[49] with a summary hosted by National Institute of Standards and Technology[50]

Venue/type: Peer-reviewed experimental characterisation study (small-angle scattering / morphology)

Publication date: Jan 2024

Link: <https://www.nist.gov/publications/morphological-characterization-self-amplifying-mrna-lipid-nanoparticles>

Concrete progress: Reports structural morphology findings for self-amplifying mRNA LNPs (including evidence of multi-compartment “bleb” structures and modelling), strengthening plausibility for dose-sparing RNA constructs and for more rigorous structure–function design rules in mRNA delivery systems. [51]

#### 15) **A microneedle vaccine printer for thermostable COVID-19 mRNA vaccines**

Authors/organisation: Aurélien vander Straeten[52] et al.

Venue/type: Nature Biotechnology[53] (peer-reviewed prototype demonstration)

Publication date: 2024 (journal volume year; month not required for core claims captured here)

Link: <https://www.nature.com/articles/s41587-023-01774-z>

Concrete progress: Demonstrates an automated process to produce dissolvable microneedle patches containing mRNA-LNP “ink,” with reported shelf stability ≥6 months at room temperature (for a model construct) and mouse immunogenicity comparable to intramuscular dosing, supporting the ART’s anticipated move from vials toward patch-like applicators and relaxed cold-chain logistics. [54]

#### 16) **Lyophilization provides long-term stability for a lipid nanoparticle-formulated, nucleoside-modified mRNA vaccine**

Authors/organisation: Hiromi Muramatsu[55] et al.

Venue/type: Molecular Therapy[56] (peer-reviewed experimental paper)

Publication date: May 2022

Link: <https://www.sciencedirect.com/science/article/pii/S1525001622000843>

Concrete progress: Shows that mRNA-LNP vaccines can be lyophilised with physicochemical properties preserved for 12 weeks at room temperature and ≥24 weeks at 4°C, retaining in vivo expression and vaccine immunogenicity in mice—directly relevant to overcoming cold-chain constraints. [57]

#### 17) **LNP-RNA Research Grade Test Material project**

Authors/organisation: National Institute of Standards and Technology[50]

Venue/type: Authoritative standards/metrology initiative (reference material + interlab study)

Publication date: Created Jul 2024 (updated Mar 2025)

Link: <https://www.nist.gov/programs-projects/lnp-rna-research-grade-test->

## material

Concrete progress: Describes a planned LNP/RNA research-grade test material intended to standardise measurement of critical quality attributes (RNA copy number/integrity/encapsulation; LNP size/morphology; lipid purity), signalling maturation of shared metrology foundations needed for reliable, software-like scaling of mRNA products. [\[58\]](#)

### 18) Draft Guideline on the quality aspects of mRNA vaccines

Authors/organisation: European Medicines Agency[\[20\]](#) (CHMP/BWP draft for consultation)

Venue/type: Authoritative regulatory guideline (quality/CMC)

Publication date: Mar 2025

Link: [https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines\\_en.pdf](https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines_en.pdf)

Concrete progress: Explicitly addresses manufacturing, characterisation, specifications, and regulatory considerations for strain updates, multivalent vaccines, self-amplifying mRNA, other delivery systems, and the “platform technology/prior knowledge” approach—strong evidence that regulators are formalising repeatable pathways consistent with a platform scaling model. [\[59\]](#)

### 19) Cardiac Complications After SARS-CoV-2 Infection and mRNA COVID-19 Vaccination

Authors/organisation: Centers for Disease Control and Prevention[\[60\]](#)

Venue/type: Public health surveillance analysis (MMWR)

Publication date: Apr 2022

Link: <https://www.cdc.gov/mmwr/volumes/71/wr/mm7114e1.htm>

Concrete progress: Reports that, across ages/sexes, the risk for cardiac complications (including myocarditis/pericarditis outcomes) was higher after SARS-CoV-2 infection than after mRNA vaccination—relevant to the ART’s “rare inflammatory reactions” constraint and the benefit–risk framing that affects adoption and regulatory posture. [\[61\]](#)

### 20) Safety of COVID-19 vaccines — myocarditis and pericarditis

Authors/organisation: European Medicines Agency[\[20\]](#)

Venue/type: Regulator safety monitoring page

Publication date: Jun 2023 (page date)

Link: <https://www.ema.europa.eu/en/human-regulatory-overview/public-health-threats/coronavirus-disease-covid-19/covid-19-medicines/safety-covid-19-vaccines>

Concrete progress: States myocarditis/pericarditis have been observed in *very rare* cases with mRNA COVID vaccines and typically occur within 14 days, underscoring a persistent platform constraint (innate/inflammatory adverse reactions) that must be managed as indications expand and dosing regimens evolve. [\[62\]](#)

## Maturity score (1–7) and reasoning

### Final maturity score

6

### Evidence-to-rubric mapping

### Why the evidence rules out levels 1–5

The ART is well beyond theory, lab validation, or single-prototype PoC because multiple

mRNA-LNP vaccines have entered regulated markets with documented CMC controls, packaging, expiry dating, and formal benefit–risk assessments. [63]

It is also beyond a single-company early commercial pilot: national regulators have executed **large-scale batch release testing** across many batches with extensive analytical panels (identity, integrity, potency, encapsulation, LNP size/PDI, lipid identity/content) and report consistent compliance and comparability. [11]

In parallel, the platform is actively expanding into **non-vaccine therapeutic modalities** with peer-reviewed human evidence—ranging from personalised cancer vaccines in randomised adjuvant melanoma (phase 2b) to repeat-dose IV mRNA protein replacement in a rare disease (phase 1/2), plus in vivo gene-editing programmes that depend on delivery of mRNA components and show clinically meaningful pharmacodynamic/clinical endpoints. [64]

### Why the evidence supports level 6 specifically

Level 6 requires “products are being delivered to customers in increasing amounts; application areas are expanding; expansion of production has been clearly financed; and progress is recent.” The strongest direct indicators here are:

- **Commercial delivery with regulator-confirmed lot consistency:** the Australian regulator reports 167 tested batches supplied nationally with no adverse quality trends, a hallmark of scaled delivery and quality system maturity. [25]
- **Expansion beyond COVID into additional licensed products and formats:** the FDA’s RSV vaccine approval documentation describes an mRNA-LNP vaccine supplied as prefilled syringes with defined storage/expiry claims, and the EMA EPAR documents multi-site process qualification and platform comparability logic. [10]
- **Platform-friendly regulatory formalisation:** the EMA draft guideline explicitly addresses strain updates, multivalent constructs, self-amplifying mRNA, and a platform/prior-knowledge approach—an institutional prerequisite for high-frequency updates and broad platform pipelines. [59]
- **Scaling enablers moving into standardisation:** metrology and reference materials for LNP/RNA characterisation are being developed by NIST, supporting interoperability and repeatability across labs and manufacturers. [58]
- **Distributed capacity building underway:** the WHO reports technology transfer from the mRNA hub to multiple partners across regions—evidence of efforts to broaden manufacturing participation beyond a few originators, which aligns with platform scaling over time. [27]

Together, these meet level 6’s emphasis on real product delivery plus expansion and infrastructure maturing (QC, regulatory pathways, and manufacturing ecosystems). [65]

### What is missing to justify level 7

Level 7 implies broad, competitive delivery with *rising* customer demand and strong internally financed competition across applications. While mRNA vaccines clearly have competing products and massive historical deployment, the evidence set here does not demonstrate **rising demand across the platform as a whole**, nor does it show widespread commercial delivery of mRNA therapeutics across multiple non-vaccine indications. The clearest therapeutic programmes are still in clinical trial phases (e.g., phase 2b for personalised melanoma vaccines; phase 1/2 for protein replacement; early-to-mid stage for in vivo gene editing), and key future enablers—high-precision targeting to diverse tissues, truly cold-

chain-independent formulations at scale, and streamlined regulation for frequent personalised updates—are advancing but not yet routine commercial practice. [66] In addition, safety constraints (rare inflammatory events for vaccines; infusion-related reactions in IV LNP therapeutics) remain non-trivial and continue to shape product design and surveillance expectations, which is consistent with an expanding—but not yet fully “frictionless”—platform. [9]

### Sub-score breakdown and aggregation approach

Because this ART bundles multiple application areas whose maturities differ meaningfully, the score is an **average-weighted platform view**, not the maximum.

- **Infectious-disease mRNA vaccines (COVID + RSV): maturity ~6–7** (licensed products, regulator-tested batch consistency, strain updates leveraging platform processes). Key sources: [67]
- **mRNA therapeutics (protein replacement; personalised cancer immunotherapy): maturity ~4–5** (human trials with clinically relevant endpoints; phase 2b randomised efficacy signal in melanoma; ongoing phase 1/2 for rare-disease protein replacement). Key sources: [68]
- **In vivo gene-editing therapies using LNP-delivered mRNA components: maturity ~4–5** (randomised placebo-controlled outcomes for hereditary angioedema; longer-term follow-up emerging in ATTR-PN). Key sources: [69]
- **Next-generation delivery targeting (organ-selective / retuned LNPs): maturity ~3–4** (repeatable engineering workflow; strong preclinical tooling; still not broadly proven at commercial scale across many tissues/indications). Key sources: [70]
- **Cold-chain-relaxed presentations (lyophilised; microneedle patches): maturity ~3–4** (validated stability gains in peer-reviewed studies; promising devices; not yet the dominant commercial presentation). Key sources: [71]
- **Manufacturing/QC standardisation and regulatory scaffolding: maturity ~5–6** (formal guideline development; national lot testing; reference material initiatives). Key sources: [72]

Aggregating these into a single ART-wide score yields **6** because the platform’s core function—regulated manufacture and delivery of mRNA vaccines at scale with expanding indications—is already in mature operational reality, while several future-defining capabilities (precision targeting, stable “patch/powder-first” logistics, routine personalised updates) remain earlier-stage. [73]

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[1] [7] [10] [19] [49] [56] [63] [67] [73] <https://www.fda.gov/media/179634/download>

<https://www.fda.gov/media/179634/download>

[2] [16] [23] <https://www.fda.gov/media/167306/download>

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[3] [12] [33] [36] [52] [53] <https://www.nature.com/articles/s41586-024-07266-7>

<https://www.nature.com/articles/s41586-024-07266-7>



[4] [5] [29] [46] [59] [72] [https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines\\_en.pdf](https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines_en.pdf)

[https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines\\_en.pdf](https://www.ema.europa.eu/en/documents/scientific-guideline/draft-guideline-quality-aspects-mrna-vaccines_en.pdf)

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<https://www.ema.europa.eu/en/human-regulatory-overview/public-health-threats/coronavirus-disease-covid-19/covid-19-medicines/safety-covid-19-vaccines>

[11] [25] [26] [39] [43] [50] [65] <https://www.tga.gov.au/resources/publication/tga-laboratory-testing-reports/quality-assurance-and-control-test-results-covid-19-mrna-vaccines-pfizer-and-moderna>

<https://www.tga.gov.au/resources/publication/tga-laboratory-testing-reports/quality-assurance-and-control-test-results-covid-19-mrna-vaccines-pfizer-and-moderna>

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[15] [17] <https://pubmed.ncbi.nlm.nih.gov/38091530/>

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[20] [35] [69] <https://pubmed.ncbi.nlm.nih.gov/39445704/>

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[24] [54] <https://www.nature.com/articles/s41587-023-01774-z>

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[27] [37] [https://apps.who.int/gb/ebwha/pdf\\_files/WHA78/A78\\_34Rev1-en.pdf](https://apps.who.int/gb/ebwha/pdf_files/WHA78/A78_34Rev1-en.pdf)

[https://apps.who.int/gb/ebwha/pdf\\_files/WHA78/A78\\_34Rev1-en.pdf](https://apps.who.int/gb/ebwha/pdf_files/WHA78/A78_34Rev1-en.pdf)

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[38] <https://pubmed.ncbi.nlm.nih.gov/41002250/>

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[51] <https://www.nist.gov/publications/morphological-characterization-self-amplifying-mrna-lipid-nanoparticles>

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[58] <https://www.nist.gov/programs-projects/lnp-rna-research-grade-test-material>

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[61] <https://www.cdc.gov/mmwr/volumes/71/wr/mm7114e1.htm>

<https://www.cdc.gov/mmwr/volumes/71/wr/mm7114e1.htm>

## ART 09.069 Cellular Agriculture & Cultured Meat

### ART extraction

#### A) Primary capability claimed (1–3 bullets)

- Produce animal-like foods (meat-like cell mass and structured muscle/fat tissues) by expanding animal cells in controlled bioreactors instead of raising whole animals. [1]
- Produce functional food components and/or bulk protein biomass via microbial cultivation (“precision fermentation” and gas-fed single-cell protein), potentially using CO<sub>2</sub> plus H<sub>2</sub> generated by renewable-electricity-driven water electrolysis. [2]
- Deliver more consistent output (composition, safety, traceability) by industrial-style process control: dense sensing, asepsis/contamination controls, and documented batch procedures akin to biomanufacturing. [3]

#### B) Key sub-components / variants (3–7 sub-threads)

- **Cell lines & cell banking:** robust, stable lines; (ideally) high-growth, suspension-adapted, food-safe cell banks; sometimes using non-GMO immortalisation routes. [4]
- **Culture media:** serum-free / animal-component-free formulations; growth-factor cost reduction; potential media recycling and waste management. [5]
- **Bioreactor scale-up & intensified operation:** stirred-tank vs airlift vs perfusion/continuous strategies; oxygen transfer, shear, and high cell density as central constraints. [6]
- **Tissue structuring:** edible scaffolds and structured growth environments to achieve

muscle/fat-like textures; hybrid plant+cell approaches. [7]

- **Quality systems & contamination control:** aseptic operations, environmental monitoring, validated sanitation, HACCP-style plans, traceability, and in-process testing (including viral/mycoplasma risk management). [3]

- **Precision fermentation (ingredient track):** engineered microbes producing discrete proteins (e.g., dairy/egg proteins) with food regulatory pathways (GRAS in the US). [8]

- **Gas fermentation / electro-bioprocessing (biomass track):** hydrogen-oxidising bacteria or chemolithoautotrophs converting  $\text{CO}_2 + \text{H}_2$  (+  $\text{O}_2$ ) into protein-rich biomass; includes  $\text{H}_2$  handling and gas–liquid mass transfer engineering. [9]

### C) Maturity indicators for this ART (what would count as strong evidence)

- **Validated high-density processes** (e.g.,  $\geq 10^8$  cells/mL for animal cells; high protein fraction for microbial biomass) sustained over meaningful durations or multiple harvest cycles. [10]

- **Techno-economic analyses grounded in realistic bioreactor scaling** showing plausible pathways toward competitive cost of goods (COGS) and identifying dominant cost drivers (media, energy, reactors, downstream). [11]

- **Regulatory progress** (pre-market consultation closures, GRAS “no questions” letters, novel food approvals) and documented compliance frameworks (GMP/HACCP equivalents). [12]

- **Real-world market evidence** beyond tastings: inspected production facilities, repeatable batches, and early commercial sales (even if limited). [13]

- **Scale-up hardware demonstrations** (pilot-plant /  $\geq 100$  L–300 L class bioreactors for gas fermentation; larger installations and supply-chain readiness for cultivated animal cells). [14]

### Evidence (10–20 recent, reliable sources)

#### 1) Empirical economic analysis shows cost-effective continuous manufacturing of cultivated chicken using animal-free medium

Authors/organisation: Laura Pasitka et al.

Venue/type: *Nature Food* (peer-reviewed paper)

Publication date: Aug 2024 (published 21 Aug 2024)

Link: <https://www.nature.com/articles/s43016-024-01022-w>

Concrete progress: Demonstrates continuous manufacturing with tangential flow filtration sustaining multiple harvests for >20 days and achieving up to  $130 \times 10^6$  cells/mL (reported as 43% w/v yield), directly addressing manufacturability and yield—two core plausibility/maturity constraints. [15]

#### 2) Spontaneous immortalization of chicken fibroblasts generates stable, high-yield cell lines for serum-free production of cultured meat

Authors/organisation: L. Pasitka et al.

Venue/type: *Nature Food* (peer-reviewed paper)

Publication date: 2023 (vol. 4, pp. 35–50)

Link: <https://www.nature.com/articles/s43016-022-00658-w>

Concrete progress: Reports non-GMO (“spontaneous”) immortalised chicken fibroblast lines adapted to suspension and serum-free culture reaching  $108 \times 10^6$  cells/mL (36% w/v yield) and demonstrating adipogenesis plus a hybrid product concept where cultured fat drives flavour. [16]

#### 3) Simple and effective serum-free medium for sustained expansion of bovine satellite cells for cell cultured meat

Authors/organisation: Andrew J. Stout et al.

Venue/type: *Communications Biology* (peer-reviewed paper; open access)

Publication date: Jun 2022 (published 2 Jun 2022)

Link: <https://www.nature.com/articles/s42003-022-03423-8>

Concrete progress: Demonstrates sustained bovine satellite-cell expansion in a serum-free medium (“Beefy-9”) with ~39 h average doubling time across seven passages, supporting feasibility of serum-free growth—critical for cost, safety, and regulatory acceptability. [17]

#### 4) **Plant-based biomaterials as scaffolds for cellular agriculture**

Authors/organisation: Woo-Ju Kim et al.

Venue/type: *Future Foods* (peer-reviewed paper)

Publication date: Dec 2024 (Vol. 10, Dec 2024)

Link: <https://www.sciencedirect.com/science/article/pii/S2666833524001679>

Concrete progress: Evaluates food-grade gels (pectin/alginate and plant proteins) as edible scaffolds; reports rheological/texture performance (e.g., storage modulus >1000 Pa for selected gels) and shows 3D-printed pectin scaffolds supporting animal-cell proliferation over 5 days—direct evidence for structured-tissue enabling components. [18]

#### 5) **Exploring cost reduction strategies for serum free media development**

Authors/organisation: Jun Ping Quek et al.

Venue/type: *npj Science of Food* (peer-reviewed review; open access)

Publication date: Dec 2024 (published 21 Dec 2024)

Link: <https://www.nature.com/articles/s41538-024-00352-0>

Concrete progress: Synthesises cost drivers in serum-free media (growth factors/recombinant proteins and basal media inputs) and highlights approaches like cheaper factor production, alternative raw materials, and media recycling—evidence for a known cost bottleneck and active R&D pathways to relieve it. [19]

#### 6) **Techno-economic modeling and assessment of cultivated meat: Impact of production bioreactor scale**

Authors/organisation: Patrick G. Negulescu et al.

Venue/type: *Biotechnology and Bioengineering* (peer-reviewed paper; indexed summary)

Publication date: 2023

Link: <https://pubmed.ncbi.nlm.nih.gov/36581609/>

Concrete progress: Quantifies how scale and reactor choice drive COGS, presenting scenarios such as ~42,000 L stirred-tank (COGS ~\$35/kg), ~211,000 L stirred-tank (~\$25/kg), and ~262,000 L airlift (~\$17/kg), clarifying what “industrial scale” implies and what must improve to reach commercial viability. [20]

#### 7) **Environmental Impacts of Cultured Meat: A Cradle-to-Gate Life Cycle Assessment**

Authors/organisation: Derrick Risner et al.

Venue/type: *ACS Food Science & Technology* (peer-reviewed paper; open access via PMC)

Publication date: 2024 (eCollection listed in PubMed/PMC record)

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11744764/>

Concrete progress: Uses updated TEA-derived process assumptions to show near-term animal-cell-based meat could have higher environmental impacts than beef if highly refined growth media are used, strengthening the “constraints” side of the dossier (media processing and input supply chain are decisive for scaling). [21]

## 8) Food safety aspects of cell-based food

Authors/organisation: World Health Organization[22] & Food and Agriculture Organization of the United Nations[23]

Venue/type: Joint authoritative report / publication

Publication date: Mar 2023 (28 Mar 2023)

Link: <https://www.who.int/publications/i/item/9789240070943>

Concrete progress: Provides a structured hazard-and-controls view (inputs, production steps, potential biological/chemical hazards, and regulatory approaches internationally), which is directly usable for evaluating plausibility of safe scale-up and the maturity of regulatory/scientific consensus-building. [24]

## 9) Cell Culture Consultation 000002 – Scientific Memo (cultured chicken cell material)

Authors/organisation: U.S. Food and Drug Administration[25]

Venue/type: Government technical memo (regulatory scientific review)

Publication date: Nov 2022 (published 14 Nov 2022)

Link: <https://www.fda.gov/media/163261/download>

Concrete progress: Documents the agency's scientific review of a cultured chicken process (cell banking, proliferation/differentiation, hazard controls, testing, and monitoring) and states it has “no questions” regarding the firm's safety conclusion—strong maturity evidence that a specific process has passed real regulatory scrutiny. [26]

## 10) Cell-cultivated meat: an overview

Authors/organisation: Congressional Research Service[27]

Venue/type: Government report (policy + technical/regulatory synthesis)

Publication date: Sep 2023

Link: <https://www.congress.gov/crs-product/R47697>

Concrete progress: Summarises the US regulatory pathway and records milestone market events, including facility inspection grants and early restaurant sales dates for cell-cultivated chicken—evidence that the technology has moved beyond lab prototypes into regulated, customer-facing pilots. [28]

## 11) The safety of cell culture-derived food – ready for scientific evaluation

Authors/organisation: European Food Safety Authority[29]

Venue/type: Regulator publication (preparedness / risk assessment context)

Publication date: May 2023 (published 10 May 2023)

Link: <https://www.efsa.europa.eu/en/news/safety-cell-culture-derived-food-ready-scientific-evaluation>

Concrete progress: Shows EU-level regulatory preparation (scientific colloquium, risk assessment readiness) and explicitly notes that, at the time, EFSA had not yet evaluated cultured animal-cell foods—important for maturity assessment across regions and for forecasting approval timelines. [30]

## 12) How do microbial safety issues associated with meat apply to cell cultivated products?

Authors/organisation: Food Standards Agency[31] (FSA Research and Evidence; authored report entry)

Venue/type: Government research report (hazard identification + evidence gaps)

Publication date: Sep 2025 (24 Sep 2025)

Link: <https://science.food.gov.uk/article/144237-how-do-microbial-safety->

### issues-associated-with-meat-apply-to-cell-cultivated-products

Concrete progress: Assembles literature plus expert elicitation to identify where microbial hazards can enter cell-cultivated production and what monitoring/mitigations are credible (EMP, asepsis, PAT-style monitoring), reinforcing that contamination control is a first-order scaling limiter. [32]

### 13) GRAS Notice (GRN) 001145 – Agency response letter ( $\beta$ -lactoglobulin)

Authors/organisation: (US) FDA letter responding to Imagindairy Ltd. [33]

Venue/type: Government regulatory letter (GRAS “no questions”)

Publication date: Dec 2023 (digitally signed 18 Dec 2023)

Link: <https://www.fda.gov/media/187530/download>

Concrete progress: Concludes FDA has “no questions” about the firm’s GRAS conclusion for  $\beta$ -lactoglobulin produced by *Aspergillus oryzae* for use as a protein ingredient—maturity evidence that precision-fermented animal-identical proteins are entering mainstream regulatory pathways. [34]

### 14) GRAS Notice (GRN) 001249 – Agency response letter (ovalbumin preparation)

Authors/organisation: FDA letter responding to Onego Bio, Inc. [35]

Venue/type: Government regulatory letter (GRAS “no questions”)

Publication date: Sep 2025 (filed/issued September 2025)

Link: <https://www.fda.gov/media/188998/download>

Concrete progress: Provides a “no questions” response for an ovalbumin ingredient intended to replace egg/egg-white proteins in foods (with allergen-labelling considerations), demonstrating expanding regulatory acceptance of fermentation-derived functional proteins. [36]

### 15) Simultaneous biogas upgrading and single cell protein production using hydrogen oxidizing bacteria

Authors/organisation: Rui Li et al.

Venue/type: *Chemical Engineering Journal* (peer-reviewed paper)

Publication date: Jun 2024 (15 Jun 2024)

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S1385894724030638>

Concrete progress: Demonstrates  $H_2$ -oxidising bacteria upgrading biogas (e.g.,  $CH_4$  from 57.09% to 98.46% in 72 h; max  $CO_2$  assimilation efficiency 27 mL/(L·h)) while producing protein-rich biomass (up to ~70.83% protein) and includes a techno-economic comparison—direct evidence for the “ $CO_2/H_2$ -fed microbial protein” track plus its engineering/safety considerations. [37]

### 16) Performance of a pilot scale pressurized deep-jet gas bioreactor for SCP production with *Cupriavidus necator* H16

Authors/organisation: Kay Domenico Novak et al.

Venue/type: *Journal of Biotechnology* (peer-reviewed paper)

Publication date: Dec 2025 (Vol. 408, Dec 2025)

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S0168165625002159>

Concrete progress: Reports a custom 300-L pressurised gas bioreactor for  $CO_2$ -to-protein biomass with high gas transfer, achieving up to 90 g/L cell dry weight and ~80% crude protein,



with reported H<sub>2</sub>/O<sub>2</sub>/CO<sub>2</sub> consumption rates—strong scale-up evidence beyond benchtop for gas-fed protein systems. [38]

#### 17) **A novel electrolytic gas lift reactor for efficient microbial electrosynthesis of hydrogen-oxidizing bacterial single-cell protein from CO<sub>2</sub>**

Authors/organisation: Jinpeng Yu et al.

Venue/type: *Systems Microbiology and Biomanufacturing* (peer-reviewed paper)

Publication date: Jun 2025 (published online 18 Jun 2025)

Link: <https://journal.hep.com.cn/smab/EN/10.1007/s43393-025-00336-5>

Concrete progress: Demonstrates an integrated electrolysis + gas-lift bioreactor design for HOB-based SCP with reported maximum biomass yield of 0.20 g CDW/L/day, protein content 58.3%, and reported H<sub>2</sub> utilisation efficiency of 100%, directly supporting plausibility of tighter coupling between renewable electricity and microbial protein production. [39]

#### 18) **Global potential of sustainable single-cell protein based on variable renewable electricity**

Authors/organisation: Mahdi Fasihi et al.

Venue/type: *Nature Communications* (peer-reviewed paper; open access)

Publication date: Feb 2025 (published 10 Feb 2025)

Link: <https://www.nature.com/articles/s41467-025-56364-1>

Concrete progress: Provides a geographically resolved “power-to-protein” scale-up roadmap (industrial-scale start ~2028) and explicit cost trajectories for renewable-electricity-based protein (e.g., ~5.5–6.1 €/kg in 2028 at best sites, falling further by 2030 and beyond), supporting plausibility while also highlighting that large-scale deployment is still forward-looking. [40]

#### 19) **Singapore first to approve protein ‘made from air’**

Authors/organisation: Singapore Economic Development Board[41] (describing approval by Singapore Food Agency[42]); mentions Solar Foods[43] and its product Solein

Venue/type: Government-agency insight article (regulatory milestone description)

Publication date: Oct 2022 (27 Oct 2022)

Link: <https://www.edb.gov.sg/en/business-insights/insights/singapore-first-to-approve-protein-made-from-air.html>

Concrete progress: Reports Singapore’s approval of Solein and describes the process concept (microbes fed with H<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>; electrolysis and direct air capture framing) and product characteristics (65–70% protein; nine essential amino acids), giving a concrete regulatory and early-market anchor point for CO<sub>2</sub>/H<sub>2</sub>-based microbial protein. [44]

### **Maturity score (1–7) and reasoning**

#### **Final maturity score: 5**

#### **Why this is at least level 5 (rules out levels 1–4)**

- Cultivated animal-cell food has progressed beyond lab proof-of-principle into **regulated production prototypes**: US pre-market consultations have been closed (“no questions” conclusions) with detailed scientific review memos describing cell banking, aseptic controls, monitoring, and hazard-management systems. [45]

- There is evidence of **early real-world commercial exposure** (highly limited, but beyond tastings): the US path included facility inspection/grants and first restaurant sales in July 2023, demonstrating functional end-to-end production and regulatory viability, consistent

with post-PoC development by multiple actors. [46]

- Technical “hard parts” are being addressed with **peer-reviewed, quantitative progress**: sustained high-density or continuous/harvestable operation (e.g.,  $130 \times 10^6$  cells/mL over >20 days via tangential flow filtration) and stable high-yield cell lines in serum-free conditions demonstrate that key manufacturing primitives are feasible, not merely conceptual. [47]

- Independent TEA/LCA work quantifies **what scale and costs would need to look like** (including 42,000–262,000 L-scale scenarios and cost drivers), which is typical of a field moving from lab prototypes into engineering-for-scale and investor/regulator-facing design constraints. [48]

### Why this is not yet level 6 (what is still missing)

- Level 6 requires products being delivered to customers “in increasing amounts” with clearly financed expansion and expanding application areas; the best public evidence accessible here supports **limited early sales and process prototypes**, but not broad, increasing-volume supply chains for cultivated meat at competitive prices. [49]

- Major bottlenecks (media cost/supply chain, energy/input intensity, and sterility/contamination risk management at industrial scale) remain decisive; the literature and safety reports emphasise that cost-effective serum-free media and reliable safety systems are still active constraints, and environmental analyses warn that near-term systems can be resource-intensive depending on media refinement. [50]

### Sub-score breakdown and aggregation

Because this ART bundles two partially different application tracks (cultivated animal tissue vs fermentation-derived ingredients/biomass) with different maturity levels, the overall score is an **average-based score**.

- **Cultivated animal cells → maturity ~5**

Evidence: Regulatory scientific review memos and US regulatory milestones plus early sales show post-PoC, production-prototype status, but limited scale. [51]

- **Precision fermentation of functional proteins → maturity ~6**

Evidence: Multiple FDA GRAS “no questions” letters for fermentation-derived animal-identical proteins (e.g.,  $\beta$ -lactoglobulin; ovalbumin) indicate products are reaching deployable ingredient status under established regulatory pathways; however, the dossier here does not itself prove large, steadily increasing commercial volumes across many customers. [52]

- **CO<sub>2</sub>/H<sub>2</sub>-fed microbial protein biomass → maturity ~4–5**

Evidence: Peer-reviewed lab-to-pilot scale demonstrations (including a 300-L pressurised CO<sub>2</sub>-to-protein bioreactor reaching 90 g/L CDW and ~80% protein) support plausibility and pilot maturity; modelling roadmaps place large-scale deployment starting later (e.g., ~2028), indicating scaling is still emerging rather than broadly commercial. [53]

**Aggregation rationale:** The three tracks share a “cellular agriculture” industrial bioprocess core, but their application pathways and scaling status differ; averaging (~5 overall) reflects (i) cultivated meat’s post-PoC status, (ii) precision fermentation’s stronger regulatory maturity, and (iii) gas-fed microbial protein’s pilot-to-early-scale trajectory. [54]

<https://www.nature.com/articles/s43016-024-01022-w>

[2] [9] [31] [37] [42]

<https://www.sciencedirect.com/science/article/abs/pii/S1385894724030638>

<https://www.sciencedirect.com/science/article/abs/pii/S1385894724030638>

[3] [12] [26] [45] [51] <https://www.fda.gov/media/163261/download>

<https://www.fda.gov/media/163261/download>

[4] [16] [22] <https://www.nature.com/articles/s43016-022-00658-w>

<https://www.nature.com/articles/s43016-022-00658-w>

[5] [17] <https://www.nature.com/articles/s42003-022-03423-8>

<https://www.nature.com/articles/s42003-022-03423-8>

[7] [18] [33] <https://www.sciencedirect.com/science/article/pii/S2666833524001679>

<https://www.sciencedirect.com/science/article/pii/S2666833524001679>

[8] [23] [29] [34] [52] <https://www.fda.gov/media/187530/download>

<https://www.fda.gov/media/187530/download>

[11] [20] [48] <https://pubmed.ncbi.nlm.nih.gov/36581609/>

<https://pubmed.ncbi.nlm.nih.gov/36581609/>

[13] [46] [49] [54]

[https://www.congress.gov/crs\\_external\\_products/R/PDF/R47697/R47697.3.pdf](https://www.congress.gov/crs_external_products/R/PDF/R47697/R47697.3.pdf)

[https://www.congress.gov/crs\\_external\\_products/R/PDF/R47697/R47697.3.pdf](https://www.congress.gov/crs_external_products/R/PDF/R47697/R47697.3.pdf)

[14] [38] [53] <https://www.sciencedirect.com/science/article/abs/pii/S0168165625002159>

<https://www.sciencedirect.com/science/article/abs/pii/S0168165625002159>

[19] [50] <https://www.nature.com/articles/s41538-024-00352-0>

<https://www.nature.com/articles/s41538-024-00352-0>

[21] [25] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11744764/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11744764/>

[24] <https://www.who.int/publications/i/item/9789240070943>

<https://www.who.int/publications/i/item/9789240070943>

[28] <https://www.congress.gov/crs-product/R47697>

<https://www.congress.gov/crs-product/R47697>

[30] <https://www.efsa.europa.eu/en/news/safety-cell-culture-derived-food-ready-scientific-evaluation>

<https://www.efsa.europa.eu/en/news/safety-cell-culture-derived-food-ready-scientific-evaluation>

[32] <https://science.food.gov.uk/article/144237-how-do-microbial-safety-issues-associated-with-meat-apply-to-cell-cultivated-products>

<https://science.food.gov.uk/article/144237-how-do-microbial-safety-issues-associated-with-meat-apply-to-cell-cultivated-products>

[36] [41] <https://www.fda.gov/media/188998/download>

<https://www.fda.gov/media/188998/download>

[39] [43] <https://journal.hep.com.cn/smab/EN/10.1007/s43393-025-00336-5>

<https://journal.hep.com.cn/smab/EN/10.1007/s43393-025-00336-5>

[40] <https://www.nature.com/articles/s41467-025-56364-1>

<https://www.nature.com/articles/s41467-025-56364-1>

[44] <https://www.edb.gov.sg/en/business-insights/insights/singapore-first-to-approve-protein-made-from-air.html>

<https://www.edb.gov.sg/en/business-insights/insights/singapore-first-to-approve-protein-made-from-air.html>

## ART 09.070 Organoids & Tissue Engineering

### ART extraction

#### Primary capability

- Produce **repeatable, human-derived “living test articles”** (organoids to tissue patches) that better capture 3D structure and function than 2D cell layers, improving predictive power for human biology in R&D and QC.
- Enable **standardisable, automatable workflows** (plates, microfluidic chips, imaging pipelines) so constructs can be produced, monitored, compared across sites, and (in some cases) shipped/handled more like engineered products.
- Incorporate **bioengineering features** (perfusion/vascular-like microchannels, multicell co-culture, mechanical cues, embedded sensing) to reduce size/maturation limits and improve readouts.

#### Key sub-components or variants

- **Organoid production at scale** (stirred/spinning bioreactors, suspension culture, SOPs, “recipe-like” differentiation).
- **Perfusion and vascularisation strategies** (microfluidic vascular beds, synthetic microchannel networks, endothelial integration, anastomosis).
- **Organoid-on-chip / microphysiological systems (MPS)** integration (controlled flow, oxygen tension, tissue–tissue interfaces).

- **Embedded / in situ sensing and longitudinal monitoring** (TEER/barrier integrity, oxygen, pH, metabolic markers; continuous multi-day monitoring).
- **Automation + software QC** (robotic handling, high-content imaging, machine-learning classifiers to detect drift/abnormal growth).
- **Translational endpoints:** clinical correlation for patient-derived organoid drug response; tissue-engineered patches for regenerative medicine; larger organ-scale perfusion scaffolds.

#### What maturity indicators would constitute evidence

- **Repeatable lab prototypes** showing sustained function, perfusion/vascular integration, and improved maturation vs. baseline culture.
- **High-throughput/automation demonstrations** in standard formats (multiwell plates; parallelised chips; robotic liquid handling).
- **Quantified monitoring** (multi-parameter sensing, stability over weeks, reproducibility metrics, QC classifiers).
- **Standardisation/quality frameworks** from standards bodies and cross-sector consortia (terminology, reporting, fit-for-purpose qualification).
- **Regulatory traction** (official roadmaps/programmes that explicitly accept organoids/MPS as supportive evidence; validation studies; pilot qualification pathways).
- **Clinical/real-world correlation** (prospective trials demonstrating organoid drug response predicts patient outcomes; early human use of engineered tissues).

#### Evidence (10–20 recent, reliable sources)

##### 1) Creating a kidney organoid-vasculature interaction model using a novel organ-on-chip system

Authors/organisation: Amanda Bas-Cristóbal Menéndez[1] et al.

Venue/type: *Scientific Reports* (peer-reviewed experimental paper, open access)

Publication date: Nov 2022

Link: <https://www.nature.com/articles/s41598-022-24945-5>

Key result / why it matters: Demonstrates **in vitro vascularisation cues via microfluidic flow** and co-culture, including **endothelial ingrowth and lumen-like structures** inside kidney organoids—direct evidence that chip-mediated perfusion/cues can partially address the “size/maturation without perfusion” bottleneck. [2]

##### 2) Large-scale perfused tissues via synthetic 3D soft microfluidics

Authors/organisation: Sergei Grebenyuk[3] et al.

Venue/type: *Nature Communications* (peer-reviewed experimental paper, open access)

Publication date: Jan 2023

Link: <https://www.nature.com/articles/s41467-022-35619-1>

Key result / why it matters: Shows **synthetic 3D microfluidic networks** enabling **large-scale perfusion** through engineered tissues—directly supports feasibility of **microchannel-based perfusion** to push constructs beyond diffusion-limited dimensions. [4]

##### 3) Sustained in vivo perfusion of a re-endothelialized tissue engineered kidney graft in a human-scale animal model

Authors/organisation: James S. Uzarski[5] et al.

Venue/type: *Frontiers in Bioengineering and Biotechnology* (peer-reviewed experimental paper)

Publication date: Jun 2023

Link: <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2023.1184408/full>

Key result / why it matters: Reports **human-scale scaffold perfusion performance** (e.g., quantified perfusion percentages over days), underscoring that **perfusion and endothelialisation are measurable engineering targets** for scale-up—even if full organ function remains a longer-term challenge. [6]

#### 4) Scalable production of tissue-like vascularized liver organoids from human PSCs

Authors/organisation: Sean P. Harrison[7] et al.

Venue/type: *Experimental & Molecular Medicine* (peer-reviewed experimental paper, open access)

Publication date: Sep 2023

Link: <https://www.nature.com/articles/s12276-023-01074-1>

Key result / why it matters: Demonstrates **scalable, ECM-independent production** of liver-like organoids with **vascular luminal structures** plus liver functions (e.g., metabolism, urea/coagulation-related outputs), supporting plausibility of **high-volume organoid manufacturing** with richer cellular composition than simple hepatic spheroids. [8]

#### 5) A microfluidic platform integrating functional vascularized organoids-on-chip

Authors/organisation: Clément Quintard[9] et al.

Venue/type: *Nature Communications* (peer-reviewed experimental paper, open access)

Publication date: Feb 2024

Link: <https://www.nature.com/articles/s41467-024-45710-4>

Key result / why it matters: Demonstrates a **parallelised microfluidic device** (10 channels) designed in **COC plastic suitable for mass production** and reports **controlled perfusion/anastomosis** with vascularised organoids and spheroids maintained **up to ~30 days**, directly supporting maturity of “organoid perfusion as a workflow-compatible add-on”. [10]

#### 6) From animal testing to in vitro systems: advancing standardization in microphysiological systems

Authors/organisation: Darwin R. Reyes[11] et al. (stakeholders incl. National Institute of Standards and Technology[12] and industry participants)

Venue/type: *Lab on a Chip* (peer-reviewed perspective; standards/translation-focused)

Publication date: Feb 2024

Link: <https://pubs.rsc.org/en/content/articlelanding/2024/lc/d3lc00994g>

Key result / why it matters: Summarises concrete standardisation gaps and efforts (terminology, interfaces, validation concepts) and evidences **multi-stakeholder coordination**—a key maturity signal when moving from bespoke academic prototypes to interoperable, comparable platforms. [13]

#### 7) Recommendations on fit-for-purpose criteria to establish quality management for microphysiological systems and for monitoring their reproducibility

Authors/organisation: David Pamies[14] et al.

Venue/type: *Stem Cell Reports* (peer-reviewed perspective; quality management / reproducibility)



Publication date: Apr 2024

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11103889/>

Key result / why it matters: Provides **fit-for-purpose quality management recommendations** for MPS/organoid-like systems (qualification, reproducibility monitoring), directly addressing the ART constraint of **batch drift/variability** and showing the field is formalising QC norms needed for scaling and cross-site adoption. [15]

#### 8) CEN-CENELEC Focus Group Organ-on-Chip Roadmap

Authors/organisation: CEN-CENELEC[16] (Focus Group on Organ-on-Chip)

Venue/type: Standards roadmap/report (authoritative standards-body publication)

Publication date: Jul 2024

Link: <https://www.cencenelec.eu/media/publication-july-2024-fg-ooc-roadmap.pdf>

Key result / why it matters: Details a Europe-wide standardisation roadmap spanning **reliability, sterilisation, material–liquid interactions, experimental design/data management, and regulatory/ethical aspects**—evidence of mature ecosystem work to make organoid/MPS platforms comparable and auditable at scale. [17]

#### 9) Development of an automated 3D high content cell screening platform for organoid phenotyping

Authors/organisation: Suleyman B. Bozal[18] et al.

Venue/type: *SLAS Discovery* (peer-reviewed experimental/methods paper, open access)

Publication date: Oct 2024

Link: <https://www.sciencedirect.com/science/article/pii/S2472555224000443>

Key result / why it matters: Demonstrates **384-well high-content organoid screening** with **robotic liquid handling** and shows image-based phenotyping can be more sensitive than basic viability assays—direct evidence that organoids can “fit existing workflows” while moving toward industrialised screening throughput. [19]

#### 10) Organ chips with integrated multifunctional sensors enable continuous metabolic monitoring at controlled oxygen levels

Authors/organisation: Zohreh Izadifar[20] et al.

Venue/type: *Biosensors and Bioelectronics* (peer-reviewed experimental paper, open access)

Publication date: Aug 2024 (epub); Dec 2024 (issue)

Link: <https://www.sciencedirect.com/science/article/pii/S0956566324006894>

Key result / why it matters: Demonstrates organ-chip devices with integrated **TEER, oxygen, and pH sensors**, operated with a **commercial culture instrument**, and reports **continuous, non-invasive monitoring up to ~23 days** in human gut/liver chip cultures—highly aligned with the ART’s “embedded sensors + longitudinal monitoring” claim. [21]

#### 11) Non-Invasive Quality Control of Organoid Cultures Using Mesofluidic CSTR Bioreactors and High-Content Imaging

Authors/organisation: Seleipiri Charles[22] et al.

Venue/type: *Advanced Materials Technologies* (peer-reviewed experimental paper; with linked preprint history)

Publication date: Aug 2024 (epub); Feb 2025 (issue)

Link: <https://pubmed.ncbi.nlm.nih.gov/40248044/>

Key result / why it matters: Integrates a **mesofluidic bioreactor** with longitudinal imaging and a **machine-learning classifier** to distinguish normal vs abnormal development, explicitly

targeting **heterogeneity/reproducibility**—a direct maturity marker for scalable “software QC” organoid pipelines. [23]

#### 12) Accelerated production of human epithelial organoids in a miniaturized spinning bioreactor

Authors/organisation: Shicheng Ye[24] et al.

Venue/type: *Cell Reports Methods* (peer-reviewed methods/experimental paper)

Publication date: Nov 2024

Link: <https://pubmed.ncbi.nlm.nih.gov/39561715/>

Key result / why it matters: Presents a miniaturised spinning bioreactor with SOP-like settings and reports faster proliferation (e.g., **multi-fold increases for liver/intestine/pancreas organoids vs static culture**) while maintaining phenotypes—strong evidence of progress on **standardisation + cost/time reduction via automation**. [25]

#### 13) Personalized Vascularized Tumor Organoid-on-a-Chip for Tumor Metastasis and Therapeutic Targeting Assessment

Authors/organisation: Yang Du[26] et al.

Venue/type: *Advanced Materials* (peer-reviewed experimental paper)

Publication date: Dec 2024 (epub); Feb 2025 (issue)

Link: <https://pubmed.ncbi.nlm.nih.gov/39726096/>

Key result / why it matters: Reports a **vascularised patient-derived tumour organoid chip** with **hierarchical microvasculature** to study tumour–vascular dynamics and drug response, evidencing feasibility of “more realistic co-culture microenvironments” beyond avascular tumoroids. [27]

#### 14) Engineered heart muscle allografts for heart repair in primates and humans

Authors/organisation: Ahmad-Fawad Jebran[28] et al.

Venue/type: *Nature* (peer-reviewed experimental translational paper, open access)

Publication date: Jan 2025

Link: <https://www.nature.com/articles/s41586-024-08463-0>

Key result / why it matters: Shows **centimetre-scale engineered heart muscle** tested in primates and humans, signalling that parts of tissue engineering have progressed beyond in vitro models into **advanced preclinical/early clinical translation**, while also highlighting the high bar for full regulatory/market maturity. [29]

#### 15) Roadmap to Reducing Animal Testing in Preclinical Safety Studies

Authors/organisation: U.S. Food and Drug Administration[30]

Venue/type: Government roadmap/report (authoritative regulatory document)

Publication date: Apr 2025

Link:

[https://www.fda.gov/files/newsroom/published/roadmap\\_to\\_reducing\\_animal\\_testing\\_in\\_preclinical\\_safety\\_studies.pdf](https://www.fda.gov/files/newsroom/published/roadmap_to_reducing_animal_testing_in_preclinical_safety_studies.pdf)

Key result / why it matters: Explicitly treats **organoids and organ-on-chip/MPS** as NAMs and states FDA intent to **welcome organoid results in IND/BLA packages as supportive data**; it also cites a **Human Liver-on-Chip** evaluated for DILI prediction and accepted into an FDA pilot programme, indicating accelerating regulatory pull for these platforms. [31]

#### 16) A feedback-driven brain organoid platform enables automated maintenance and high-resolution neural activity monitoring

Authors/organisation: Kateryna Voitiuk[32] et al.

Venue/type: *Internet of Things* (peer-reviewed experimental systems paper)

Publication date: Jul 2025 (epub); Sep 2025 (issue)

Link: <https://pubmed.ncbi.nlm.nih.gov/41522195/>

Key result / why it matters: Demonstrates an **IoT-style integrated platform** combining **microfluidics + imaging + electrophysiology**, including computer-vision feedback to correct perfusion deviations and enabling frequent neural recordings—directly aligned with “software recipes + monitored by imaging + QC/automation”. [33]

#### 17) **Gastruloids enable modeling of the earliest stages of human cardiac and hepatic vascularization**

Authors/organisation: Oscar J. Abilez[34] et al.

Venue/type: *Science* (peer-reviewed experimental paper)

Publication date: Jun 2025

Link: <https://pubmed.ncbi.nlm.nih.gov/40472086/>

Key result / why it matters: Shows micropatterned gastruloids and factor combinations that yield **branched vascular networks** in cardiac and hepatic contexts—strong plausibility evidence that **developmental programmes can be engineered** to improve organoid vascularisation (a key stated constraint). [35]

#### 18) **Patient-Derived Organoids Predict Treatment Response in Metastatic Colorectal Cancer**

Authors/organisation: Jeanine M.L. Roodhart[36] et al.

Venue/type: *Clinical Cancer Research* (peer-reviewed prospective multicentre clinical/translational study; open access via PMC)

Publication date: Dec 2025 (issue date)

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12666313/>

Key result / why it matters: Interim results from the OPTIC multicentre prospective study report that PDO drug sensitivity **correlates with lesion response** and demonstrates **predictive performance metrics** (e.g., PPV/NPV and AUC ranges) for chemotherapy response—direct maturity evidence that organoids can move from “plausible model” to **clinically predictive test article** in real patient workflows. [37]

#### 19) **Emulate Liver-Chip R1: A human-relevant model of the liver sinusoid using a novel, low-drug-absorbing chip**

Authors/organisation: Emulate, Inc.[38]

Venue/type: Vendor technical doc (application note with engineering specs + performance characterisation)

Publication date: Oct 2024

Link: [https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note\\_Characterization-and-Toxicity.pdf](https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note_Characterization-and-Toxicity.pdf)

Key result / why it matters: Provides concrete **engineering change + measurable specifications** (e.g., thermoplastic materials to reduce absorption, membrane pore size/thickness, flow/shear targets) and summarises hepatotoxicity-related functional readouts, illustrating that vendors are iterating toward **productised, better-controlled organ-chip consumables**—a maturity signal beyond academic one-offs. [39]

#### 20) **Upscaling: efficient generation of human lung organoids from induced pluripotent stem cells using a stirring bioreactor**

Authors/organisation: B Budeus[40] et al.

Venue/type: *Frontiers in Bioengineering and Biotechnology* (peer-reviewed experimental paper)

Publication date: Dec 2025

Link: <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2025.1684315/full>

Key result / why it matters: Demonstrates **bioreactor-based upscaling** of hiPSC lung organoid differentiation (including design details like agitation and bubble-free aeration), supporting the plausibility of moving from artisanal organoid culture into **bioprocess-style scale-up**. [41]

### **Maturity score (1–7) and reasoning**

#### **Final maturity score: 5**

This ART (organoids + tissue engineering as “living test articles” with perfusion/sensing/automation and early translational use) best fits **Level 5: multiple well-capitalised actors are actively developing production prototypes post-PoC, with rapid progress and visible moves toward standardisation and regulatory uptake**.

#### **Evidence-to-rubric mapping**

#### **What rules out Levels 1–3 (the field is beyond “principle proven” and beyond early lab verification):**

Multiple independent peer-reviewed experimental programmes show not just theoretical feasibility but **working prototypes** for key bottlenecks: perfusion/vascularisation (kidney organoids on-chip; vascularised organoids-on-chip platforms; synthetic perfused microfluidics) and scalable production routes (spinning/bioreactor organoid expansion; high-throughput phenotyping). [42]

#### **Why Level 4 is clearly met (PoC prototypes meeting real workflow needs):**

Several systems demonstrate functions aligned with commercialisation requirements—**parallelisation, multi-week stability, sensorised monitoring, and automation**. Examples include: organoids-on-chip perfused up to ~30 days with device features framed around manufacturability (COC plastics), continuous multi-sensor monitoring up to ~23 days on a commercial instrument, and automated ML-based QC for selecting “normal” organoids during long culture. [43]

#### **Why the overall bundle reaches Level 5 (ecosystem and translation signals):**

- Standardisation and quality governance are being formalised by major standards bodies and cross-sector stakeholder groups (EU roadmap; quality management recommendations; standardisation perspective with metrology and industry participation). [44]
- Regulatory pull is explicit: the FDA’s April 2025 roadmap frames **organoids/MPS** as NAMs, indicates willingness to accept organoid results as supportive data in IND/BLA packages, and references pilot/validation activity (including an MPS example evaluated for DILI prediction and accepted into a pilot programme). [31]
- Some applications have crossed into **prospective, multicentre clinical validation** for predictive value (PDOs predicting response in metastatic colorectal cancer), showing the “living test article” concept can operate in real patient-facing pipelines—an advanced maturity indicator compared with purely academic demonstrations. [37]

### What is still missing to justify Level 6 (scaled product delivery with clear expansion economics):

While there is clear evidence of **commercial products and vendor iteration** (e.g., detailed organ-chip consumable specs and performance characterisation) and regulatory momentum, this dossier does not provide hard, auditable proof that **organoid/MPS “test article” production is being delivered to customers in increasing volumes with demonstrated economies of scale** across multiple competing products and broad routine adoption. [45]

In other words: the technology is beyond PoC and has a strong ecosystem, but **scaling evidence is uneven across sub-threads**, especially for more complex vascularised, sensorised, multicellular constructs and for regenerative tissue patches.

### Sub-scores and aggregation approach

Because this ART bundles multiple related but non-identical technologies, the maturity score is best treated as a **weighted average** (rather than pure max), with emphasis on the “living test article for R&D/QC” value proposition.

- **High-throughput organoid/MPS for drug response and screening** → ~5  
Key support: 384-well automated screening workflow (Oct 2024) and multicentre clinical correlation of PDO drug response with patient outcomes (Dec 2025). [46]
- **Perfusion/vascularisation enabling larger/more functional constructs** → ~4–5  
Key support: vascularised organoids-on-chip with perfusion and manufacturable materials (Feb 2024); kidney organoid vascularisation on-chip (Nov 2022); synthetic perfused microfluidics (Jan 2023). [47]
- **Automation + ML QC + longitudinal monitoring (the “software recipes + QC” layer)** → ~4–5  
Key support: mesofluidic bioreactor + ML classification for QC (epub Aug 2024); IoT feedback-driven organoid maintenance platform (Sep 2025). [48]
- **Therapeutic tissue patches / regenerative tissue engineering** → ~4  
Key support: engineered heart-muscle allografts tested in primates and humans (Jan 2025), indicating translation is possible but still far from commodity production and broad clinical deployment. [29]

**Aggregation to one score:** weighting the “living test article for R&D/QC” components most heavily (since that is the central claim of the ART description) yields an overall maturity at **Level 5**, with some sub-threads approaching 6 in specific niches but not enough broad production-scale evidence across the whole bundle. [49]

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<https://pubmed.ncbi.nlm.nih.gov/40248044/>

[12] [16] [39] [45] [https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note\\_Characterization-and-Toxicity.pdf](https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note_Characterization-and-Toxicity.pdf)

[https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note\\_Characterization-and-Toxicity.pdf](https://emulatebio.com/wp-content/uploads/2024/10/Emulate-Liver-Chip-R1-Application-Note_Characterization-and-Toxicity.pdf)

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## ART 09.071 Synthetic Biology & Designer Microbes

### 1. ART extraction

#### Primary capability the ART claims

- Programmable “designer microbes” that convert low-value inputs into target molecules/materials in bioreactors, using modular genetic “control logic” to schedule and regulate production. [1]
- Embedded sensing-and-response: microbes detect internal/external conditions (metabolites, temperature, stress, etc.) and automatically shift metabolic fluxes or gene expression to optimise outputs. [2]
- Robustness and containment by design (auxotrophies, kill switches, multi-layer safeguards) to reduce persistence outside controlled environments and support traceability/regulatory acceptance. [3]

#### Key sub-components or variants

- **Standardised chassis and host onboarding** (bacteria/yeast; including non-model hosts) for diverse feedstocks and operating conditions. [4]
- **Dynamic regulation circuits** (quorum-sensing control, temperature-responsive logic, biosensor-triggered CRISPRi) to decouple growth and production or to perform ordered multi-stage pathway control. [5]
- **Design-build-test-learn (DBTL) automation and design representation** (standards like SBOL; metrology and reproducibility infrastructure; computational design automation) to make circuit behaviour more predictable and transferable. [6]
- **Biocontainment modules** (synthetic auxotrophy, CRISPR-based kill systems, layered/orthogonal safeguards) suitable for industry and/or applied deployments. [3]

- **Downstream processing / separations & TEA** (purification cost, ISPR approaches, minimum selling price sensitivity to feedstock and utilities). [7]
- **Commercial-scale deployments** where engineered microbes already operate at industrial scale (fuels/chemicals/enzymes), providing a maturity anchor for parts of the ART. [8]

#### What would count as maturity evidence for this ART

- Repeatable **pilot-relevant demonstrations** (e.g., litre-scale/5-L+ fermentations) showing improved titres/yields/productivity using autonomous genetic control (not manual inducer addition) and stable behaviour across runs. [5]
- **Validated robustness/containment**: multi-layer safeguards with demonstrated evolutionary stability (e.g., >100 generations under permissive conditions) and clear performance in relevant chassis. [9]
- **Standardisation + metrology adoption** (interlab-compatible measurement practices; machine-readable design standards; shared protocols/datasets) that reduce “one-lab-only” effects. [10]
- **Evidence of scaling and industry pull**: funded consortia with explicit scale-up/DBTL objectives, regulatory filings showing commercial operation, and regulatory dossiers describing containment/quality controls. [11]
- **Economics evidence**: TEA/ISPR showing that separation and feedstock/utility costs can plausibly meet target MSP ranges under realistic scenarios. [12]

#### Evidence (10–20 recent, reliable sources)

#### 2. Evidence (10–20 recent, reliable sources)

##### Sources (all within the strict 4-year window: Feb 2022–Feb 2026)

##### 1) Meeting Measurement Precision Requirements for Effective Engineering of Genetic Regulatory Networks

Authors/Org: Jacob Beal[13] et al.

Venue/type: ACS Synthetic Biology[14] (peer-reviewed paper)

Publication date: **Feb 2022** (web publication date)

Link: <https://pubs.acs.org/doi/abs/10.1021/acssynbio.1c00488>

Annotation: Derives an “engineering error inequality” linking model accuracy and measurement precision, and recommends ~**1.5-fold** target standard deviation; shows via an interlaboratory flow cytometry study that such requirements can be met with matched channels and independent calibration—supporting plausibility of predictable, modular genetic control. [15]

##### 2) Synthetic biology open language (SBOL) version 3.1.0

Authors/Org: Lukas Buecherl[16] et al.

Venue/type: Journal of Integrative Bioinformatics[17] (peer-reviewed standards paper)

Publication date: **Mar 2023** (published online)

Link: <https://www.degruyter.com/document/doi/10.1515/jib-2022-0058/pdf>

Annotation: Updates SBOL with clarified semantics and validation rules, strengthening machine-readable representation of genetic designs—directly aligned with the ART’s “software-defined” circuits and interoperable workflows. [18]

### 3) **Protocols, datasets, and software for engineering biology**

Authors/Org: National Institute of Standards and Technology[19] (programme page)

Venue/type: Government lab programme resources / protocols

Publication date: **Jun 2024**

Link: <https://www.nist.gov/programs-projects/protocols-datasets-and-software-engineering-biology>

Annotation: Curates reproducibility-focused automation protocols and datasets (including automated culture/measurement and DNA template preparation), indicating institutional investment in standardised measurement and repeatable DBTL pipelines—critical to scaling programmable microbes. [20]

### 4) **2023 Project Peer Review Report: Agile BioFoundry Consortium (ABF section)**

Authors/Org: U.S. Department of Energy Bioenergy Technologies Office[21] (authoritative programme report section)

Venue/type: Government programme peer-review report (report/PDF)

Publication date: **Apr 2024** (posted)

Link: [https://www.energy.gov/sites/default/files/2024-04/beto-2023-peer-review-report\\_03-agile-biofoundry.pdf](https://www.energy.gov/sites/default/files/2024-04/beto-2023-peer-review-report_03-agile-biofoundry.pdf)

Annotation: Documents major, multi-lab DBTL/scale-up infrastructure with ~**\$86.9M** DOE investment reviewed, and frames ABF's mission and industrial engagement (including targets such as reducing time to scale-up)—evidence of well-capitalised actors pushing beyond lab PoC. [22]

### 5) **A pathway independent multi-modular ordered control system based on thermosensors and CRISPRi improves bioproduction in *Bacillus subtilis***

Authors/Org: Wenwen Yu[23] et al.

Venue/type: Nucleic Acids Research[24] (peer-reviewed experimental paper)

Publication date: **Jun 2022** (24 Jun 2022)

Link: <https://academic.oup.com/nar/article/50/11/6587/6603658>

Annotation: Demonstrates programmable temperature-responsive circuits plus CRISPRi logic for ordered metabolic control; reports **2'-fucosyllactose 28.2 g/L in a 5-L bioreactor** (and 5.16× improvement in shake flask), providing strong plausibility evidence for “software-like” production timing in existing fermenters. [25]

### 6) **A quorum sensing-controlled type I CRISPRi toolkit for dynamically regulating metabolic flux**

Authors/Org: Han Zheng[26] et al.

Venue/type: Nucleic Acids Research (peer-reviewed experimental paper)

Publication date: **Jul 2025** (published 19 Jul 2025)

Link: <https://academic.oup.com/nar/article/53/14/gkaf693/8208113>

Annotation: Builds an inducer-free QS→CRISPRi dynamic regulator; reports **14.97 g/L D-pantothenic acid in 5-L fed-batch** and **2.49× riboflavin** improvement—pilot-relevant evidence that autonomous logic can materially improve titres without costly external inducers. [27]

### 7) **Engineering genetic circuits for dynamic control of central metabolism**

Authors/Org: Yusong Zou[28] et al.

Venue/type: Metabolic Engineering[29] (peer-reviewed experimental paper)

Publication date: **Sep 2025**

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S109671762500093X>

Annotation: Establishes a pyruvate-responsive biosensor (PdhR) and uses it for dynamic flux control; reports **trehalose 3.72 g/L (2.33×)** and **4-hydroxycoumarin 491.5 mg/L (1.63×)**, illustrating generalisable central-metabolism triggers for programmable cell factories. [30]

#### 8) **Computational design of allulose-responsive biosensor toolbox for auto-inducible protein expression and CRISPRi mediated dynamic metabolic regulation**

Authors/Org: Qianzhen Dong[31] et al.

Venue/type: Nature Communications (peer-reviewed experimental paper)

Publication date: **Dec 2025** (published 22 Dec 2025)

Link: <https://www.nature.com/articles/s41467-025-67669-6>

Annotation: Structure-guided design yields an allulose-responsive sensor with **EC50 reduced from 16 mM to 0.8 mM** and wide detection range; demonstrates auto-inducible expression and allulose-triggered CRISPRi dynamic regulation, supporting the ART's "sense→actuate" logic with quantitative performance. [32]

#### 9) **Precision engineering of biological function with large-scale measurements and machine learning**

Authors/Org: Drew S. Tack[33] et al.

Venue/type: PLOS ONE[34] (peer-reviewed experimental paper)

Publication date: **Mar 2023** (published 29 Mar 2023)

Link:

<https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0283548>

Annotation: Demonstrates "precision engineering" of genetic sensors using large-scale genotype–phenotype data and ML, including multi-objective tuning of sensor EC50 and output—evidence that genetic "control logic" can become more predictable and designable. [35]

#### 10) **Energy Aware Technology Mapping of Genetic Logic Circuits**

Authors/Org: Erik Kubaczka[36] et al.

Venue/type: ACS Synthetic Biology (peer-reviewed paper; design automation)

Publication date: **Oct 2024**

Link: <https://garcialab.berkeley.edu/publications/Kubaczka2024.pdf>

Annotation: Introduces automated mapping of Boolean genetic circuits with energy/efficiency objectives; reports **~37.2% average energy-efficiency improvement** versus function-optimised variants, a concrete step toward scalable software-defined genetic circuit design under resource constraints. [37]

#### 11) **A robust yeast biocontainment system with two-layered regulation switch dependent on unnatural amino acid**

Authors/Org: T. Chang[38] et al.

Venue/type: Nature Communications[39] (peer-reviewed experimental paper)

Publication date: **Oct 2023** (published 14 Oct 2023)

Link: <https://www.nature.com/articles/s41467-023-42358-4>

Annotation: Demonstrates synthetic auxotrophy in budding yeast dependent on an unnatural amino acid as a robust containment strategy—direct evidence that "engineered dependencies" can be implemented in an industrially relevant chassis. [40]

### 12) **GenoMine: a CRISPR-Cas9-based kill switch for biocontainment of *Pseudomonas putida***

Authors/Org: Enrique Asin-Garcia[41] et al.

Venue/type: Frontiers in Bioengineering and Biotechnology[42] (peer-reviewed experimental paper)

Publication date: **Sep 2024** (published 16 Sep 2024)

Link: <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2024.1426107/full>

Annotation: Presents a CRISPR-Cas9 kill switch targeting repetitive genomic elements in the biotechnological workhorse *P. putida*, supporting plausibility of programmable safeguards beyond lab strains. [43]

### 13) **A multilayered biocontainment system for laboratory and probiotic yeast**

Authors/Org: Carla Maneira[44] et al.

Venue/type: Metabolic Engineering (peer-reviewed experimental paper)

Publication date: **Sep 2025**

Link: <https://www.sciencedirect.com/science/article/pii/S1096717625000953>

Annotation: Builds single-input safeguards (synthetic auxotrophy and CRISPR-based kill switch) and combines them into an orthogonal two-input system; reports circuits stable for **>100 generations** and aligned to NIH guideline expectations—important maturity step for containment engineering. [45]

### 14) **Genetic “expiry-date” circuits control lifespan of synthetic scavenger bacteria for safe bioremediation**

Authors/Org: Kha Mong Tran[46] et al.

Venue/type: Nucleic Acids Research (peer-reviewed experimental paper)

Publication date: **Jul 2025** (published 24 Jul 2025)

Link: <https://academic.oup.com/nar/article/53/14/gkaf703/8211935>

Annotation: Implements genetic “expiry-date” circuits to limit lifespan of engineered bacteria for safer applications, demonstrating timed self-limitation logic relevant to both containment and field-facing variants of the ART. [47]

### 15) **A bumpy road ahead for genetic biocontainment**

Authors/Org: Dalton R. George[48] et al.

Venue/type: Nature Communications (peer-reviewed commentary)

Publication date: **Jan 2024** (20 Jan 2024)

Link: <https://www.nature.com/articles/s41467-023-44531-1>

Annotation: Argues that few real-world biotech products currently include intrinsic biocontainment, highlighting testing capacity and regulatory uncertainty—evidence that containment remains a maturity limiter for “deployable” designer microbes. [49]

### 16) **GRAS Notice 1104: Non-animal egg white protein produced by *Komagataella phaffii***

Authors/Org: U.S. Food and Drug Administration[50] (regulatory dossier; submitter: Clara Foods / EVERY)

Venue/type: Regulatory technical dossier (manufacture, monitoring, purification)

Publication date: **Sep 2022** (received stamp SEP 12 2022)

Link: <https://www.fda.gov/media/170789/download>

Annotation: Describes an engineered-yeast precision fermentation process with defined unit operations (fermentation → cell separation → purification → drying) and in-process checks

aimed at contamination control and specifications—direct maturity evidence for regulatory traceability and QA/QC workflows around engineered microbes. [51]

**17) GRAS Notice 1139: Transglutaminase enzyme produced by genetically modified *Bacillus licheniformis***

Authors/Org: U.S. FDA (regulatory dossier; submitter: Novozymes)

Venue/type: Regulatory technical dossier (identity, strain lineage, safety studies)

Publication date: **Apr 2023** (date of receipt: Apr 3 2023)

Link: <https://www.fda.gov/media/178428/download>

Annotation: Specifies a production organism and construct details (GM *Bacillus* carrying a *Streptomyces* transglutaminase gene) and documents safety-study expectations—concrete evidence that engineered microbial “factories” and their products already traverse formal regulatory pathways. [52]

**18) Form 10-Q (quarter ended 31 Mar 2025): LanzaTech Global, Inc.**

Authors/Org: LanzaTech Global, Inc. [53] filing with U.S. Securities and Exchange Commission [54]

Venue/type: Public company regulatory filing (commercial operations evidence)

Publication date: **2025** (reporting quarter ended Mar 2025)

Link:

<https://www.sec.gov/Archives/edgar/data/1843724/000162828025026381/lnza-20250331.htm>

Annotation: States that as of **31 Mar 2025** the company’s technology was operated by licensees at **multiple commercial-scale ethanol plants** (including four in China and one in Belgium, with one commissioning in India), anchoring that engineered-microbe industrial bioprocessing is already commercially deployed at scale. [55]

**19) Techno-economic analysis as a valuable tool for the selection of high-potential extractive fermentation approaches for large-scale prodigiosin production**

Authors/Org: Ulises Andres Salas-Villalobos [56] et al.

Venue/type: Chemical Engineering Journal [57] (peer-reviewed TEA; open access)

Publication date: **Feb 2024** (Vol 481, 1 Feb 2024)

Link: <https://www.sciencedirect.com/science/article/pii/S1385894723070110>

Annotation: Shows downstream/separation and process mode materially change economics: continuous extractive operation decreased costs **4.73×** vs batch and includes a concrete scale design point (reactor volume/flow), matching the ART’s constraint focus on DSP and separations. [58]

**20) Techno-Economic Analysis of 2,3-Butanediol Production from Sugarcane Bagasse**

Authors/Org: Siddharth Gadkari [59] et al.

Venue/type: ACS Sustainable Chemistry & Engineering (peer-reviewed TEA; open access)

Publication date: **May 2023** (published 22 May 2023)

Link: <https://pureadmin.qub.ac.uk/ws/files/554168093/gadkari-et-al-2023-techno-economic-analysis-of-2-3-butanediol-production-from-sugarcane-bagasse.pdf>

Annotation: Models an industrially scaled plant (96 MT/day bagasse) and quantifies MSP/NPV sensitivity to feedstock/utilities; reports scenario MSP spanning **~US\$1.86–3.99/kg** and provides explicit capital/operating cost tables—direct evidence that economics hinge on feedstock and separation assumptions. [60]



## Maturity score (1–7) and reasoning

### 3. Maturity score (1–7) and reasoning

Final maturity score: 5

#### Why the evidence rules out lower levels

- The ART is well beyond “principle only” (levels 1–2) because multiple peer-reviewed experiments show programmable genetic control systems that improve titres/yields, including in **5-L bioreactors/fed-batch** at tens of g/L for some products—this is beyond basic lab principle verification. [\[61\]](#)
- The ART is beyond “single lab prototype” (level 3) because several independent, recent demonstrations cover different control modalities (thermosensors+CRISPRi, QS→CRISPRi, metabolite biosensors) and show quantified performance gains on relevant chassis. [\[5\]](#)
- There is clear evidence of **serious scale-up ecosystem and funding** (e.g., ABF peer review with large DOE investment) and of regulatory-ready manufacturing descriptions (FDA GRAS dossiers), indicating the field is operating in a post-PoC landscape rather than exploratory science. [\[62\]](#)

#### Why the evidence does not justify the next higher level

- Level 6 would require that the **core ART functionality**—a broadly standardised, reconfigurable “software-defined” platform for multiple outputs with predictable behaviour across chassis and batches—be routinely delivered and scaled as products/services, not merely demonstrated project-by-project. Current evidence shows strong **domain-specific** successes and real commercial deployments for certain engineered-microbe processes, but not a universally plug-and-play programmable microbe platform. [\[63\]](#)
- Containment remains a gating factor for broader deployment outside closed systems; even commentary in a leading journal notes limited real-world incorporation of intrinsic biocontainment and points to regulatory/testing uncertainties. [\[64\]](#)
- TEA and extractive-fermentation studies underscore that downstream processing and feedstock/utility costs remain dominant determinants of viability (i.e., scaling is not “solved by circuits alone”), which is consistent with the ART’s stated constraints and suggests remaining barriers to generalised, low-capex distributed deployment. [\[12\]](#)

#### Sub-score breakdown and aggregation

- **Industrial microbial factories already delivering outputs (enzymes/fuels/ingredients) → ~6**  
Supporting evidence: FDA GRAS dossiers documenting industrial fermentation, purification, and QA/QC (Sep 2022; Apr 2023). [\[65\]](#)  
Supporting evidence: SEC filing describing multiple commercial-scale industrial plants operating with the firm’s bioprocess technology (Mar 2025). [\[55\]](#)
- **Programmable genetic circuits for dynamic control in production-like settings → ~4–5**  
Supporting evidence: 5-L bioreactor/fed-batch PoCs with large titre gains using thermosensor/CRISPRi and QS→CRISPRi dynamic regulation. [\[66\]](#)  
Supporting evidence: Metabolite-responsive biosensors improving titres and demonstrating generalisable central-metabolism triggers. [\[67\]](#)

- **Biocontainment modules suitable for industrial organisms → ~4**

Supporting evidence: Robust yeast containment via synthetic auxotrophy and layered safeguards, including stability claims (>100 generations) in a peer-reviewed engineering journal. [68]

Limiter evidence: commentary emphasising the gap between lab proposals and real-world deployment for intrinsic containment. [64]

- **Standardisation, metrology, and DBTL automation to make “genetic control logic” modular/predictable → ~4–5**

Supporting evidence: Interlab measurement precision guidance (Feb 2022), SBOL 3.1 standardisation (Mar 2023), NIST protocols for reproducibility/automation (Jun 2024), and design automation advances that quantify resource trade-offs (Oct 2024). [69]

Supporting evidence: Government scale-up consortia emphasising DBTL infrastructure and industrial engagement. [22]

**Aggregation method:** average across sub-components (because the ART’s value proposition depends on integration of production microbes + programmable control + containment + scalable/standardised workflows). Using approximate sub-scores (6, 4.5, 4, 4.5) gives ~4.75 → **rounded to 5** as the single ART maturity score. [70]

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[1] [2] [4] [5] [19] [21] [36] [39] [46] [53] [57] [59] [61] [66]

<https://academic.oup.com/nar/article/50/11/6587/6603658>

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[https://www.energy.gov/sites/default/files/2024-04/beto-2023-peer-review-report\\_03-agile-biofoundry.pdf](https://www.energy.gov/sites/default/files/2024-04/beto-2023-peer-review-report_03-agile-biofoundry.pdf)

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## ART 09.072 Microbiome Engineering

### ART extraction

#### Primary capability claimed

- Practical **steering of complex microbial ecosystems** (human gut, soil, water, engineered bioprocesses) by *measuring* community state, *predicting* responses, and *actuating* targeted perturbations—rather than treating the ecosystem as an opaque “black box”. [1]
- A **configurable “toolkit”** that makes microbial dynamics measurable and actionable for non-specialists (e.g., through rapid sequencing, reference standards, dashboards, and validated intervention form factors like capsules/coatings/sprays). [2]

#### Key sub-components and variants

- **Measurement / profiling:** shotgun/long-read metagenomics; absolute quantification; rapid sample-to-result workflows; reference materials; standards for data processing and reporting; time-series monitoring dashboards. [3]
- **Design / prediction:** metabolic/ecological modelling pipelines and data-driven methods that connect composition  $\leftrightarrow$  function  $\leftrightarrow$  intervention (e.g., modelling metabolic interactions to identify “keystone” species). [4]
- **Actuation (non-genetic):** selective antimicrobials, phage cocktails, nutrient/prebiotic “nudges”, community reseedling with defined consortia or microbiota-derived products. [5]
- **Actuation (genetic / precision):** in situ bacterial editing, engineered phage delivering CRISPR payloads, engineered living therapeutics with control circuits. [6]
- **Delivery & operations:** stable formulations, dosing regimens, shelf life, manufacturing controls (CMC), and deployment logistics across clinical, agricultural, and environmental settings. [7]

- **Safety & governance:** biocontainment systems, strategies to block gene transfer and environmental escape, plus regulatory/standardisation frameworks. [8]

#### Maturity indicators that would constitute strong evidence

- **Regulated products** (or late-stage clinical pipelines) demonstrating repeatable clinical outcomes and manufacturable dosing forms. [9]
- **Large multi-site trials / real-world cohorts** (hundreds of participants) showing safety and durable outcomes across heterogeneous populations. [10]
- **Field trials** in agriculture/environment showing quantified functional benefit (e.g., kg N/ha delivered; pollutant degradation), plus “commercial-grade” formulations. [11]
- **Standardisation & QA infrastructure:** ISO technical specifications, government/consortium standardisation reports, and validated reference materials supporting workflow benchmarking. [12]
- **Rapid monitoring + feedback loops** demonstrated with real-time analytics and dashboards (moving from “sample once” to “operate continuously”). [13]
- **Biosafety controls** validated in vivo/ex situ (e.g., preventing escape, blocking horizontal transfer, or timed self-destruction). [14]

#### Evidence (10–20 recent, reliable sources)

##### Portfolio coverage

The dossier below intentionally spans (i) **gut microbiome actuation** (regulated products + defined consortia trials), (ii) **environmental/soil actuation** (field and bioremediation demonstrations), and (iii) enabling infrastructure for a “toolkit” approach—**measurement, standards, benchmarking, and monitoring**—plus (iv) **precision/engineered interventions and biocontainment** for safety and governance. [15]

#### 1) ISO/TS 24420:2023 Biotechnology — Massively parallel DNA sequencing — General requirements for data processing of shotgun metagenomic sequences

Authors/Org: International Organization for Standardization[16] (ISO)

Venue/type: Standards body technical specification

Publication date: May 2023 (Edition 1, 2023-05)

Link: <https://www.iso.org/standard/78741.html>

Key evidence: Establishes requirements and guidance for **QC, metadata, storage and interoperability** for shotgun metagenomic processing across host-associated and environmental metagenomes—an indicator that microbiome measurement pipelines are moving from artisanal practice toward standardised, auditable workflows. [17]

#### 2) Challenges and current actions to address standardisation of the human gut microbiome analysis (JRC139121 / EUR 40029)

Authors/Org: Brigitte Toussaint[18]; European Commission Joint Research Centre[19]

Venue/type: Authoritative government lab/report (EU)

Publication date: September 2024

Link:

[https://www.researchgate.net/publication/384596584\\_Challenges\\_and\\_current\\_actions\\_to\\_address\\_standardisation\\_of\\_the\\_human\\_gut\\_microbiome\\_analysis](https://www.researchgate.net/publication/384596584_Challenges_and_current_actions_to_address_standardisation_of_the_human_gut_microbiome_analysis)

Key evidence: Documents that gut microbiome analysis is already “on the market” but highlights key maturity blockers—**high inter-individual variability, reference material**

**scarcity, and incomplete standardisation**—which directly maps to the ART’s stated constraints and validation burden. [20]

### 3) **Analytical assessment of metagenomic workflows for pathogen detection with NIST RM 8376 and two sample matrices**

Authors/Org: Jason G. Kralj[21] et al.; (uses National Institute of Standards and Technology[22] RM 8376)

Venue/type: Peer-reviewed paper (Microbiology Spectrum)

Publication date: April 2025

Link: <https://doaj.org/article/e7ab083aaa624feabb7a0088ab64e67c>

Key evidence: Uses a NIST reference material to benchmark **analytical performance** of metagenomic workflows for pathogen detection—strong evidence that microbiome measurement/control is developing the QA/validation scaffolding needed for regulated and industrial deployments. [23]

### 4) **Rapid absolute quantification of pathogens and ARGs by nanopore sequencing**

Authors/Org: Yu Yang[24] et al.

Venue/type: Peer-reviewed paper (Science of The Total Environment)

Publication date: February 2022 (Volume 809, 25 Feb 2022)

Link:

<https://www.sciencedirect.com/science/article/abs/pii/S0048969721072661>

Key evidence: Demonstrates **near real-time (1-hour sequencing)** nanopore metagenomics with cellular spike-ins for *absolute* quantification of pathogens and antibiotic-resistance genes in wastewater—directly supporting feasible “monitoring + feedback” loops rather than slow batch testing. [25]

### 5) **Nanopore long-read-only metagenomics enables complete and high-quality genome reconstruction from mock and complex metagenomes**

Authors/Org: Lei Liu[26] et al.

Venue/type: Peer-reviewed paper (Microbiome)

Publication date: December 2022 (02.12.2022)

Link: <https://vbn.aau.dk/en/publications/nanopore-long-read-only-metagenomics-enables-complete-and-high-qu>

Key evidence: Reports a pipeline (“NanoPhase”) enabling **high-quality genome reconstruction directly from nanopore long reads** (including 275 MAGs from activated sludge with ~90% median completeness), enabling higher-resolution tracking and design of community functions. [27]

### 6) **A rapid bacterial pathogen and antimicrobial resistance diagnosis workflow using Oxford nanopore adaptive sequencing method**

Authors/Org: Hang Cheng[28] et al.

Venue/type: Peer-reviewed paper (Briefings in Bioinformatics)

Publication date: November 2022 (Volume 23, Issue 6)

Link: <https://academic.oup.com/bib/article-abstract/23/6/bbac453/6762743>

Key evidence: Shows a clinical metagenomics workflow achieving **~4.5 hours sample-to-result** and **≥8× microbial sequence yield** in 21 BALF samples—evidence that rapid microbiome/pathogen profiling can reach clinically relevant timelines. [29]



### 7) **MMonitor for real-time monitoring of microbial communities using long reads**

Authors/Org: Timo N. Lucas[30] et al.

Venue/type: Peer-reviewed software platform paper (open access; GUI + web dashboard)

Publication date: January 2026 (collection date 26 Jan 2026)

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12853177/>

Key evidence: Provides an open-source **real-time analysis + visualisation dashboard** for nanopore metagenomics (taxonomic composition over time, diversity indices, correlations), explicitly targeting “monitoring” use-cases rather than offline analysis—matching the ART’s “dashboard + at-home/field tests” direction. [31]

### 8) **Engineering natural microbiomes toward enhanced bioremediation by microbiome modeling**

Authors/Org: Zhepu Ruan[32] et al.

Venue/type: Peer-reviewed paper (Nature Communications)

Publication date: June 2024 (Published 01 Jun 2024)

Link: <https://www.nature.com/articles/s41467-024-49098-z>

Key evidence: Demonstrates a top-down + bottom-up framework where herbicide + inoculation drives **convergent community succession**, and introduces **SuperCC** to model metabolic interactions; constructs a synthetic microbiome using **18 “keystone” species** for enhanced soil bioremediation—direct evidence that modelling-guided community design is becoming practical. [4]

### 9) **U.S. Food and Drug Administration[33] product page: REBYOTA (fecal microbiota, live-jslm)**

Authors/Org: FDA (product page; manufacturer listed as Ferring Pharmaceuticals Inc.[34])

Venue/type: Government regulator product record

Publication date: December 2022 (content current as of 19 Dec 2022)

Link: <https://www.fda.gov/vaccines-blood-biologics/vaccines/rebyota>

Key evidence: Confirms REBYOTA’s regulated indication (prevention of recurrent CDI after antibiotics) and provides regulatory artefacts (approval letter/SBRA), indicating microbiome-based ecosystem “reset” is beyond PoC and into licensed medical products. [35]

### 10) **Efficacy and Safety of RBX2660 in PUNCH CD3... for the Prevention of Recurrent Clostridioides difficile Infection**

Authors/Org: Sahil Khanna[36] et al.

Venue/type: Peer-reviewed Phase III RCT paper (Drugs, open access)

Publication date: October 2022 (Published 26 Oct 2022)

Link: <https://link.springer.com/article/10.1007/s40265-022-01797-x>

Key evidence: Phase III placebo-controlled trial reports Bayesian model estimates of **treatment success 70.4% vs 58.1%** (RBX2660 vs placebo) within 8 weeks, supporting plausibility and manufacturable delivery (single-dose enema) for microbiome therapeutics. [37]

### 11) **PUNCH CD3-OLS: A Phase 3 prospective observational cohort study... (REBYOTA) in adults with recurrent CDI**

Authors/Org: Paul Feuerstadt[38] et al.

Venue/type: Peer-reviewed paper (Clinical Infectious Diseases)

Publication date: January 2025 (15 Jan 2025)

Link: <https://academic.oup.com/cid/article/80/1/43/7740543>

Key evidence: Reports a large open-label cohort with **697 treated participants** and **73.8% treatment success at 8 weeks** plus **91.0% sustained response at 6 months** among successes—evidence of late-stage maturity and broad-population performance beyond tightly controlled RCTs. [10]

#### 12) **FDA news release: approval of Vowst as first orally administered fecal microbiota product for preventing recurrent CDI**

Authors/Org: FDA (approval granted to Seres Therapeutics Inc.[39] noted)

Venue/type: Government regulator press announcement

Publication date: April 2023 (26 Apr 2023)

Link: <https://www.fda.gov/news-events/press-announcements/fda-approves-first-orally-administered-fecal-microbiota-product-prevention-recurrence-clostridioides>

Key evidence: Provides controlled-trial effectiveness data (**12.4% recurrence vs 39.8% placebo** through 8 weeks) and an oral capsule regimen (4 capsules daily for 3 days), signalling a major maturity step: clinically validated, patient-friendly form factor. [40]

#### 13) **Vowst Summary Basis for Regulatory Action (SBRA) (PDF)**

Authors/Org: FDA CBER review (SBRA document)

Venue/type: Government regulator technical review (CMC + clinical summary)

Publication date: April 2023 (dated 26 Apr 2023)

Link: <https://www.fda.gov/media/168002/download>

Key evidence: Specifies product engineering details: Vowst is a spore suspension in capsules with **1×10<sup>6</sup> to 3×10<sup>7</sup> spore CFU per capsule**, dosed **4 capsules/day for 3 days**, and reports **36-month shelf life** when stored at 2°C–25°C—clear maturity signals for manufacturing, stability and deployment logistics. [41]

#### 14) **VE303, a defined bacterial consortium, for prevention of recurrent CDI: a randomised clinical trial**

Authors/Org: Thomas Louie[42] et al.

Venue/type: Peer-reviewed paper (JAMA randomised clinical trial)

Publication date: April 2023 (Published online 15 Apr 2023)

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10105904/>

Key evidence: Tests a **defined 8-strain consortium**; through week 8, recurrence was **13.8% (high dose)** vs **45.5% (placebo)** under an inclusive outcome definition—direct evidence that “engineered” can mean rationally defined consortia, not only donor-derived mixtures. [43]

#### 15) **In situ targeted base editing of bacteria in the mouse gut**

Authors/Org: Andreas K. Brödel[44] et al.

Venue/type: Peer-reviewed experimental paper (Nature)

Publication date: July 2024 (Published 10 Jul 2024; issue Aug 2024)

Link: <https://www.nature.com/articles/s41586-024-07681-w>

Key evidence: Demonstrates “actuation” at the gene level: a phage-derived (M13) particle delivering a base editor achieved **high in situ editing efficiency (reported ~93%)** in gut bacteria in mice—strong plausibility evidence for precision microbiome engineering, albeit preclinical. [45]

#### 16) **Engineered phage with antibacterial CRISPR-Cas selectively reduce E. coli burden in mice**

Authors/Org: Yilmaz Emre Gencay[46] et al. (affiliations include SNIPR BIOME ApS[47])

Venue/type: Peer-reviewed experimental paper (Nature Biotechnology)

Publication date: February 2024 (Epub May 2023)

Link: <https://pubmed.ncbi.nlm.nih.gov/37142704/>

Key evidence: Screens 162 wild-type phages, engineers selected phages with tail fibres + CRISPR-Cas payloads, and reports a 4-phage cocktail (SNIPR001) that is **well tolerated in mice and minipigs** and reduces gut E. coli burden; paper notes entry into clinical development—evidence bridging lab engineering to translational pipelines. [48]

#### 17) **Cas9-assisted biological containment of a genetically engineered human commensal bacterium and genetic elements**

Authors/Org: Naoki Hayashi[49] et al.

Venue/type: Peer-reviewed experimental paper (Nature Communications)

Publication date: March 2024 (Published 07 Mar 2024)

Link: <https://www.nature.com/articles/s41467-024-45893-w>

Key evidence: Implements a biocontainment architecture combining thymidine auxotrophy with a CRISPR device designed to **prevent escape via horizontal gene transfer** and **block transgene dissemination**, validated in vitro and in vivo—directly addressing the ART’s safety constraints. [50]

#### 18) **Biocontainment strategies for in vivo applications of Saccharomyces boulardii**

Authors/Org: Karl Alex Hedin[51] et al.

Venue/type: Peer-reviewed experimental paper (Frontiers in Bioengineering and Biotechnology)

Publication date: February 2023 (Published 20 Feb 2023)

Link: <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2023.1136095/full>

Key evidence: Reports a **multi-layered biocontainment** strategy for a probiotic yeast chassis (thiamine auxotrophy; temperature sensitivity), showing restricted growth and **in-mouse tolerance** with retained peptide production—evidence that containment engineering is becoming a practical design axis, not an afterthought. [52]

#### 19) **Genetic “expiry-date” circuits control lifespan of synthetic scavenger bacteria for safe bioremediation**

Authors/Org: Kha Mong Tran[53] et al.

Venue/type: Peer-reviewed experimental paper (Nucleic Acids Research)

Publication date: July 2025 (Published 24 Jul 2025; issue Aug 2025)

Link: <https://academic.oup.com/nar/article/53/14/gkaf703/8211935>

Key evidence: Demonstrates engineered “expiry-date” kill circuits achieving an escape rate **below a cited NIH release standard ( $<10^{-10}$ )** and shows ex situ soil bioremediation where **0.1 g/kg phenol** is detoxified within **4 days** followed by bacterial self-elimination—evidence toward “single-function then fade-out” actuation demanded in the ART. [54]

#### 20) **Genetic remodeling of soil diazotrophs enables partial replacement of synthetic nitrogen fertilizer with biological nitrogen fixation in maize**

Authors/Org: Rafael Martinez-Feria[55] et al.

Venue/type: Peer-reviewed field + lab paper (Scientific Reports)

Publication date: November 2024 (Published 12 Nov 2024)

Link: <https://www.nature.com/articles/s41598-024-78243-3>

Key evidence: Uses non-transgenic gene-edited strains and reports multiple evidence layers (in vitro/in planta/field, including  $^{15}\text{N}$  tracers); inoculation with a “commercial-grade” formulation (PIVOT BIO PROVEN® 40) provides **~21 kg N/ha** to maize by VT-R1 stages on average—strong evidence that soil microbiome “nudges” can be quantified in agronomic field conditions. [11]

### Maturity score (1–7) and reasoning

#### Final maturity score

5

#### Evidence-to-rubric mapping

##### What rules out levels 1–4 (why this is beyond early research):

Clinical microbiome actuation is no longer limited to lab prototypes: multiple peer-reviewed Phase III/late-phase datasets show statistically meaningful reductions in recurrent CDI using microbiota-based therapies and defined consortia, and regulator publications document licensed/approved products and manufacturing considerations (dosing, potency ranges, shelf life). [56]

In parallel, environmental/soil microbiome interventions have crossed into field-quantified performance with isotope tracer evidence and “commercial-grade” formulations in maize systems. [11]

Measurement and operational infrastructure is maturing via standards, reference materials, and real-time monitoring tools—indicating an ecosystem forming around deployment and validation, not just discovery. [57]

##### Why the evidence does not yet justify level 6 for the ART as a whole:

Some sub-areas clearly reach “product” status (notably recurrent CDI treatments), but the ART claim is broader: a **configurable toolkit** with reliable measurement → prediction → actuation across *many* biomes and outcomes. Key blockers remain: (i) predictive design still looks context-specific (even where modelling exists), (ii) standardisation and reference materials are still described as incomplete, and (iii) for many high-value applications (metabolic/inflammatory modulation, ecosystem management at scale), evidence is still dominated by preclinical demonstrations and targeted PoCs rather than widespread scaled operations with documented adoption curves. [58]

Level 5 best matches today’s overall state: **multiple well-capitalised actors and parallel translational tracks** (FDA-regulated products; defined consortia; engineered phage approaches moving into clinical development; agricultural formulations with field evidence) are advancing quickly, but broad scaling and general-purpose predictive control remain incomplete. [59]

#### Sub-score breakdown and aggregation

- **Measurement + monitoring tooling** → ~6  
Rationale: rapid, operationally plausible sequencing workflows (including near real-time quantification) plus standards/benchmarking and monitoring dashboards. [3]
- **Design / predictive models for community steering** → ~4  
Rationale: modelling pipelines and design frameworks exist and can select/construct functional microbiomes (e.g., SuperCC + 18 keystone species), but broad

generalisation and robust closed-loop control across domains is not yet established. [4]

- **Actuation in human gut (microbiota-derived products + defined consortia)** → ~6  
Rationale: multiple late-stage clinical outcomes and regulator-documented products with defined regimens (including oral capsule delivery). [60]
- **Actuation in soil/environment (bioinoculants / synthetic microbiomes)** → ~5  
Rationale: field and tracer evidence with quantified benefit and commercial-grade formulations; still heterogeneous and context-dependent. [61]
- **Precision actuation + containment (engineered phage, in situ editing, biocontainment circuits)** → ~3–4  
Rationale: strong preclinical in vivo feasibility and concrete containment strategies, but limited evidence of routine, regulated real-world deployment at scale. [62]

**Aggregation method:** average-based (bundle with materially different application contexts). Averaging the above (6, 4, 6, 5, ~3.5) yields ~4.9 → rounded to **5**, reflecting that while some applications are already “product-level”, the ART’s defining bottleneck—**repeatable design + control across ecosystems**—is not yet at the deployment-and-scaling stage required for a 6–7 overall score. [63]

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<https://www.nature.com/articles/s41467-024-49098-z>

[2] [13] [28] [31] <https://pmc.ncbi.nlm.nih.gov/articles/PMC12853177/>

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[https://www.researchgate.net/publication/384596584\\_Challenges\\_and\\_current\\_actions\\_to\\_address\\_standardisation\\_of\\_the\\_human\\_gut\\_microbiome\\_analysis](https://www.researchgate.net/publication/384596584_Challenges_and_current_actions_to_address_standardisation_of_the_human_gut_microbiome_analysis)

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[27] [47] <https://vbn.aau.dk/en/publications/nanopore-long-read-only-metagenomics-enables-complete-and-high-qu>

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## ART 09.073 Precision Medicine & Genomic Diagnostics

### ART extraction

#### A) Primary capability claimed (core output of the ART)

- Combine low-cost whole-genome (or near-whole-genome) sequencing with repeatable, minimally invasive molecular sampling (e.g., blood-based multi-omics) to produce *actionable* risk estimates, treatment response predictions, and longitudinal monitoring markers. [\[1\]](#)
- Deliver results as plain-language summaries with confidence and follow-up recommendations (rather than raw genomic data), and expose standardised software interfaces so authorised tools can query results and trigger clinical decision support. [\[2\]](#)
- Operate as an evolving “learning” system: continuously updated reference datasets and models, plus audit trails tying recommendations to supporting evidence. [\[3\]](#)

#### B) Key sub-components / sub-threads in the bundle (technology + deployment stack)

- Clinical-grade whole-genome sequencing (short-read WGS as current workhorse, plus increasing long-read WGS to resolve complex genes/structural variants). [\[4\]](#)
- Variant interpretation infrastructure (curated knowledgebases and classification processes; ongoing updating and re-interpretation workflows). [\[5\]](#)
- Interoperability layer (standardised APIs and data models linking genomics repositories to EHR/workflow apps). [\[6\]](#)
- Longitudinal molecular monitoring (cfDNA methylation-based multicancer early detection; blood-based multi-omics predictors of therapy response; proteomic risk prediction models). [\[7\]](#)
- Population-scale reference datasets with improved diversity representation (required for generalisable risk estimation). [\[8\]](#)
- Operational governance in real health systems (test directories/commissioning, turnaround-time monitoring, national data flows) and associated privacy/consent controls. [\[9\]](#)

#### C) What maturity indicators would count as evidence for this ART

- National or population-scale deployments producing and using genomic data at high volume (clear indicator of scale, pipeline stability, and investment). [\[10\]](#)
- Clinical commissioning / routine service integration (e.g., a national test directory specifying which genomic tests are paid for, and by whom). [\[11\]](#)
- Demonstrated clinical feasibility and quantified false-positive/false-negative burden for longitudinal monitoring (especially screening/early detection). [\[12\]](#)
- Peer-reviewed evidence that new modalities improve actionable performance vs prior baselines (e.g., diagnostic yield uplift from long-read sequencing; improved prediction from proteomics). [\[13\]](#)
- Standardised data exchange mechanisms (published interfaces/operations; evidence of pilots/ballots) enabling cross-organisation tooling. [\[6\]](#)

- Evidence maintenance/updates in interpretation knowledgebases (a practical requirement for continuous learning and auditability). [5]

## 2. Evidence (10–20 recent, reliable sources)

**Source selection note:** All entries below are within the strict window **Feb 2022–Feb 2026** and prioritise peer-reviewed papers plus authoritative public programmes and standards artefacts.

### 1) Recommendations for whole genome sequencing in diagnostics for rare diseases

**Authors/organisation:** EuroGentest[14] and the Solve-RD[15] initiative (multi-author guidance)

**Venue/type:** Peer-reviewed guideline article (European Journal of Human Genetics)

**Publication date:** May 2022 (version of record; issue date Sept 2022)

**Link:** <https://www.nature.com/articles/s41431-022-01113-x>

**Why it matters:** Explicitly frames WGS as increasingly introduced for rare disease diagnostics and motivates updated guidance because WGS can capture multiple variant classes (including structural variants and repeat expansions), directly supporting plausibility and clinical integration signals. [16]

### 2) Recommendations for reporting results of diagnostic genomic testing

**Authors/organisation:** European Society of Human Genetics[17]-led expert group (multi-author consensus)

**Venue/type:** Peer-reviewed guideline article (European Journal of Human Genetics)

**Publication date:** April 2022 (published online)

**Link:** <https://doi.org/10.1038/s41431-022-01091-0>

**Why it matters:** Provides concrete reporting guidance intended to reduce misinterpretation and explicitly recognises modern result types (including CNVs and mentions of polygenic risk scores/pharmacogenetics), aligning with the ART’s “plain-language summary + careful communication” requirement. [18]

### 3) National genomic test directory: Testing criteria for rare and inherited disease (Eligibility criteria), Version 7

**Authors/organisation:** NHS England[19]

**Venue/type:** National commissioning criteria (authoritative health-system document)

**Publication date:** July 2024

**Link:** <https://www.england.nhs.uk/wp-content/uploads/2024/07/national-genomic-test-directory-rare-and-inherited-disease-eligibility-criteria-v7.pdf>

**Why it matters:** Demonstrates “real system” maturity: the document states the National Genomic Test Directory governs which tests are commissioned and paid for by the NHS and must be delivered by Genomic Laboratory Hubs—strong evidence of operational integration beyond research pilots. [11]

### 4) England Rare Diseases Action Plan 2024: main report

**Authors/organisation:** UK Government (Department of Health and Social Care)

**Venue/type:** Government programme report / roadmap

**Publication date:** 2024

**Link:** <https://www.gov.uk/government/publications/england-rare-diseases-action-plan-2024/england-rare-diseases-action-plan-2024-main-report>

**Why it matters:** States that transfer of whole-genome sequencing data to the national congenital anomaly and rare disease registration service was expected in early 2024 and intended to expand after initial proof-of-principle, indicating scaling of genomic data flows and governance—not just sequencing capacity. [20]

#### 5) NHS Genomic Medicine Service data release v1 (15/06/2022)

**Authors/organisation:** Genomics England[21]

**Venue/type:** Programme data release note (authoritative consortium technical documentation)

**Publication date:** June 2022

**Link:** [https://re-docs.genomicsengland.co.uk/gms\\_release1/](https://re-docs.genomicsengland.co.uk/gms_release1/)

**Why it matters:** A dated “data release” indicates durable operational infrastructure (data models, release processes, and controlled access) consistent with an ecosystem where genomic outputs “travel across organisations over time.” [22]

#### 6) NHS Genomic Medicine Service data release v5 (28/08/2025)

**Authors/organisation:** Genomics England

**Venue/type:** Programme data release note (authoritative consortium technical documentation)

**Publication date:** August 2025

**Link:** [https://re-docs.genomicsengland.co.uk/gms\\_release5/](https://re-docs.genomicsengland.co.uk/gms_release5/)

**Why it matters:** Later release numbering and dated publishing show the programme is iterating continuously (release cadence + change summaries), supporting maturity as an evolving “learning” data platform rather than a one-off project. [23]

#### 7) DNA Sequencing Costs: Data

**Authors/organisation:** National Human Genome Research Institute[24]

**Venue/type:** Authoritative government cost-tracking dataset and methodology note

**Publication date:** May 2023

**Link:** <https://www.genome.gov/about-genomics/fact-sheets/DNA-Sequencing-Costs-Data>

**Why it matters:** Provides the cost-per-genome tracking framework (including assumptions such as genome size and coverage parameters) used widely to quantify the “low-cost genome” trajectory; this underpins plausibility of shifting comprehensive profiling from thousands toward lower price bands over time. [25]

#### 8) Genomic data in the All of Us Research Program

**Authors/organisation:** All of Us Research Program[26] Genomics Investigators

**Venue/type:** Peer-reviewed large-scale data release paper (Nature)

**Publication date:** 2024

**Link:** <https://www.nature.com/articles/s41586-023-06957-x>

**Why it matters:** Reports a data release of ~245,000 clinical-grade genome sequences within a scalable framework aiming toward ≥1 million participants; this is direct evidence that industrialised WGS generation and linkage to health data is already occurring at national scale. [27]

#### 9) All of Us Genomic Quality Report (release metrics)

**Authors/organisation:** All of Us Research Program (user support / platform release documentation)

**Venue/type:** Authoritative programme technical report (release counts)

**Publication date:** February 2025 (release date specified)

**Link:** <https://support.researchallofus.org/hc/en-us/articles/29390274413716-All-of-Us-Genomic-Quality-Report>

**Why it matters:** States that (as of Feb 3, 2025) the programme released genomic data including **414,830 short-read WGS samples, 97,061 structural-variant-call sets, and 2,800 long-read WGS samples**—hard scale evidence for both sequencing and variant-calling pipelines. [28]

#### 10) **Introducing HL7 FHIR Genomics Operations: a developer-friendly approach to genomics–EHR integration**

**Authors/organisation:** HL7 International[29]-aligned multi-stakeholder authorship (FHIR genomics operations work)

**Venue/type:** Peer-reviewed informatics standards/implementation paper (JAMIA)

**Publication date:** December 2022 (issue March 2023)

**Link:** <https://academic.oup.com/jamia/article/30/3/485/6957062>

**Why it matters:** Describes **15 FHIR Genomics Operations** designed for clinical scenarios including variant discovery, hereditary/pharmacogenomic screening, and variant reanalysis, and notes maturation via balloting, connectathons, and pilots—direct evidence for the ART’s “standardised software interface” claim. [30]

#### 11) **HL7 Genomics Reporting Implementation Guide package build record (STU2 / v2.0.0 build timestamp)**

**Authors/organisation:** HL7 Genomics Reporting IG build artefact (package list)

**Venue/type:** Standards artefact / build metadata (implementation guide packaging)

**Publication date:** May 2022 (build timestamp shown)

**Link:** <https://build.fhir.org/ig/paciowg/sample-data-fsh/>

**Why it matters:** The build metadata lists the Genomics Reporting IG package and a May 2022 build timestamp for a released package version, supporting that computable genomics reporting structures exist as maintained standard artefacts (a prerequisite for interoperable decision platforms). [31]

#### 12) **Longitudinal multi-omics analysis identifies early blood-based predictors of anti-TNF therapy response in inflammatory bowel disease**

**Authors/organisation:** Multi-institution academic collaboration (longitudinal multi-omics cohort study)

**Venue/type:** Peer-reviewed experimental paper (Genome Medicine)

**Publication date:** September 2022

**Link:** <https://link.springer.com/article/10.1186/s13073-022-01112-z>

**Why it matters:** Demonstrates that repeated blood-based multi-omics can yield early predictors of drug response (anti-TNF), supporting the plausibility of “repeatable molecular snapshots” feeding decision models beyond genomics alone. [32]

#### 13) **PATHFINDER: A Prospective Cohort Study of Blood-Based Multi-cancer Early Detection**

**Authors/organisation:** Multi-site US health network cohort; funded by GRAIL[33]

**Venue/type:** Peer-reviewed prospective cohort study (MCED feasibility; accessible via PMC)

**Publication date:** 2023 (year shown; detailed protocol/results)

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11027492/>

**Why it matters:** In 6,662 adults  $\geq 50$ , the test produced 1.4% “cancer signal detected” results with **35 true positives vs 57 false positives**, and quantified downstream diagnostic workups and time-to-resolution—highly relevant to both feasibility *and* the ART’s acknowledged false-positive/communication constraints. [12]

#### 14) Proteomic signatures improve risk prediction for common and rare diseases

**Authors/organisation:** UKB-PPP / external replication cohorts (large-scale proteomics modelling)

**Venue/type:** Peer-reviewed experimental paper (Nature Medicine)

**Publication date:** 2024

**Link:** <https://www.nature.com/articles/s41591-024-03142-z>

**Why it matters:** Shows that sparse plasma protein models can generalise (replication in EPIC-Norfolk for multiple diseases) and improve prediction beyond clinical benchmarks for tested outcomes—direct evidence that non-genomic molecular layers can become actionable risk/monitoring signals. [34]

#### 15) Long-read genome sequencing and variant reanalysis increase diagnostic yield in neurodevelopmental disorders

**Authors/organisation:** Academic clinical genomics collaboration using PacBio[35] HiFi

**Venue/type:** Peer-reviewed clinical reanalysis study (accessible via PMC)

**Publication date:** 2024

**Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11610584/>

**Why it matters:** Applies long-read genome sequencing to **96 short-read-negative probands** and frames long reads as a more comprehensive variant detection approach; this supports the plausibility of consolidating otherwise fragmented diagnostics toward a single assay as costs fall. [36]

#### 16) Utility of long-read sequencing for All of Us

**Authors/organisation:** Long-read pilot analysis within All of Us (multi-team evaluation)

**Venue/type:** Peer-reviewed technology evaluation (Nature Communications)

**Publication date:** 2024

**Link:** <https://www.nature.com/articles/s41467-024-44804-3>

**Why it matters:** Compares long-read approaches and reports that HiFi reads were most accurate for both small and large variants, highlighting concrete performance trade-offs for “near-whole-genome” completeness targeted at medically relevant complex genes. [37]

#### 17) Structural variation in 1,019 diverse humans based on long-read sequencing

**Authors/organisation:** International long-read population resource team (1000 Genomes populations)

**Venue/type:** Peer-reviewed population reference paper (Nature)

**Publication date:** 2025

**Link:** <https://www.nature.com/articles/s41586-025-09290-7>

**Why it matters:** Builds a long-read SV resource across **26 populations**, directly supporting the ART claim that model quality depends on representation and that reference datasets are actively expanding beyond historically narrow ancestries. [38]

#### 18) The clinical application of polygenic risk scores: a points to consider statement

**Authors/organisation:** American College of Medical Genetics and Genomics[39]

**Venue/type:** Peer-reviewed professional guidance (Genetics in Medicine)

**Publication date: May 2023****Link:** <https://pubmed.ncbi.nlm.nih.gov/36920474/>**Why it matters:** Provides explicit guardrails on where PRS are (and are not) ready for clinical use—evidence that “risk estimates” exist but require careful validation and communication, matching the ART’s constraints around uncertainty, shifting interpretation, and population bias. [40]**19) ClinVar: updates to support classifications of both germline and somatic variants****Authors/organisation:** ClinVar[41] team (NCBI/NLM ecosystem)**Venue/type:** Peer-reviewed database update paper (Nucleic Acids Research)**Publication date: 2025****Link:** <https://academic.oup.com/nar/article/53/D1/D1313/7907366>**Why it matters:** Describes concrete platform updates (e.g., VCV pages displaying multiple classification types and support for broader submissions), which is essential infrastructure for continuous evidence updates and transparent interpretation—core to the ART’s “learning + audit trail” layer. [42]**20) CIViCdb 2022: evolution of an open-access cancer variant interpretation knowledgebase****Authors/organisation:** CIViC[43] community + curator/moderator team**Venue/type:** Peer-reviewed database/resource update paper (Nucleic Acids Research)**Publication date: November 2022** (published online)**Link:** <https://academic.oup.com/nar/article/51/D1/D1230/6827107>**Why it matters:** Reports continued expansion of structured, literature-derived evidence items and interoperability features, directly supporting the feasibility of evidence-backed recommendations that can be accessed “globally and in real time” rather than re-curated per institution. [44]**3. Maturity score (1–7) and reasoning****A) Final maturity score: 6****B) Evidence-to-rubric justification****What rules out levels 1–4 (the ART is beyond theory/lab-only PoC):**

Large-scale, operational genomic production and data integration are demonstrably happening in major programmes and national systems. The All of Us programme describes a release of ~245,000 clinical-grade genomes with a scalable framework, and programme release documentation indicates hundreds of thousands of short-read WGS samples with variant calls are already released to researchers—this is far beyond laboratory prototype or isolated proof-of-concept. [45] Likewise, NHS England’s National Genomic Test Directory acts as commissioning infrastructure for genomics tests within a national health service, indicating that genomic diagnostics are embedded in routine care pathways (even as modalities evolve). [11]

**Why level 6 (not level 5):**

Level 6 requires that “products are being delivered ... in increasing amounts” and that scale-up is underway. Across the bundle, multiple components meet this bar:



- **Genome sequencing at industrial scale:** All of Us release metrics and the Nature data release paper jointly indicate sustained high-throughput generation, QC, and dissemination of WGS and derived variant sets (including SV calls and long-read WGS subsets). [46]
- **Health-system operationalisation:** The NHS test directory commissioning logic and government action-plan commitments to expand WGS data transfer into national registries indicate that genomics is not merely “post-PoC competing prototypes,” but part of ongoing service delivery and data governance. [9]
- **Interoperability mechanisms moving into deployable standards/pilots:** HL7 FHIR Genomics Operations (15 defined operations) are explicitly described as being matured through balloting, connectathons, and pilots—an adoption pathway aligned with deployable interfaces rather than research-only formats. [30]
- **Expanding application areas (beyond rare disease):** Evidence spans rare disease diagnostics guidance (WGS), cancer screening feasibility via cfDNA methylation, proteomic risk prediction for multiple diseases, and therapy response prediction from longitudinal multi-omics—consistent with clinical expansion rather than a single niche. [47]

**What is still missing to justify level 7 (full competitive, demand-driven mass-market maturity of the integrated platform):**

The ART description implies a *unified* “testing-and-decision platform” that routinely combines low-cost genome-scale sequencing plus repeated multi-omic monitoring with harmonised APIs, plain-language outputs, and robust audit trails across organisations. The evidence shows strong maturity in **sequencing + national scale data** and credible progress in **multi-omics monitoring** and **standards**, but gaps remain for level 7:

- **Clinical utility at population scale for continuous molecular screening/monitoring** is not yet established as routine standard of care (PATHFINDER explicitly frames feasibility and the need for further clinical-utility evidence; false positives and diagnostic cascades remain material). [12]
- **Uniform, cross-vendor interoperability at the point of care** is still a work-in-progress (FHIR genomics operations and IG artefacts exist, but broad, consistent deployment across EHRs and labs is not demonstrated here as ubiquitous). [6]
- **Risk modelling generalisability and representation** remains an active frontier: even with major diversity-driven resources (All of Us; long-read SV resources across 26 populations), the ART’s emphasis on model robustness across populations implies ongoing work before “routine risk estimates” are universally dependable. [8]
- **Polygenic risk scoring as routine clinical tooling** is constrained by explicit professional guidance emphasising careful clinical application and limitations—suggesting that some “risk estimate” outputs are still in maturation rather than universally productised. [40]

**C) Sub-component maturity breakdown and aggregation approach**

Because the ART is a bundle where sub-components are at meaningfully different stages, the score reflects a *weighted average* (heavier weight to genome sequencing + core clinical diagnostics infrastructure, lighter weight to emerging longitudinal multi-omics and universal interoperability).

- **Clinical-grade short-read WGS in health systems** → **6** (scaled programmes + commissioning infrastructure) → supported by NHS commissioning criteria and All of Us scale evidence. [48]
- **Long-read WGS as a clinical diagnostic upgrade** → **4–5** (demonstrated clinical reanalysis benefit; still transitioning toward broader routine) → supported by rare-disease reanalysis and All of Us long-read evaluation papers. [49]
- **Variant interpretation “learning layer” (knowledgebases + updates)** → **6** (mature, continuously updated infrastructure used broadly) → supported by ClinVar and CIViCdb update papers. [5]
- **Longitudinal multi-omics monitoring for prediction/response** → **4–5** (strong feasibility/association evidence; uneven routine adoption and outcome validation) → supported by PATHFINDER feasibility metrics, IBD drug-response multi-omics, and proteomic risk modelling. [7]
- **Standardised software interfaces for querying results (genomics ↔ EHR)** → **5** (defined operations + maturation pathway; not shown as ubiquitous) → supported by HL7 FHIR Genomics Operations paper and IG artefact evidence. [6]

**Aggregation to one score:** with sequencing + service infrastructure and interpretation knowledgebases already operating at scale (pulling upward) and longitudinal multi-omics + universal interoperability still uneven (pulling downward), the combined maturity most consistently matches **Level 6** rather than Level 5 or Level 7. [50]

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[1] [4] [16] [47] <https://www.nature.com/articles/s41431-022-01113-x>

<https://www.nature.com/articles/s41431-022-01113-x>

[2] [18] <https://d-nb.info/1272932427/34>

<https://d-nb.info/1272932427/34>

[3] [10] [14] [28] [46] [50] <https://support.researchallofus.org/hc/en-us/articles/29390274413716-All-of-Us-Genomic-Quality-Report>

<https://support.researchallofus.org/hc/en-us/articles/29390274413716-All-of-Us-Genomic-Quality-Report>

[5] [42] <https://academic.oup.com/nar/article/53/D1/D1313/7907366>

<https://academic.oup.com/nar/article/53/D1/D1313/7907366>

[6] [21] [24] [26] [30] [33] [35] [43] <https://academic.oup.com/jamia/article/30/3/485/6957062>

<https://academic.oup.com/jamia/article/30/3/485/6957062>

[7] [12] [19] [39] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11027492/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11027492/>

[8] [15] [27] [41] [45] <https://www.nature.com/articles/s41586-023-06957-x>

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[9] [11] [48] <https://www.england.nhs.uk/wp-content/uploads/2024/07/national-genomic-test-directory-rare-and-inherited-disease-eligibility-criteria-v7.pdf>

<https://www.england.nhs.uk/wp-content/uploads/2024/07/national-genomic-test-directory-rare-and-inherited-disease-eligibility-criteria-v7.pdf>

[13] [17] [36] [49] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11610584/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11610584/>

[20] [29] <https://www.gov.uk/government/publications/england-rare-diseases-action-plan-2024/england-rare-diseases-action-plan-2024-main-report>

<https://www.gov.uk/government/publications/england-rare-diseases-action-plan-2024/england-rare-diseases-action-plan-2024-main-report>

[22] [https://re-docs.genomicsengland.co.uk/gms\\_release1/](https://re-docs.genomicsengland.co.uk/gms_release1/)

[https://re-docs.genomicsengland.co.uk/gms\\_release1/](https://re-docs.genomicsengland.co.uk/gms_release1/)

[23] [https://re-docs.genomicsengland.co.uk/gms\\_release5/](https://re-docs.genomicsengland.co.uk/gms_release5/)

[https://re-docs.genomicsengland.co.uk/gms\\_release5/](https://re-docs.genomicsengland.co.uk/gms_release5/)

[25] <https://www.genome.gov/about-genomics/fact-sheets/DNA-Sequencing-Costs-Data>

<https://www.genome.gov/about-genomics/fact-sheets/DNA-Sequencing-Costs-Data>

[31] <https://build.fhir.org/ig/paciowg/sample-data-fsh/>

<https://build.fhir.org/ig/paciowg/sample-data-fsh/>

[32] <https://link.springer.com/article/10.1186/s13073-022-01112-z>

<https://link.springer.com/article/10.1186/s13073-022-01112-z>

[34] <https://www.nature.com/articles/s41591-024-03142-z>

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[37] <https://www.nature.com/articles/s41467-024-44804-3>

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<https://academic.oup.com/nar/article/51/D1/D1230/6827107>

## ART 09.074 Organs-on-Chips & Bio-Computational Hybrids

### . ART extraction

**A) Primary capability claimed (core “what it does”)** - Microfluidic **organs-on-chips**: sealed, miniaturised tissue systems that provide **instrumented, controllable, human-relevant physiological readouts** (e.g., metabolism, barrier integrity, electrophysiology) with lower material/wet-lab overhead than many conventional assays. [1]

- Progression toward **modular, linked multi-tissue platforms** (“multi-organ-on-chip” / “body-on-chip”) with controlled fluid exchange, timed stimulation, and automated sampling for studying organ crosstalk and systemic drug effects. [2]

- **Bio-computational hybrids**: living neural networks (2D cultures or 3D organoids) coupled to electrodes/optics and conventional processors, enabling **closed-loop stimulation + readout** where biological networks can be “trained” to perform simple computational tasks (e.g., reservoir computing, game control). [3]

**B) Key sub-components / variants (bundle sub-threads)** - Microfluidic chip hardware: channels, membranes, pumps/microvalves, closed circulation loops; materials that mitigate absorption/compatibility issues. [4]

- Tissue/cell constructs: cell lines, primary cells, iPSC-derived organoids; co-cultures and multicellular “quad culture” approaches in liver chips; long-term maintenance and functionality. [5]

- Embedded sensing & actuation: TEER/electrode arrays, pH/ion sensing, cytokine/biomarker sensing (e.g., IL-6), electrophysiology interfaces, and integrated electronics/packaging compatible with lab instrumentation. [6]

- Multi-organ integration: linked compartments (e.g., gut–liver axis), peristaltic micropumps, scaling/flow management, and inter-organ pharmacology/toxicology. [2]

- Bio-computing interfaces: high-density MEAs; closed-loop protocols; decoding biological dynamics with ML; stability/reproducibility challenges for training and deployment. [7]

- Regulatory/quality infrastructure: fit-for-purpose validation concepts, quality management plans, emerging standardisation (CEN/CENELEC, ISO activity), and regulator-led qualification pathways (e.g., IStand). [8]

**C) Maturity indicators that would count as strong evidence - Predictive validation against clinical outcomes** (sensitivity/specificity; blinded compound sets; reproducibility across donors/labs), especially in high-value contexts like DILI. [9]

- **Regulatory pathway milestones** (formal acceptance into a qualification programme; published regulator roadmaps for integrating NAMs/MPS). [10]

- **Demonstrations of multi-organ crosstalk** with stable operation over weeks and controlled fluidic integration (pumps/valves, closed-loop flow). [2]

- **Embedded-sensor/electronics integration** that supports continuous, in situ measurement (TEER, pH, biomarkers, electrophysiology) with manufacturable components (e.g., PCB/FPC approaches). [11]

- **Evidence of standardisation and QA frameworks** (roadmaps, standards committees, consensus on fit-for-purpose criteria). [12]

- For bio-computational hybrids: **closed-loop learning/capability demonstrations**, plus improved **long-term interface stability** and scaling of electrode/recording hardware. [13]

### 2. Evidence (10–20 recent, reliable sources)

### 1) Performance assessment and economic analysis of a human Liver-Chip for predictive toxicology

- **Authors/organisation:** Lorna Ewart[14] et al.
- **Venue/type:** *Communications Medicine* (peer-reviewed experimental + economic analysis)
- **Publication date:** Dec 2022 (published 06 Dec 2022)
- **Link (URL):** <https://www.nature.com/articles/s43856-022-00209-1>
- **What it reports & why it matters:** Analysed **870 Liver-Chips** against a blinded set of **27 drugs**, reporting **87% sensitivity** and **100% specificity** for DILI prediction—direct plausibility evidence that organ chips can reach clinically relevant predictive performance. It also quantifies potential industry value from adoption, supporting maturation beyond “interesting lab demo” into workflow-relevant PoC. [15]

### 2) FDA’s IStand Pilot Program accepts a submission of first organ-on-a-chip technology designed to predict human drug-induced liver injury (DILI)

- **Authors/organisation:** U.S. Food and Drug Administration[16] (CDER statement)
- **Venue/type:** Regulatory announcement / qualification programme milestone (authoritative regulator source)
- **Publication date:** Sep 2024 (24 Sep 2024)
- **Link (URL):** <https://www.fda.gov/drugs/drug-safety-and-availability/fdas-istand-pilot-program-accepts-submission-first-organ-chip-technology-designed-predict-human-drug>
- **What it reports & why it matters:** Confirms acceptance of a **human Liver-Chip DDT LOI** into IStand for use in supporting **IND submissions** in a defined DILI context, indicating concrete regulatory traction (a key maturity signal). It also explicitly frames the system as enabling **real-time monitoring** and compares candidate drugs’ relative DILI risk—evidence of intended high-stakes use. [17]

### 3) Roadmap to Reducing Animal Testing in Preclinical Safety Studies

- **Authors/organisation:** U.S. Food and Drug Administration[16]
- **Venue/type:** Authoritative regulator roadmap/report (PDF)
- **Publication date:** Apr 2025 (10 Apr 2025)
- **Link (URL):** [https://www.fda.gov/files/newsroom/published/roadmap\\_to\\_reducing\\_animal\\_testing\\_in\\_preclinical\\_safety\\_studies.pdf](https://www.fda.gov/files/newsroom/published/roadmap_to_reducing_animal_testing_in_preclinical_safety_studies.pdf)
- **What it reports & why it matters:** Sets an agency roadmap explicitly naming **organ-on-a-chip microphysiological systems** as NAMs for reducing animal testing and notes a Liver-Chip validation example identifying **87%** of hepatotoxic drugs, linking policy momentum to concrete performance evidence. This strengthens maturity assessment by showing a **top-down adoption pathway** (validation → qualification → routine regulatory use) rather than isolated academic progress. [18]

### 4) Potential Approaches to Drive Future Integration of New Alternative Methods for Regulatory Decision-Making

- **Authors/organisation:** FDA Science Board / New Alternative Methods Subcommittee (report to the Science Board)
- **Venue/type:** Authoritative government advisory report (PDF)
- **Publication date:** Oct 2024
- **Link (URL):** <https://www.fda.gov/media/182478/download>
- **What it reports & why it matters:** A regulator-facing strategy document that explicitly

includes **microphysiological systems (MPS), including organs-on-chips**, as “newer and complementary methods” relevant to regulatory decision-making—evidence of institutional integration planning. Helps maturity scoring because it speaks to scaling barriers (context-of-use framing, evidence standards) and governance structures needed for adoption. [19]

#### 5) Focus Group Organ-on-Chip Standardization Roadmap

- **Authors/organisation:** CEN-CENELEC[20] Focus Group (secretariat NEN; with European partners)
- **Venue/type:** Standards roadmap/report (PDF; standards bodies)
- **Publication date:** Jul 2024 (date shown as 2024-07)
- **Link (URL):** <https://www.cencenelec.eu/media/publication-july-2024-fg-ooc-roadmap.pdf>
- **What it reports & why it matters:** Provides an explicit **standardisation roadmap** for organ-on-chip technologies—direct evidence that the field is moving from bespoke devices toward **shared definitions, test methods, and interoperability**, which is critical for scale and regulatory confidence. Standardisation roadmaps are a maturity marker because they typically emerge when multiple stakeholders are preparing for broader deployment. [21]

#### 6) News from EURL ECVAM (February 2025): A new ISO Subcommittee to develop standards for Organ-on-Chip

- **Authors/organisation:** Joint Research Centre[22] / EURL ECVAM[23] (newsletter)
- **Venue/type:** Government lab / standards ecosystem update (authoritative newsletter)
- **Publication date:** Feb 2025
- **Link (URL):** <https://ec.europa.eu/newsroom/jrcispra/newsletter-archives/60295>
- **What it reports & why it matters:** Reports that International Organization for Standardization[24] set up a new subcommittee (ISO/TC 276/SC2) on “**Microphysiological systems and Organ-on-Chip**”, explicitly tying this to the CEN-CENELEC roadmap—evidence of global standardisation infrastructure forming. This matters to maturity because standards committees typically respond to rising utilisation and the need for reproducibility/transferability between labs and vendors. [25]

#### 7) New Approach Methodologies: EU-IN Horizon Scanning Report

- **Authors/organisation:** European Medicines Agency[26] / HMA
- **Venue/type:** Regulatory horizon scanning report (PDF; authoritative)
- **Publication date:** Feb 2025
- **Link (URL):** [https://www.ema.europa.eu/en/documents/report/new-approach-methodologies-eu-horizon-scanning-report\\_en.pdf](https://www.ema.europa.eu/en/documents/report/new-approach-methodologies-eu-horizon-scanning-report_en.pdf)
- **What it reports & why it matters:** Describes the state-of-art and trends in NAMs and notes that current use in EMA submissions is limited but increasing, framing barriers around regulator experience and developer data-sharing behaviour—critical contextual maturity evidence for adoption timelines. Helps evaluate the ART’s constraint set (regulatory acceptance, evidence standards) for Europe specifically. [27]

#### 8) 3Rs Working Party Biennial Report 2023/2024

- **Authors/organisation:** European Medicines Agency[26] (3Rs Working Party)
- **Venue/type:** Regulatory activities report (PDF; authoritative)
- **Publication date:** 2025 (year shown; month not specified in PDF front matter)
- **Link (URL):** <https://www.ema.europa.eu/en/documents/report/3rs-working->



party-biennial-report-2023-2024\_en.pdf

- **What it reports & why it matters:** Documents EMA work to revise acceptance guidance and prepare annexes defining regulatory acceptance criteria for **complex in vitro models**, explicitly including “liver-on-chip” for DILI contexts—direct evidence that regulators are operationalising evaluation criteria. This matters for maturity because it signals movement from “interest” to **formalised acceptance frameworks**. [28]

#### 9) Recommendations on fit-for-purpose criteria to establish quality management for microphysiological systems and for monitoring their reproducibility

- **Authors/organisation:** David Pamies[29] et al.

- **Venue/type:** *Stem Cell Reports* (peer-reviewed recommendations / governance framework)

- **Publication date:** Apr 2024 (25 Apr 2024)

- **Link (URL):** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11103889/>

- **What it reports & why it matters:** Proposes practical **quality management and QC criteria** for MPS (“fit-for-purpose”) aimed at reproducibility without freezing innovation—directly addressing key constraints in the ART description (chip-to-chip consistency, QA, trust). This is maturity-relevant evidence because quality frameworks are prerequisites for scaling across facilities and for regulatory-grade usage. [30]

#### 10) Integrated-gut-liver-on-a-chip platform as an in vitro human model of non-alcoholic fatty liver disease

- **Authors/organisation:** Jiandong Yang[31] et al.

- **Venue/type:** *Communications Biology* (peer-reviewed experimental paper)

- **Publication date:** Mar 2023 (23 Mar 2023)

- **Link (URL):** <https://www.nature.com/articles/s42003-023-04710-8>

- **What it reports & why it matters:** Demonstrates an integrated gut–liver microfluidic platform with **closed circulation**, and describes the use of **microvalves and an integrated micropump** for controlled perfusion and compartment accessibility—direct evidence for multi-tissue modularisation on compatible microfabricated hardware. Shows feasibility of longer, multi-day protocols (1–7 days) for disease modelling in linked compartments, a key step towards modular multi-organ platforms. [32]

#### 11) A High-Throughput Microphysiological Liver Chip System to Model Drug-Induced Liver Injury Using Human Liver Organoids

- **Authors/organisation:** Sophia R. Meyer[33] et al.

- **Venue/type:** *Gastro Hep Advances* (peer-reviewed experimental paper; open access via journal/PubMed)

- **Publication date:** Aug 2024 (12 Aug 2024)

- **Link (URL):** <https://pubmed.ncbi.nlm.nih.gov/39529647/>

- **What it reports & why it matters:** Evaluates a **high-throughput microfluidic liver-on-chip** system (“Curio Barrier Liver Chips”) maintaining **viability and liver functions for 28 days**, with sensitivity to hepatotoxicants at **micromolar** concentrations—evidence of maturity toward industrial screening constraints (throughput + longer exposures). Conflicts section indicates commercial production relevance (industry involvement), supporting multi-actor competition and near-term deployment dynamics. [34]

#### 12) Multi-Organ Microphysiological Systems Targeting Specific Organs for Recapitulating Disease Phenotypes via Organ Crosstalk

- **Authors/organisation:** POSTECH-led author team (PMC version)

- **Venue/type:** *Small Science* (peer-reviewed; PMC-hosted)
- **Publication date:** 2024 (received Jun 2024; revised Aug 2024; collection date Nov 2024)
- **Link (URL):** <https://pmc.ncbi.nlm.nih.gov/articles/PMC11935247/>
- **What it reports & why it matters:** Summarises and discusses concrete multi-organ MPS implementations—e.g., a chip with integrated **peristaltic micropumps** and organ compartments (intestine/liver/skin/kidney) maintaining function **up to 28 days**, highlighting practical engineering constraints (system complexity, PDMS absorption). Provides evidence that multi-organ platforms exist at a lab/prototype stage with multi-week operation, but still face materials and integration issues that limit standard deployment. [35]

### 13) An organ-on-chip device with integrated charge sensors and recording microelectrodes

- **Authors/organisation:** Hande Aydogmus[36] et al.
- **Venue/type:** *Scientific Reports* (peer-reviewed experimental paper)
- **Publication date:** May 2023 (18 May 2023)
- **Link (URL):** <https://www.nature.com/articles/s41598-023-34786-5>
- **What it reports & why it matters:** Demonstrates a **silicon-polymer hybrid** organ-on-chip that can host active electronics, integrating a **floating-gate FET** for real-time pH monitoring and microelectrodes for recording action potentials, with compatibility toward common MEA setups and small (~30  $\mu$ L) volumes. This directly supports the ART's plausibility claim that organ chips can embed sensing/control electronics using semiconductor-compatible approaches. [37]

### 14) An Organ-on-a-Chip Modular Platform with Integrated Immunobiosensors for Monitoring the Extracellular Environment

- **Authors/organisation:** Anastasia Kanioura[38] et al.
- **Venue/type:** *Micromachines* (peer-reviewed experimental paper)
- **Publication date:** Jun 2025 (25 Jun 2025)
- **Link (URL):** <https://www.mdpi.com/2072-666X/16/7/740>
- **What it reports & why it matters:** Demonstrates modular OoC integration of a biosensor array and real-time detection of **IL-6**, and explicitly highlights using **commercially fabricated PCB components** to address cost and manufacturing scalability for sensor-integrated chips. This is direct evidence for the ART's "existing cleanroom/PCB workflows" compatibility and the direction toward cartridge-like modules with embedded sensing. [39]

### 15) Innovative electrode and chip designs for transendothelial electrical resistance measurements in organs-on-chips

- **Authors/organisation:** Muriel A. Holzreuter[40] & Loes I. Segerink
- **Venue/type:** *Lab on a Chip* (peer-reviewed technical review with practical design considerations)
- **Publication date:** Jan 2024 (first published 02 Jan 2024)
- **Link (URL):** <https://pubs.rsc.org/en/content/articlehtml/2024/lc/d3lc00901g>
- **What it reports & why it matters:** Reviews integrated electrode/channel designs for **continuous TEER** in OoC and explicitly argues that fixed electrode integration can improve reproducibility—directly aligned with the ART's embedded monitoring/control requirement and reproducibility bottleneck. Also highlights measurement/geometry issues and the need for comparability across chip designs, directly informing maturity limits. [41]

#### 16) Brain organoid reservoir computing for artificial intelligence

- **Authors/organisation:** Hongwei Cai[42] et al.
- **Venue/type:** *Nature Electronics* (peer-reviewed experimental paper)
- **Publication date:** Dec 2023 (11 Dec 2023)
- **Link (URL):** <https://www.nature.com/articles/s41928-023-01069-w>
- **What it reports & why it matters:** Demonstrates “Brainware” in which computation is performed by sending/receiving information via a **high-density microelectrode array** coupled to a human brain organoid; authors report tasks including **speech recognition** and nonlinear prediction in a reservoir computing framework. This is direct plausibility evidence for bio-computational hybrids with living neural substrates plus conventional decoding/control. [43]

#### 17) In vitro neurons learn and exhibit sentience when embodied in a simulated game-world

- **Authors/organisation:** Brett J Kagan[44] et al. (includes Cortical Labs[45])
- **Venue/type:** *Neuron* (peer-reviewed experimental paper; PubMed/PMC indexed)
- **Publication date:** Oct/Dec 2022 (Epub Oct 2022; issue Dec 2022)
- **Link (URL):** <https://pubmed.ncbi.nlm.nih.gov/36228614/>
- **What it reports & why it matters:** Demonstrates “DishBrain”: neuronal cultures interfaced to a simulated environment via a **high-density multielectrode array** with closed-loop stimulation/recording, showing learning effects in minutes under feedback conditions—key proof of concept for training biological networks through repeated inputs. This supports plausibility of “living components trained through repeated inputs” but also underscores early-stage maturity (highly experimental setup; not yet standardised deployment). [46]

#### 18) 360° size-adjustable microelectrode array system for electrophysiological monitoring of cerebral organoids

- **Authors/organisation:** Takashi Ozaki[47] et al. (entity["company", "Toyota Central R&D Labs", "japanese research lab"])
- **Venue/type:** *Frontiers in Bioengineering and Biotechnology* (peer-reviewed prototype/instrumentation paper)
- **Publication date:** Jul 2025 (22 Jul 2025)
- **Link (URL):** <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2025.1596009/full>
- **What it reports & why it matters:** Presents a 64-channel, 360° adjustable MEA system fabricated with **flexible printed circuit** technology and demonstrates stable recording for **two weeks** around organoids—direct evidence for the “interface hardware” sub-stack required by bio-computational hybrids. Also explicitly discusses challenges (manual alignment; need for automation/perfusion) that map to remaining maturity gaps for reproducible deployment. [48]

#### 19) An organic artificial spiking neuron for in situ neuromorphic sensing and biointerfacing

- **Authors/organisation:** Tanmoy Sarkar[49] et al.
- **Venue/type:** *Nature Electronics* (peer-reviewed experimental device paper)
- **Publication date:** Nov 2022 (07 Nov 2022)
- **Link (URL):** <https://www.nature.com/articles/s41928-022-00859-y>
- **What it reports & why it matters:** Demonstrates an organic artificial neuron that operates

in liquid, is modulated by ionic/biomolecular concentrations (including dopamine), and forms a **biohybrid interface** where epithelial membrane barriers modulate spiking in real time, with reported stability over  $>10^5$  spiking cycles. This supports plausibility of tight coupling between living barriers/tissues and programmable electronics—relevant to both organ-chip sensing/control and future hybrid computing interfaces. [50]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 4

#### B) Why this score fits the rubric (evidence-to-rubric mapping)

##### - What rules out levels 1–3 (why it is beyond “just verified in lab”):

- There are **large-scale, quantitative validation studies** that go well beyond demonstrating “the principle” (e.g., 870 Liver-Chips; blinded drug set; explicit sensitivity/specificity metrics). [15]

- There is **explicit regulator engagement** that treats organ-chips as candidate tools for high-stakes submissions (ISTAND LOI acceptance for a Liver-Chip DDT for IND context-of-use). [17]

- Bio-computational hybrids have **peer-reviewed closed-loop demonstrations** (Brainware reservoir computing; DishBrain learning in a virtual game), indicating functioning prototypes rather than theoretical proposals. [3]

##### • Why it does not yet justify level 5+ for the ART as a whole:

- The ART bundle combines (i) **relatively mature organ-chip/MPS applications** and (ii) **much earlier bio-computational hybrids**. While organ-chips show regulatory momentum and standardisation activity, the bio-computational hybrid thread still has major unresolved scaling issues: stability over long durations, variability control, automated alignment/perfusion, and the lack of clear product-grade deployment/QA pathways. [51]
- Even within organ-chips, key maturity blockers remain visible in the evidence base: regulators and standards bodies are still actively defining acceptance criteria and standardisation roadmaps, implying that cross-site reproducibility and “regulatory-grade” QA are not yet broadly settled. [52]
- The best evidence supports **PoC-level functionality and viability for intended use in defined contexts** (e.g., DILI prediction workflows, multi-organ research prototypes, sensor-integrated demonstrations), but the dossier does not provide robust, recent, high-quality “shipment/volume scaling” evidence across competing vendors that would be needed to claim level 6–7 for the whole bundle under the rubric’s definitions. [53]

**Interpretation:** Level 4 (**PoC**) is justified because (a) high-performance organ-chip results exist with clinically anchored evaluation and (b) the regulatory and standards ecosystem is actively building qualification/standardisation pathways, while (c) bio-computational hybrids remain prototype-stage and not yet on a production/market scaling trajectory.

#### C) Sub-score breakdown (bundle components → maturity estimate → key evidence), then aggregation - Single-organ MPS / organ-chips for drug safety & disease modelling → ~5

- Evidence: quantitative DILI performance at scale (870 chips; 87% sensitivity; 100% specificity). [15]

- Evidence: regulator pathway milestone (ISTAND LOI acceptance for Liver-Chip DDT). [17]
- Evidence: regulator policy roadmap legitimising NAM/MPS adoption. [54]
- **Sensor- and electronics-integrated OoC platforms (TEER/pH/biomarkers; manufacturable components) → ~4**
  - Evidence: silicon–polymer OoC with integrated FET sensing and electrophysiology compatibility. [37]
  - Evidence: modular OoC with integrated IL-6 immunobiosensing and explicit PCB manufacturability angle. [39]
  - Evidence: TEER integration design space and the reproducibility rationale for fixed electrodes. [41]
- **Multi-organ “linked” platforms (organ crosstalk, closed loops, pumps) → ~3–4**
  - Evidence: closed-loop gut–liver chip with integrated micropump/microvalves (multi-day NAFLD modelling). [32]
  - Evidence: multi-organ platforms with pumps and multi-week (28-day) operation exist but are described alongside unresolved complexity/material constraints. [55]
- **Bio-computational hybrids (living neural networks + electronics + decoding/control loops) → ~3**
  - Evidence: Brainware organoid reservoir computing with MEA I/O; tasks demonstrated (speech recognition, prediction). [56]
  - Evidence: DishBrain closed-loop learning in a simulated game-world via HD-MEA. [46]
  - Evidence: enabling interface hardware advancing but still prototype-like (360° MEA; 2-week stability; manual alignment constraints). [48]
  - Evidence: device-level biointerfacing primitives for wet environments (biohybrid spiking neuron coupled to epithelial barriers). [57]

**Aggregation to one score:** Because these sub-threads have **materially different applications and maturity**, I used an **average-based** aggregation (rather than maximum): organ-chips (≈5), sensor-integrated scaling layer (≈4), multi-organ integration (≈3–4), bio-computational hybrids (≈3) → overall ≈ 4 (rounded) for the ART bundle. [58]

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<https://www.nature.com/articles/s43586-022-00118-6>

[2] [4] [20] [32] [40] [42] [49] <https://www.nature.com/articles/s42003-023-04710-8>

<https://www.nature.com/articles/s42003-023-04710-8>

[3] [7] [43] [56] <https://www.nature.com/articles/s41928-023-01069-w>

<https://www.nature.com/articles/s41928-023-01069-w>

[5] [9] [15] [24] [53] [58] <https://www.nature.com/articles/s43856-022-00209-1>

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[6] [11] [37] [38] <https://www.nature.com/articles/s41598-023-34786-5>

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[10] [17] <https://www.fda.gov/drugs/drug-safety-and-availability/fdas-istand-pilot-program-accepts-submission-first-organ-chip-technology-designed-predict-human-drug>

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[12] [21] [45] [52] <https://www.cencenelec.eu/media/publication-july-2024-fg-ooc-roadmap.pdf>

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[27] [https://www.ema.europa.eu/en/documents/report/new-approach-methodologies-eu-horizon-scanning-report\\_en.pdf](https://www.ema.europa.eu/en/documents/report/new-approach-methodologies-eu-horizon-scanning-report_en.pdf)

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<https://pmc.ncbi.nlm.nih.gov/articles/PMC11935247/>

[34] A High-Throughput Microphysiological Liver Chip System to ...

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[41] [44] <https://pubs.rsc.org/en/content/articlehtml/2024/lc/d3lc00901g>

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<https://www.nature.com/articles/s41928-022-00859-y>

## ART 09.075 Biological Aging & Longevity Barriers

### ART extraction

#### Primary capability the ART claims

- **Therapeutically reduce (or modulate) the burden and downstream effects of cellular senescence** by (i) selectively eliminating senescent “zombie” cells (senolytics) or (ii) suppressing their pro-inflammatory, tissue-degrading secretome (senomorphics), thereby improving tissue function and resilience. [1]
- **Partially reset age-associated epigenetic and transcriptional programs in somatic cells (without loss of cell identity)** via transient, tightly controlled reprogramming programmes (e.g., OSK/OSKM or chemical programmes), aiming for “rejuvenation-like” functional gains with acceptable safety. [2]
- **Operationalise ageing-targeted interventions using biomarker panels and/or imaging** (senescent burden, SASP/inflammation, tissue function; potentially epigenetic clocks) to enable periodic “maintenance” dosing and to manage safety risks (e.g., off-target cell loss, tumour risk, immune reactions). [3]

#### Key sub-components or variants

- **Small-molecule senolytics** (e.g., BCL-xL pathway inhibitors; broader “SCAP” pathway targeting), including local-delivery formulations (e.g., intravitreal) to reduce systemic toxicity. [4]
- **Immune-mediated senolytics** (e.g., uPAR-targeting CAR-T strategies) aimed at selective clearance of senescent cells and potentially longer durability per administration. [5]
- **Senomorphics / SASP modulators** (e.g., JAK/STAT inhibition; other pathway suppressors) that reduce SASP and senescence markers without necessarily killing cells. [6]
- **Genetic partial reprogramming (OSK/OSKM)** with controlled targeting (cell-state specific promoters) and delivery (commonly AAV in preclinical studies), to rejuvenate transcriptional/epigenetic states. [7]

- **Chemical partial reprogramming** (small-molecule cocktails) as a non-genetic route to mitigate tumour/identity-loss risks, currently demonstrated mainly in vitro and in short-lived organisms. [8]
- **Measurement infrastructure** for senescence: blood SASP/proteomics panels, longitudinal “SASP indices”, and senescence imaging (e.g., SA $\beta$ -gal PET probes) and ML classifiers for senescence quantification in cells/tissues. [9]

#### What maturity indicators would constitute evidence for this ART

- **Human clinical evidence** of safety and durable functional benefit (ideally RCTs) for senolytics/senomorphics, including dose-finding, adverse event characterisation, and long-term follow-up. [10]
- **Demonstrations that interventions are measurable and target-engaged**, using validated biomarkers/imaging (blood SASP panels, senescence imaging probes, tissue-based ML scores), enabling patient selection and monitoring. [11]
- **Delivery and control feasibility** for reprogramming in vivo (tight timing/dose control; tissue targeting; immune risk management), plus evidence of preserved identity and absence of teratoma/tumour promotion in rigorous animal studies. [7]
- **Manufacturability and scalability signals**, such as repeatable production of vectors/therapeutics, multi-site reproducibility, and progression into later-phase clinical trials or regulated products (not yet strongly present for systemic “ageing reversal” reprogramming). [10]

#### Evidence (10–20 recent, reliable sources)

##### Senolytics: human trials and translational anchoring

##### Therapeutic targeting of cellular senescence in diabetic macular edema: preclinical and phase 1 trial results

- Authors/organisation: Sergio Crespo-Garcia et al.
- Venue/type: *Nature Medicine* (peer-reviewed translational + Phase 1 clinical trial)
- Date: Feb 2024 (Epub 6 Feb 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/38321220/>
- Why it matters: Shows mechanistic linkage between senescent retinal cells and DME features, and reports a Phase 1 single-ascending-dose safety study of the senolytic UBX1325 (BCL-xL inhibitor) with primary safety/tolerability objective achieved—an explicit “in-human” foothold for senolysis as disease-modifying therapy (at least locally delivered). [12]

##### Safety and Efficacy of Senolytic UBX1325 in Diabetic Macular Edema

- Authors/organisation: Sharon Klier et al.
- Venue/type: *NEJM Evidence* (peer-reviewed randomised controlled trial)
- Date: May 2025 (Epub 22 Apr 2025)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/40261111/>
- Why it matters: Sham-controlled RCT testing a **single intravitreal injection** of UBX1325 with follow-up to 48 weeks; provides higher-grade clinical evidence on safety profile (ocular/systemic TEAEs) and signals of potential efficacy/durability—key for judging maturity beyond preclinical plausibility, albeit still in a specific indication and delivery route. [13]

### **Navitoclax safety, tolerability, and effect on biomarkers of senescence and neurodegeneration in aged nonhuman primates**

- Authors/organisation: Edward F. Greenberg et al.
- Venue/type: *Heliyon* (peer-reviewed preclinical, non-human primate study)
- Date: Aug 2024 (published 17 Aug 2024; eCollection Aug 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/39253182/>
- Why it matters: Addresses a key translational gap—senolytic exposure and biomarker modulation in **aged primates**—reporting intermittent navitoclax that was “safe and well tolerated” with **modest reversible thrombocytopenia** and trends in senescence/SASP and neuroinflammation biomarkers, directly informing feasibility and safety-margin concerns for BCL-xL-pathway senolytics. [14]

### **Senolytics: diversification of modalities and discovery pipelines**

#### **Prophylactic and long-lasting efficacy of senolytic CAR T cells against age-related metabolic dysfunction**

- Authors/organisation: Corina Amor et al.
- Venue/type: *Nature Aging* (peer-reviewed in vivo proof)
- Date: Mar 2024 (Epub 24 Jan 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/38267706/>
- Why it matters: Demonstrates an immune-cell modality (uPAR-targeting CAR-T) that can reduce senescent cell burden and improve metabolic/fitness phenotypes in aged mice and diet-induced metabolic dysfunction, with a **single administration** yielding long-lasting effects—relevant to the ART’s “periodic maintenance” premise, though still preclinical. [5]

#### **Discovering small-molecule senolytics with deep neural networks**

- Authors/organisation: Felix Wong et al.
- Venue/type: *Nature Aging* (peer-reviewed; ML-guided screening + in vivo test)
- Date: Jun 2023 (Epub 4 May 2023)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/37142829/>
- Why it matters: Uses graph neural networks to expand senolytic chemical space (predicting across >800,000 molecules), identifies drug-like senolytics and validates at least one compound in aged mice (reduced senescent burden/genes in kidney), indicating a plausible acceleration path towards better-tolerated, more selective senolytics. [15]

#### **Discovery of senolytics using machine learning**

- Authors/organisation: Vanessa Smer-Barreto et al.
- Venue/type: *Nature Communications* (peer-reviewed; ML + experimental validation)
- Date: Jun 2023 (10 Jun 2023)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/37301862/>
- Why it matters: Reports senolytic discovery using ML trained on published data, with validation of multiple compounds’ senolytic activity in human cell models—evidence that discovery pipelines are maturing, addressing a bottleneck of limited known senolytics and uncertain targets. [16]

### **Senomorphics: SASP modulation with measurable endpoints**

#### **Senotherapeutic peptide treatment reduces biological age and senescence burden in human skin models**

- Authors/organisation: Alessandra Zonari et al.

- Venue/type: *npj Aging* (peer-reviewed; senomorphic peptide in human skin models)
- Date: May 2023 (published 22 May 2023)
- Link (URL): <https://www.nature.com/articles/s41514-023-00109-1>
- Why it matters: Identifies a peptide (Pep 14) acting as a **senomorphic** (reducing senescence/SASP markers without high toxicity) in multiple human dermal fibroblast senescence contexts and ex vivo skin; reports reduction in skin-equivalent DNA methylation age (MolClock), making it directly relevant to feasibility of “quieting” senescent signalling with measurable rejuvenation-adjacent biomarkers. [17]

### **Ruxolitinib-based senomorphic therapy mitigates cardiomyocyte senescence in septic cardiomyopathy by inhibiting the JAK2/STAT3 signaling pathway**

- Authors/organisation: B. Yang et al.
- Venue/type: *International Journal of Biological Sciences* (peer-reviewed; in vitro + mouse models)
- Date: Aug 2024 (published 12 Aug 2024)
- Link (URL): <https://www.ijbs.com/v20p4314.htm>
- Why it matters: Provides a concrete senomorphic example where JAK inhibition attenuates SASP and senescence markers and improves functional cardiac outcomes in septic cardiomyopathy mouse models, illustrating plausibility of SASP-targeting regimens and the importance of mechanism-linked biomarkers and functional readouts. [18]

### **Controlled epigenetic reprogramming: in vivo evidence and targeting advances**

#### **In vivo partial reprogramming alters age-associated molecular changes during physiological aging in mice**

- Authors/organisation: Kristen C. Browder et al.
- Venue/type: *Nature Aging* (peer-reviewed in vivo study)
- Date: Mar 2022 (Epub 7 Mar 2022)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/37118377/>
- Why it matters: Directly supports plausibility that partial reprogramming regimens can shift multi-tissue molecular ageing signatures towards more youthful profiles in wild-type mice; also highlights that regimen timing and tissue context matter—central to “transient, tightly timed” therapy claims. [19]

#### **Targeted partial reprogramming of age-associated cell states improves markers of health in mouse models of aging**

- Authors/organisation: Sanjeeb Kumar Sahu et al.
- Venue/type: *Science Translational Medicine* (peer-reviewed, translational in vivo)
- Date: Sep 2024 (11 Sep 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/39259812/>
- Why it matters: Advances “control” by targeting reprogramming to specific ageing-associated cell states (rather than broad OSKM cycling), with organismal and tissue-level health markers improved in mouse models; highly relevant to reducing off-target risk and making dosing more “maintenance-like”. [20]

#### **Cellular rejuvenation protects neurons from inflammation-mediated cell death**

- Authors/organisation: Sienna S. Drake et al.
- Venue/type: *Cell Reports* (peer-reviewed; AAV-OSK in vivo neuroinflammation model)
- Date: Feb 2025 (Epub 11 Feb 2025; issue 25 Feb 2025)

- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/39937646/>
- Why it matters: Uses AAV delivery of OSK to retinal ganglion cells to “rejuvenate the transcriptome” and improves cell survival and visual acuity in an inflammatory model, illustrating feasibility of local delivery and functional benefit while foregrounding risks/constraints around gene delivery and tissue-specific distribution. [21]

### **Loss of epigenetic information as a cause of mammalian aging**

- Authors/organisation: Jae-Hyun Yang et al.
- Venue/type: *Cell* (peer-reviewed; mechanistic animal model + reversal)
- Date: Jan 2023 (Epub 12 Jan 2023; issue 19 Jan 2023)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/36638792/>
- Why it matters: Provides mechanistic support that epigenetic information loss can drive ageing phenotypes in mammals and reports reversibility via OSK-mediated rejuvenation in their experimental framework—strengthening plausibility claims that ageing is partly an addressable “state”, not only diffuse wear. [22]

### **Biomarkers and measurement: necessary for dosing, selection, and safety monitoring**

#### **Persistent elevation of plasma markers of cellular senescence after hip fracture: a pilot longitudinal study**

- Authors/organisation: Eric J. Lenze et al.
- Venue/type: *Frontiers in Aging* (peer-reviewed longitudinal human biomarker study)
- Date: Nov 2024 (12 Nov 2024)
- Link (URL): <https://www.frontiersin.org/journals/aging/articles/10.3389/fragi.2024.1477528/full>
- Why it matters: Demonstrates a multi-analyte “SASP index” approach in humans (hip fracture surgery) with longitudinal dynamics over weeks; supports feasibility of measuring senescence-associated systemic signalling for patient stratification and monitoring—an enabling layer for periodic dosing concepts. [23]

#### **Plasma Proteomic Signature of Cellular Senescence and Markers of Biological Aging Among Postmenopausal Women**

- Authors/organisation: Ji-Won Shin et al.
- Venue/type: *Rejuvenation Research* (peer-reviewed human proteomics)
- Date: Jun 2022 (Epub 3 Jun 2022)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/35583231/>
- Why it matters: Shows that circulating panels of SASP-related proteins can be statistically associated with age-related indicators in a human cohort, underpinning the plausibility of using blood-based panels as part of the ART’s biomarker-guided dosing/selection assumptions. [24]

#### **Novel PET Imaging Probe for Quantitative Detection of Senescence In Vivo**

- Authors/organisation: Xin Xiang et al.
- Venue/type: *Journal of Medicinal Chemistry* (peer-reviewed; imaging probe development)
- Date: Apr 2024 (Epub 20 Mar 2024; issue 11 Apr 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/38507820/>
- Why it matters: Develops and validates a PET probe targeting SA $\beta$ gal with reported radiochemical purity and labelling yield (and preclinical tumour models), supporting the

measurement infrastructure that would be required to quantify senescent burden in vivo and to manage dosing/safety in clinical programmes. [25]

### **Detection of senescence using machine learning algorithms based on nuclear features**

- Authors/organisation: Imanol Duran et al.
- Venue/type: *Nature Communications* (peer-reviewed; ML classifiers + tissue application)
- Date: Feb 2024 (3 Feb 2024)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/38310113/>
- Why it matters: Creates senescence classifiers using nuclear features, applies a “tissue senescence score” across mouse ageing/fibrosis and human fatty liver disease contexts, and demonstrates use in characterising senolytic effects—directly tackling the “how do we measure senescence reliably?” bottleneck. [26]

### **Nuclear morphology is a deep learning biomarker of cellular senescence**

- Authors/organisation: Indra Heckenbach et al.
- Venue/type: *Nature Aging* (peer-reviewed; deep learning biomarker)
- Date: Aug 2022 (Epub 15 Aug 2022)
- Link (URL): <https://pubmed.ncbi.nlm.nih.gov/37118134/>
- Why it matters: Reports a deep learning predictor that can classify senescence from nuclear morphology (high accuracy reported in the paper) and generalises to tissue contexts and human biopsies—supporting scalable quantification approaches that are critical for clinical maturity (patient selection, monitoring, and endpoint measurement). [27]

### **Additional clinical “anchor” for senescent-burden modulation feasibility**

#### **Navitoclax safety, tolerability, and effect on biomarkers of senescence and neurodegeneration in aged nonhuman primates** (full text availability)

- Authors/organisation: Edward F. Greenberg et al.
- Venue/type: *Heliyon* (peer-reviewed; open full text)
- Date: Aug 2024
- Link (URL): <https://pmc.ncbi.nlm.nih.gov/articles/PMC11382177/>
- Why it matters: Provides openly accessible methodological detail supporting the primate translational bridge (exposure in CSF, biomarker shifts, and safety observations), useful for evaluating plausibility and constraints (platelet toxicity risk, dosing strategy). [28]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 4**

#### **Why this score fits the rubric**

A score of **4 (Proof of Concept)** is supported because **multiple components have moved beyond pure laboratory principle and have demonstrated functional prototypes with clinically relevant viability in at least one domain**, especially for senolytics:

- **Evidence that rules out levels 1–3 (principle only / lab verification / early prototype)**
- There is **human clinical testing** of a senolytic with defined delivery modality and clinically relevant endpoints in a disease setting: Phase 1 safety/tolerability in DME and a sham-controlled RCT in DME for UBX1325. [4]



- The clinical and translational datasets explicitly connect senescence burden to pathology and show that targeting senescent cells can be disease-modifying in animal models and feasible to test in humans. [12]
- **Evidence still missing to justify level 5 (multiple well-capitalised actors racing to production prototypes / “finishing phase” for launch)**
- The strongest human evidence is **narrowly indication- and route-specific** (e.g., intravitreal retinal delivery), and does not yet demonstrate generalisable, scalable, systemic “ageing maintenance” therapy across tissues. [10]
- For **controlled epigenetic reprogramming**, the evidence remains **preclinical**, with hallmark risks (oncogenicity/identity loss; immunogenicity and delivery distribution) not yet resolved in humans, and thus not in a “production prototype” phase. [7]
- Measurement tooling is advancing (SASP panels, ML classifiers, PET probes) but is not yet widely standardised as regulated clinical companion diagnostics for senescence-guided dosing at scale. [29]

#### **Sub-component maturity breakdown and aggregation logic**

Because this ART is a **bundle** (senolytics/senomorphics + epigenetic reprogramming + biomarker operationalisation) with materially different maturity levels, an **average-based** score is most defensible.

- **Senolytic therapeutics (small-molecule; local delivery in retina) → ~4–5**
- Key support: Phase 1 in *Nature Medicine* (Feb 2024) and sham-controlled RCT in *NEJM Evidence* (May 2025) for UBX1325 in DME. [4]
- Interpretation: This reaches PoC in a focused clinical niche; could trend towards 5 if broader late-stage trials and production scaling were demonstrated, but that is not established by the evidence set here.
- **Senolytic immunotherapies (e.g., senolytic CAR-T) → ~3**
- Key support: uPAR-targeting senolytic CAR-T shows durable benefits with single administration in aged mice and metabolic models (preclinical). [5]
- Interpretation: Strong in vivo prototype, but far from human trials for ageing indications.
- **Senomorphics / SASP modulators → ~3–4**
- Key support: Pep 14 senomorphic peptide reduces senescence burden and reports DNA methylation age reductions in skin models; ruxolitinib-based senomorphic effects with functional outcomes in mice. [30]
- Interpretation: Compelling mechanistic/phenotypic data, but limited direct human clinical evidence aimed at ageing (as opposed to disease contexts).
- **Controlled epigenetic reprogramming therapies (OSK/OSKM; genetic and chemical) → ~2–3**
- Key support: In vivo partial reprogramming in physiologically ageing mice (*Nature Aging*, Mar 2022); targeted partial reprogramming improving health markers (*Science Translational Medicine*, Sep 2024); AAV-OSK in neuroinflammation model with functional effects (*Cell Reports*, Feb 2025). [2]

- Interpretation: Demonstrated in vivo prototypes with increasingly sophisticated targeting, but absent human efficacy/safety trials in ageing, keeping this sub-thread below PoC for clinical translation.
- **Biomarkers and senescence measurement (blood panels, ML tissue scoring, PET probes)**  
→ ~3–4
- Key support: blood SASP panels in humans (Jun 2022; Nov 2024), ML senescence classifiers applied to tissues and used to characterise senolytics (Feb 2024), PET probe for senescence imaging (Apr 2024). [31]
- Interpretation: Enabling infrastructure is real and rapidly improving; still not “standard of care” for ageing trials.

**Aggregation to one score:** averaging these (senolytic clinical PoC pulling upward; reprogramming still preclinical pulling downward) yields an overall maturity around **4**, best matching the rubric’s “functional PoC demonstrated meeting commercialisation requirements in functionality/viability” in at least one sub-domain, while recognising that the full ART vision (systemic, biomarker-guided, periodic maintenance against ageing decline) is not yet near market-scale deployment. [32]

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[1] [4] [12] <https://pubmed.ncbi.nlm.nih.gov/38321220/>

<https://pubmed.ncbi.nlm.nih.gov/38321220/>

[2] [19] <https://pubmed.ncbi.nlm.nih.gov/37118377/>

<https://pubmed.ncbi.nlm.nih.gov/37118377/>

[3] [23] <https://www.frontiersin.org/journals/aging/articles/10.3389/fragi.2024.1477528/full>

<https://www.frontiersin.org/journals/aging/articles/10.3389/fragi.2024.1477528/full>

[5] <https://pubmed.ncbi.nlm.nih.gov/38267706/>

<https://pubmed.ncbi.nlm.nih.gov/38267706/>

[6] [18] <https://www.ijbs.com/v20p4314.htm>

<https://www.ijbs.com/v20p4314.htm>

[7] [20] <https://pubmed.ncbi.nlm.nih.gov/39259812/>

<https://pubmed.ncbi.nlm.nih.gov/39259812/>

[8] <https://pubmed.ncbi.nlm.nih.gov/40588563/>

<https://pubmed.ncbi.nlm.nih.gov/40588563/>

[9] [24] [31] <https://pubmed.ncbi.nlm.nih.gov/35583231/>

<https://pubmed.ncbi.nlm.nih.gov/35583231/>

[10] [13] [32] <https://pubmed.ncbi.nlm.nih.gov/40261111/>

<https://pubmed.ncbi.nlm.nih.gov/40261111/>

[11] [25] [29] <https://pubmed.ncbi.nlm.nih.gov/38507820/>

<https://pubmed.ncbi.nlm.nih.gov/38507820/>

[14] <https://pubmed.ncbi.nlm.nih.gov/39253182/>

<https://pubmed.ncbi.nlm.nih.gov/39253182/>

[15] <https://pubmed.ncbi.nlm.nih.gov/37142829/>

<https://pubmed.ncbi.nlm.nih.gov/37142829/>

[16] <https://pubmed.ncbi.nlm.nih.gov/37301862/>

<https://pubmed.ncbi.nlm.nih.gov/37301862/>

[17] [30] <https://www.nature.com/articles/s41514-023-00109-1>

<https://www.nature.com/articles/s41514-023-00109-1>

[21] <https://pubmed.ncbi.nlm.nih.gov/39937646/>

<https://pubmed.ncbi.nlm.nih.gov/39937646/>

[22] <https://pubmed.ncbi.nlm.nih.gov/36638792/>

<https://pubmed.ncbi.nlm.nih.gov/36638792/>

[26] <https://pubmed.ncbi.nlm.nih.gov/38310113/>

<https://pubmed.ncbi.nlm.nih.gov/38310113/>

[27] <https://pubmed.ncbi.nlm.nih.gov/37118134/>

<https://pubmed.ncbi.nlm.nih.gov/37118134/>

[28] <https://pmc.ncbi.nlm.nih.gov/articles/PMC11382177/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC11382177/>

## ART 09.076 Engineered Living Materials

### ART extraction

#### Primary capability claimed

- Structural composites that **embed living cells** (microbes/algae/fungi/engineered cells) in a supporting matrix so the material can **sense, respond, and partially self-maintain** over time (e.g., self-healing, adaptive porosity/moisture handling). [1]
- **In situ crack sealing / durability extension** via biologically mediated mineralisation (e.g., CaCO<sub>3</sub> or other phases), reducing inspections and repairs in infrastructure contexts. [2]

- **Carbon capture / carbon storage in materials** by combining photosynthetic CO<sub>2</sub> fixation with durable storage routes (biomass and/or mineral carbonates embedded in the structure). [3]

#### Key sub-components and variants

- **Bacteria-based self-healing cementitious materials** (spores + nutrients + carriers/capsules; crack-triggered activation; chloride/corrosion performance in harsh exposures). [2]
- **Photosynthetic living composites** (cyanobacteria immobilised in polymer/hydrogel scaffolds; engineered responsiveness; CO<sub>2</sub> uptake and long-lived culture). [4]
- **Biomineralised “living building materials”** (cyanobacteria or other microbes precipitating CaCO<sub>3</sub> to bind granular substrates; regeneration/reuse concepts). [5]
- **Fungal/mycelium-based living materials** (self-regeneration as a repair mechanism; mineralised scaffolds to reach structural relevance). [6]
- **Sensing/condition-indicating living coatings** (damage-triggered signals such as fluorescence, enabling low-cost monitoring). [7]
- **Manufacturing and lifecycle control** (3D printing, diffusion-based cell loading to avoid toxic precursors, controllable regrowth/reprocessing). [8]

#### Maturity indicators that would count as strong evidence

- Demonstrated **macroscale prototypes** with reproducible mechanical/functional performance (not only micro-scale or conceptual). [9]
- **Long-duration operation** (months–year+) of embedded living components with stable function, including “activation” after dormancy. [10]
- **Harsh-environment testing** relevant to infrastructure (freeze–thaw + salts, marine chloride exposure, corrosion outcomes). [11]
- Evidence of **manufacturing compatibility** (printable formats, scalable production rates, reprocessible/reconfigurable growth). [12]
- Signals of **scaling and institutional commitment** (multi-project programmes/portfolios; budgets/roadmaps; regulatory workstreams). [13]

#### Evidence (10–20 recent, reliable sources)

##### Structural self-healing and durability in cementitious composites

###### 1) **Bacteria-based self-healing concrete exposed to frost salt scaling**

Authors: Vanessa Giaretton Cappellesso et al.

Venue/type: *Cement and Concrete Composites* (peer-reviewed experimental paper)

Publication date: May 2023

Link: <https://www.sciencedirect.com/science/article/abs/pii/S0958946523000902>

Annotation: Reports durability testing under freeze–thaw + de-icing salts; bacteria-based agent improved frost-salt scaling resistance by **~90%** and reduced chloride penetration by **~46%**, but only partial crack healing limited chloride blocking along cracks—directly bounding real-world plausibility and limitations. [14]

###### 2) **Self-healing concrete with a bacteria-based or crystalline admixture as healing agent to prevent chloride ingress and corrosion in a marine environment**

Authors: Vanessa Giaretton Cappellesso et al.

Venue/type: *Developments in the Built Environment* (peer-reviewed experimental paper)

Publication date: October 2024

Link: <https://www.sciencedirect.com/science/article/pii/S2666165924001674>

Annotation: Evaluates 100 µm and 300 µm cracks with **12 months** seawater submersion; bacteria-based agent reduced chloride ingress but had limits for corrosion prevention in cracked samples, while crystalline admixture prevented corrosion in healed and 100 µm-cracked cases—evidence of near-field-relevant exposure testing and remaining performance gaps. [15]

### 3) **Low Carbon Bacterial Self-Healing Concrete**

Authors: João Miguel Peres Medeiros[16] et al.

Venue/type: *Buildings* (MDPI) (peer-reviewed experimental paper)

Publication date: 2022 (issue 12(12); month not specified on landing page)

Link: <https://www.mdpi.com/2075-5309/12/12/2226>

Annotation: Tests mechanical-property interactions of a bacterial healing agent in low-carbon concrete mixes (50% GGBS replacing OPC), documenting early-age strength trade-offs and positioning bacteria-based self-healing as a durability/lifecycle lever in lower-carbon binders (a key engineering feasibility constraint for infrastructure deployment). [17]

### 4) **Bacteria-based self-healing concrete – A life cycle assessment perspective**

Authors: Ismael Justo-Reinoso[18] et al.

Venue/type: *Developments in the Built Environment* (peer-reviewed LCA + engineering analysis)

Publication date: December 2023

Link: <https://www.sciencedirect.com/science/article/pii/S2666165923001266>

Annotation: Performs an LCA of bacteria-based self-healing concrete (endospores in porous calcium silicate granules), finding **higher impacts per m<sup>3</sup>** versus conventional concrete but quantifying how *selective* use (allowing wider cracks/reducing non-structural steel) can yield **12–50%** sustainability improvements depending on category—critical evidence for maturity barriers around cost/footprint and where deployment is rational. [19]

## **Carbon capture and biomineralisation living composites**

### 5) **Engineered living photosynthetic biocomposites for intensified biological carbon capture**

Authors: Pichaya In-na[20] et al.

Venue/type: *Scientific Reports* (peer-reviewed experimental paper)

Publication date: 04 November 2022

Link: <https://www.nature.com/articles/s41598-022-21686-3>

Annotation: Builds lichen-inspired cyanobacterial biocomposites (acrylic latex on loofah scaffold) and reports **14–20×** CO<sub>2</sub> uptake improvement over suspension controls plus sustained function for **12 weeks without additional nutrient/water supplementation**, supporting plausibility for low-maintenance photosynthetic “active surfaces”. [21]

### 6) **Dual carbon sequestration with photosynthetic living materials**

Authors: Dalia Dranseike[22] et al.

Venue/type: *Nature Communications* (peer-reviewed experimental paper)

Publication date: 23 April 2025

Link: <https://www.nature.com/articles/s41467-025-58761-y>

Annotation: Demonstrates printable photosynthetic living materials that combine biomass growth with carbonate formation (photosynthetic MICP), supporting **>1 year** culture stability and quantified sequestration ( **$\sim 26 \pm 7$  mg CO<sub>2</sub> per g living material over 400 days**)—strong feasibility evidence for durable carbon-storing composites, while still being lab-scale. [23]

#### 7) **Enhanced mechanical properties of living and regenerative building materials by filamentous *Leptolyngbya boryana***

Authors: Yongjun Son[24] et al.

Venue/type: *Cell Reports Physical Science* (peer-reviewed experimental paper)

Publication date: 21 August 2024

Link: <https://www.sciencedirect.com/science/article/pii/S2666386424003734>

Annotation: Reports cyanobacteria-based, cement-free living building materials using CaCO<sub>3</sub> precipitation, showing how filamentous morphology improves granular agglomeration/void filling and proposing regeneration using old parent material—directly relevant to the “regenerate rather than replace” claim. [5]

#### 8) **Mycelium as a scaffold for biomineralized engineered living materials**

Authors: Ethan Viles[25] et al.

Venue/type: *Cell Reports Physical Science* (peer-reviewed experimental paper)

Publication date: 16 April 2025

Link: <https://www.sciencedirect.com/science/article/pii/S266638642500116X>

Annotation: Uses fungal mycelium scaffolds (self-mineralised or mineralised via ureolytic bacteria) to address two structural blockers—**internal structural complexity** and **cell viability**—reporting viability retained for  **$\geq 4$  weeks at 30 °C** and demonstrating bone-mimetic internal geometries. [26]

#### **Manufacturability, viability control, and embedded sensing/monitoring**

#### 9) **A de novo matrix for macroscopic living materials from bacteria**

Authors: Sara Molinari[27] et al.

Venue/type: *Nature Communications* (peer-reviewed experimental paper)

Publication date: 21 September 2022

Link: <https://www.nature.com/articles/s41467-022-33191-2>

Annotation: Demonstrates centimetre-scale ELMs grown bottom-up from bacteria secreting a self-interacting protein matrix, with tunability of composition/mechanics/function—key plausibility evidence that living cells can *form* macroscopic materials rather than only being “sprinkled into” them. [28]

#### 10) **Phenotypically complex living materials containing engineered cyanobacteria**

Authors: Debika Datta[29] et al.

Venue/type: *Nature Communications* (peer-reviewed 3D-printing + synthetic biology paper)

Publication date: 07 August 2023

Link: <https://www.nature.com/articles/s41467-023-40265-2>

Annotation: Shows volumetric 3D printing of cyanobacteria in hydrogel with engineered stimulus-responsiveness (fluorescent reporting, inducible enzyme production, and inducible cell death for biocontainment), directly supporting “monitor/activate/tune” concepts and biosafety design patterns. [30]

#### 11) **A responsive living material prepared by diffusion reveals extracellular enzyme activity of cyanobacteria**



Authors: L. Tang[31] et al.

Venue/type: *PNAS* (peer-reviewed experimental paper; open access via PMC)

Publication date: Issue date 06 May 2025

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC12067278/>

Annotation: Introduces a diffusion-based method to load cyanobacteria into a temperature-responsive hydrogel *after* polymerisation, enabling ELM fabrication even when precursors are cytotoxic; also reports cell-driven changes in stiffness/shape over time—important manufacturing/viability evidence for “real matrices” rather than only benign gels. [32]

## 12) **Bacterially grown living materials with resistant and on-demand functionality**

Authors: Jeong Joo Oh[33] et al.

Venue/type: *Science Advances* (peer-reviewed experimental paper; PDF via TU Delft)

Publication date: 10 October 2025

Link: [https://repository.tudelft.nl/file/File\\_5a493461-96d9-4fd9-ad28-86364c3894f6](https://repository.tudelft.nl/file/File_5a493461-96d9-4fd9-ad28-86364c3894f6)

Annotation: Demonstrates autonomously grown bacterial-cellulose composites integrating dormant **Bacillus** endospores, enabling post-processing/handling and “activate on demand” functionality; reports engineered culture conditions and large improvements in spore incorporation (order-of-magnitude changes) supporting practicality of standardised starter-culture approaches. [34]

## 13) **Mechanically driven bacteria-based crack detection**

Authors: Ellen W. van Wijngaarden[35] et al.

Venue/type: *Materials Advances* (Royal Society of Chemistry) (peer-reviewed experimental paper; open access)

Publication date: 09 December 2025

Link: <https://www.sciencedirect.com/org/science/article/pii/S2633540925007054>

Annotation: Presents a durable engineered living coating embedding bacterial spores in a polymer that generates a **fluorescence signal upon crack formation**, directly supporting the ART’s “embedded condition signal / low-power monitoring” pathway for structural materials. [7]

## 14) **Mechanically Tunable, Compostable, Healable and Scalable Engineered Living Materials**

Authors: Avinash Manjula-Basavanna[36] et al.

Venue/type: *Nature Communications* (peer-reviewed experimental paper)

Publication date: 12 November 2024

Link: <https://www.nature.com/articles/s41467-024-53052-4>

Annotation: Reports ELM fabrication in scalable quantities (0.5–1 g/L) from bacterial biomass with engineered protein nanofibres and quantifies broad mechanical tunability (Young’s modulus reported across **6–450 MPa**) plus healability—evidence that ELMs can hit non-trivial mechanical envelopes, even if not yet structural-civil grade. [37]

## 15) **Reconfigurable Growth of Engineered Living Materials**

Authors: Suitu Wang[38] et al.

Venue/type: *Advanced Materials* (peer-reviewed paper; abstract via PubMed)

Publication date: Epub 09 February 2024 (journal issue August 2024)

Link: <https://pubmed.ncbi.nlm.nih.gov/38288578/>

Annotation: Demonstrates growth- and recovery-driven reprocessing of yeast-based magnetic ELMs (reported ~259% volume expansion; shape fixity up to ~99%), repeated

multiple times—supporting manufacturability narratives around “regrow/reform” materials rather than discard-and-replace. [39]

#### 16) **Leveraging the versatile properties of bacterial spores in materials**

Authors: Likhitha Reddy Kummetha et al.

Venue/type: *Trends in Biotechnology* (peer-reviewed review; open access)

Publication date: April 2025

Link: <https://www.sciencedirect.com/science/article/pii/S0167779924002804>

Annotation: Synthesises why spores matter for ELM maturity (dormancy, harsh-condition resistance, reduced cold-chain and lifespan constraints) and outlines remaining challenges for high-performance spore-based materials—useful as an evidence-backed framing of durability/shelf-life bottlenecks. [40]

#### **Programmes and portfolio signals for scaling and governance**

#### 17) **Engineered Living Materials (ELM) programme description in DARPA FY2023 budget justification (PB 2023)**

Organisation: [?entity?["organization","Defense Advanced Research Projects Agency","us r&d agency"]?] (DARPA)

Venue/type: Government programme budget justification / plans (authoritative)

Publication date: April 2022

Link:

[https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget\\_justification/pdfs/03\\_RDT\\_and\\_E/RDTE\\_Vol1\\_DARPA\\_MasterJustificationBook\\_PB\\_2023.pdf](https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf)

Annotation: Official programme text explicitly targets engineering biological systems for functional materials and infrastructure/logistics, including durability characterisation plans and named application vectors—evidence of sustained, mission-driven investment beyond small academic prototypes. [41]

#### 18) **EIC Pathfinder portfolio report: “Engineered Living Materials” (overview of activities carried out in 3rd year; planned 4th year)**

Organisation: European Innovation Council[42] / European Commission[43] (via Publications Office)

Venue/type: EU portfolio report / roadmap for funded project cluster (authoritative)

Release date: 06 January 2026 (Published: 2025)

Link: <https://op.europa.eu/en/publication-detail/-/publication/124c9d47-ec43-11f0-8d3c-01aa75ed71a1/language-en>

Annotation: Documents a coordinated, multi-project ELM portfolio with explicit objectives around advancing production technologies, addressing ethical/legal/regulatory issues, and identifying adoption/commercialisation obstacles—strong maturity signal that the field is organising around shared blockers. [44]

#### 19) **Unlocking the societal potential of engineered living materials**

Authors: Chelsea M. Heveran[45] et al.

Venue/type: *Matter* (peer-reviewed perspective based on multi-stakeholder workshop)

Publication date: 04 September 2024

Link: <https://www.sciencedirect.com/science/article/pii/S2590238524004041>

Annotation: Reports outcomes of an academic–industry–agency workshop identifying barriers to societal adoption (manufacturing scale/complexity, governance, perception,

regulation) and notes that only a limited number of ELMs have been commercialised so far—useful for mapping what is missing between lab success and market maturity. [46]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 3**

### **Evidence-to-rubric mapping**

#### **Why this is above Level 2 (verified principle) and merits Level 3 (laboratory prototype demonstrated)**

- Multiple peer-reviewed works demonstrate **macroscale, functional prototypes**: centimetre-scale bottom-up bacterial matrices (macroscopic ELMs) [28], printable photosynthetic living materials (structured hydrogels with measured CO<sub>2</sub> sequestration) [23], and mechanically-relevant biohybrid coatings that generate a damage signal on cracking [7].
- Several studies address **previously blocking engineering constraints** (viability/processing/harsh conditions): diffusion-based cell incorporation to bypass toxic precursors [32], spore-based architectures for dormant storage and on-demand activation [47], and harsh-environment concrete durability testing (freeze–thaw + salts, marine exposure) [11].

#### **Why this is not yet Level 4 (PoC meeting commercialisation requirements) for the ART as a whole**

- The strongest “near-real” evidence is for **bacteria-based self-healing concrete**, but even there performance is conditional: incomplete crack healing can still allow chloride transport along cracks [14] and bacteria-based agents showed limitations in preventing corrosion in cracked samples under marine exposure [15]—in other words, key civil-infrastructure requirements are not consistently met across crack sizes/exposures.
- The carbon-capture and mineralising living composites show **long-duration laboratory operation** (months to >1 year) and quantified capture, but remain in **lab-scale demonstrations** without field-validated auditing/maintenance regimes or code-accepted service-life models. [3]
- Manufacturing and governance themes are actively being organised (EU portfolio, DARPA programme intent), yet the evidence set does not show broad **production qualification** (shelf-life specs, QA/QC standards, reproducibility across manufacturers) or large-scale deployments that would indicate PoC-to-product readiness for structural infrastructure. [48]

### **Sub-component breakdown and aggregation**

#### **Bacteria-based self-healing concrete (infrastructure durability) → 4 (early PoC in constrained cases)**

- Rationale: Realistic durability exposures are demonstrated (freeze–thaw + salts; marine submersion; chloride/corrosion endpoints), with measurable benefits but also clear limitations. [11]
- Key sources: [49]

#### **Photosynthetic carbon-capturing living materials → 3 (laboratory prototypes with strong feasibility data)**

- Rationale: Quantified CO<sub>2</sub> uptake and long-term function exist, including >1-year culture stability and combined mineral + biomass capture, but deployment/auditing/maintenance

and outdoor durability are not shown here. [3]

- Key sources: [3]

### **Biomineralised living building materials (cyanobacteria/mycelium scaffolds) → 3 (lab prototypes approaching structural relevance)**

- Rationale: Demonstrations show  $\text{CaCO}_3$  precipitation and regeneration concepts (cyanobacteria) and month-scale viability plus complex geometry (mycelium scaffolds), but not yet tied to civil-structural qualification regimes. [50]

- Key sources: [51]

### **Embedded sensing/condition signalling (damage detection coatings) → 3 (lab prototype)**

- Rationale: A functional engineered living coating reports cracks via fluorescence under diverse conditions, but field durability/maintenance cycles are not established. [7]

- Key source: [7]

### **Manufacturing pathways and lifecycle control (printability, regrowth, viability management) → 3 (demonstrated methods; not industrialised)**

- Rationale: Reconfigurable growth and reprocessing cycles and diffusion-based cell loading show credible manufacturing routes, yet remain research-stage relative to industrial throughput and certification. [8]

- Key sources: [52]

### **Aggregation to one score:**

- These subcomponents share a common “living-in-matrix for durable function” core, but their application contexts diverge (civil infrastructure vs. carbon capture vs. sensing/manufacturing). Using an average-based assessment across the major subthreads yields roughly **3.x**, with the most mature subthread (self-healing concrete) offset by earlier-stage carbon-capture and biomineralisation scaffolds. A conservative single-score assignment is therefore **3**, because the overall ART has not yet shown general PoC-level performance and scaling across contexts. [53]

[1] [9] [28] [31] <https://www.nature.com/articles/s41467-022-33191-2>

<https://www.nature.com/articles/s41467-022-33191-2>

[2] [11] [14] [49] [53]

<https://www.sciencedirect.com/science/article/abs/pii/S0958946523000902>

<https://www.sciencedirect.com/science/article/abs/pii/S0958946523000902>

[3] [4] [20] [21] [22] [29] [33] [35] [36] <https://www.nature.com/articles/s41598-022-21686-3>

<https://www.nature.com/articles/s41598-022-21686-3>

[5] [50] [51] <https://www.sciencedirect.com/science/article/pii/S2666386424003734>

<https://www.sciencedirect.com/science/article/pii/S2666386424003734>

[6] [26] <https://www.sciencedirect.com/science/article/pii/S266638642500116X>

<https://www.sciencedirect.com/science/article/pii/S266638642500116X>

- [7] [16] [24] [42] <https://www.sciencedirect.com/org/science/article/pii/S2633540925007054>  
<https://www.sciencedirect.com/org/science/article/pii/S2633540925007054>
- [8] [39] [45] [52] <https://pubmed.ncbi.nlm.nih.gov/38288578/>  
<https://pubmed.ncbi.nlm.nih.gov/38288578/>
- [10] [23] [38] <https://www.nature.com/articles/s41467-025-58761-y>  
<https://www.nature.com/articles/s41467-025-58761-y>
- [12] [18] [37] <https://www.nature.com/articles/s41467-024-53052-4>  
<https://www.nature.com/articles/s41467-024-53052-4>
- [13] [27] [41]  
[https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget\\_justification/pdfs/03\\_RDT\\_and\\_E/RDTE\\_Vol1\\_DARPA\\_MasterJustificationBook\\_PB\\_2023.pdf](https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf)  
[https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget\\_justification/pdfs/03\\_RDT\\_and\\_E/RDTE\\_Vol1\\_DARPA\\_MasterJustificationBook\\_PB\\_2023.pdf](https://comptroller.war.gov/Portals/45/Documents/defbudget/fy2023/budget_justification/pdfs/03_RDT_and_E/RDTE_Vol1_DARPA_MasterJustificationBook_PB_2023.pdf)
- [15] <https://www.sciencedirect.com/science/article/pii/S2666165924001674>  
<https://www.sciencedirect.com/science/article/pii/S2666165924001674>
- [17] <https://www.mdpi.com/2075-5309/12/12/2226>  
<https://www.mdpi.com/2075-5309/12/12/2226>
- [19] <https://www.sciencedirect.com/science/article/pii/S2666165923001266>  
<https://www.sciencedirect.com/science/article/pii/S2666165923001266>
- [25] [44] [48] <https://op.europa.eu/en/publication-detail/-/publication/124c9d47-ec43-11f0-8d3c-01aa75ed71a1/language-en>  
<https://op.europa.eu/en/publication-detail/-/publication/124c9d47-ec43-11f0-8d3c-01aa75ed71a1/language-en>
- [30] [43] <https://www.nature.com/articles/s41467-023-40265-2>  
<https://www.nature.com/articles/s41467-023-40265-2>
- [32] <https://pmc.ncbi.nlm.nih.gov/articles/PMC12067278/>  
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12067278/>
- [34] [47] [https://repository.tudelft.nl/file/File\\_5a493461-96d9-4fd9-ad28-86364c3894f6](https://repository.tudelft.nl/file/File_5a493461-96d9-4fd9-ad28-86364c3894f6)  
[https://repository.tudelft.nl/file/File\\_5a493461-96d9-4fd9-ad28-86364c3894f6](https://repository.tudelft.nl/file/File_5a493461-96d9-4fd9-ad28-86364c3894f6)
- [40] <https://www.sciencedirect.com/science/article/pii/S0167779924002804>  
<https://www.sciencedirect.com/science/article/pii/S0167779924002804>

[46] <https://www.sciencedirect.com/science/article/pii/S2590238524004041>

<https://www.sciencedirect.com/science/article/pii/S2590238524004041>

## ART 09.077 Gene Drive Pest Control

153. ART extraction

### Primary capability claimed

- A self-propagating genetic system that **biases inheritance** so a selected trait spreads through a **wild, sexually reproducing target population** over multiple generations.
- Configurable outcomes: **population suppression** (reduced viability/fertility) and **population modification** (changed traits, e.g., reduced pathogen transmission) via engineered genetic payloads.

### Key sub-components and variants

- **CRISPR “homing” gene drives** (copying a drive allele onto the homologous chromosome in the germline).
- **Suppression drives** (e.g., fertility/sex-determination disruption) versus **modification drives** (payloads reducing vector competence/pathogen transmission).
- **Confinable/localised drive architectures** (e.g., split drives; low-threshold vs higher-threshold systems; transient/self-exhausting elements).
- **Drive robustness engineering** (multiplexed gRNAs; target-site choice under natural genetic diversity; promoter optimisation to tune germline expression and reduce embryo/somatic cleavage).
- **Resistance management** (minimising functional resistance alleles; multi-target strategies; modelling resistance dynamics).
- **Controllability features** (anti-drive/anti-CRISPR or other countermeasures; governance “controls” defining where/when releases occur).
- **Monitoring and verification infrastructure** (genotyping, population sampling, environmental DNA, field surveillance toolchains; modelling and risk assessment workflows).
- **Governance/regulatory frameworks** (risk assessment guidance for transboundary spread; phased testing; consent/social licence).

### Maturity indicators that would constitute strong evidence

- Reproducible **lab/cage demonstrations** of: high inheritance bias, spread dynamics, and meaningful population effects (suppression or payload propagation) in relevant species.
- Evidence that major blockers are being mitigated: **resistance allele formation**, **fitness costs**, **promoter/drive timing**, and **containment/control** mechanisms.
- **Semi-field / contained field trials** (large cages/field-like environments) with monitoring data and ecological endpoints.
- Clear **regulatory pathway readiness** (WHO/Cartagena/CBD-aligned risk assessment materials; national/regional guidance; trial protocols).
- **Operational readiness** signals: scalable rearing/release concepts, validated monitoring protocols, long-term stewardship plans, and resourced governance.



- For higher maturity (4+): evidence of **authorised field trials**, then repeatable deployments at increasing scale.

#### Evidence (10–20 recent, reliable sources)

##### 154. Evidence (10–20 recent, reliable sources)

Most experimental demonstrations below are peer-reviewed in Nature Communications[1], Proceedings of the National Academy of Sciences[2], eLife[3], PLOS Genetics[4], BMC Genomics[5], BMC Biology[6], and Malaria Journal[7].

#### Experimental demonstrations and engineering progress

##### 1) A suppression-modification gene drive for malaria control targeting the ultra-conserved RNA gene mir-184

Authors/organisation: Sebald A. N. Verkuijl[8] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: April 2025

Link: <https://doi.org/10.1038/s41467-025-58954-5>

Concrete progress: Reports **near-optimal drive transmission** (e.g., ~99.6% from females; ~97.1% from males) and **cage invasion to fixation** (around generation ~14), while carrying fitness costs that can reduce vectorial capacity; also demonstrates coupled spread of a separate antimalarial effector allele in cages. Why it matters: Direct evidence that high-efficiency inheritance bias plus “suppression-modification” design can work in controlled populations, while highlighting fitness/resistance considerations that bound real-world maturity. [9]

##### 2) Gene drive-based population suppression in the malaria vector *Anopheles stephensi*

Authors/organisation: Xuejiao Xu[10] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: January 2025

Link: <https://doi.org/10.1038/s41467-025-56290-2>

Concrete progress: Constructs a dsx-targeting suppression (“homing”) drive with **two gRNAs**, detects **very low resistance allele formation**, and shows that pairing the drive with a vasa-Cas9 line can boost conversion to **100%** (suggesting a continuous-release strategy). Why it matters: Demonstrates portability of suppression-drive ideas into a key invasive malaria vector species while exposing promoter/species-dependence and the role of combined systems in achieving high conversion. [11]

##### 3) A population modification gene drive targeting both Saglin and Lipophorin impairs *Plasmodium* transmission in *Anopheles* mosquitoes

Authors/organisation: Emily I. Green[12] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: December 2023

Link: <https://doi.org/10.7554/eLife.93142>

Concrete progress: Builds and tests CRISPR-based gene drives intended to spread antimalarial traits; reports that a Saglin-based drive reached **high levels in caged populations** and promoted spread of an antimalarial Lipophorin::Sc2A10 allele, while also observing drive-resistant alleles and multiplex-array instability. Why it matters: Shows

feasibility of “population modification” payload propagation in a malaria vector, and provides practical evidence about instability/resistance issues that influence deployability. [13]

#### 4) **Anti-CRISPR Anopheles mosquitoes inhibit gene drive spread under challenging behavioural conditions in large cages**

Authors/organisation: Rocco D’Amato[14] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: February 2024

Link: <https://doi.org/10.1038/s41467-024-44907-x>

Concrete progress: Demonstrates an AcrIIA4-based “anti-drive” that can **block spread** of a doublesex-targeting drive and **prevent population collapse** in age-structured cage environments with challenging feeding/behavioural conditions, backed by stochastic modelling. Why it matters: Direct evidence for a key maturity enabler—**controllability**—supporting the ART’s claim that governance/limits and “brakes” can be engineered, even if field deployment remains distant. [15]

#### 5) **Homing gene drives can transfer rapidly between Anopheles gambiae strains with minimal carryover of flanking sequences**

Authors/organisation: Poppy Pescod[16] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: August 2024

Link: <https://doi.org/10.1038/s41467-024-51225-9>

Concrete progress: Provides experimental evidence that drive-associated genetic changes can **move between strains** while leaving **minimal linked (flanking) sequence carryover**, clarifying how drives may move across genetic backgrounds. Why it matters: Supports plausibility of spread across heterogeneous real populations (maturity enabler) while simultaneously sharpening risk assessment needs for gene flow and monitoring. [17]

#### 6) **Germline Cas9 promoters with improved performance for homing gene drive**

Authors/organisation: Jie Du[18] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: May 2024

Link: <https://doi.org/10.1038/s41467-024-48874-1>

Concrete progress: Screens many germline promoters and reports improved drive conversion / reduced embryo resistance for selected designs; includes cage experiments where a selected construct enabled **successful elimination of a cage population** with a multiplexed suppression drive. Why it matters: Shows progress on a historically blocking engineering variable—**timing/location of Cas9 expression**—which is central to performance, resistance, and safety profiles. [19]

#### 7) **A multiplexed, confinable CRISPR/Cas9 gene drive can propagate in caged Aedes aegypti populations**

Authors/organisation: Michelle A. E. Anderson[20] et al.

Venue/type: Peer-reviewed experimental paper

Publication date: January 2024

Link: <https://doi.org/10.1038/s41467-024-44956-2>

Concrete progress: Demonstrates a split-drive design in *Aedes aegypti* where carrier frequency rises from ~50% to **up to ~89%** in cage trials, with deep sequencing suggesting multiplexing may mitigate resistance allele formation. Why it matters: Extends gene drive

maturity beyond “best-studied” *Anopheles* systems toward broader pest/vector targets, while remaining clearly at laboratory-cage scale. [21]

#### 8) **Closing the gap to effective gene drive in *Aedes aegypti* by exploiting germline regulatory elements**

Authors/organisation: Anderson et al.

Venue/type: Peer-reviewed experimental paper

Publication date: January 2023

Link: <https://doi.org/10.1038/s41467-023-36029-7>

Concrete progress: Builds multiple *Ae. aegypti* Cas9 germline expression lines and reports high inheritance bias in outcrosses (e.g., ~86% and ~94% for a top-performing line in males and females respectively), with modelling suggesting faster/higher spread versus prior split-drive systems. Why it matters: Demonstrates that improving germline regulatory control can materially raise inheritance bias in a harder-to-drive species, supporting plausibility for configurable design tooling. [22]

#### 9) **A CRISPR endonuclease gene drive reveals distinct mechanisms of inheritance bias**

Authors/organisation: Verkuijl et al.

Venue/type: Peer-reviewed experimental paper

Publication date: November 2022

Link: <https://doi.org/10.1038/s41467-022-34739-y>

Concrete progress: Shows that apparent inheritance bias in a CRISPR drive context can arise via **different mechanisms** (e.g., not always homing), and argues DNA repair outcomes can be more context-dependent than assumed. Why it matters: Directly informs both plausibility and maturity: gene drive “works,” but mechanistic uncertainty and context dependence remain major blockers for predictable, governed field outcomes. [23]

#### 10) **Improving the suppressive power of homing gene drive by co-targeting a distant-site female fertility gene**

Authors/organisation: Nicky R. Faber[24] et al.

Venue/type: Peer-reviewed modelling + experimental paper

Publication date: October 2024

Link: <https://doi.org/10.1038/s41467-024-53631-5>

Concrete progress: Proposes and models a “two-target” architecture where suppression depends more on cutting efficiency than conversion efficiency, then constructs a two-target drive in *Drosophila* with both components functioning; also identifies persistent challenges (maternal deposition and heterozygote fitness costs). Why it matters: Supports the ART’s “configurable layer” claim (architectural knobs), while underscoring why current maturity is still short of field-ready robustness. [25]

#### 11) **CRISPR-Cas9 and Cas12a target site richness reflects genomic diversity in natural populations of *Anopheles gambiae* and *Aedes aegypti* mosquitoes**

Authors/organisation: Travis C. Collier[26] et al.

Venue/type: Peer-reviewed computational/population genomics paper

Publication date: July 2024

Link: <https://doi.org/10.1186/s12864-024-10597-4>

Concrete progress: Analyses global natural-population genomes (multi-continent) and shows how polymorphism patterns affect availability of low-polymorphism target sites; demonstrates that using both Cas9 and Cas12a increases targets per gene and screens

gRNAs for sex-determination genes. Why it matters: Directly addresses a key feasibility bottleneck for field plausibility—designing drives that remain effective across **real genetic diversity**, reducing “surprise resistance” risk. [27]

#### 12) **Leveraging a natural murine meiotic drive to suppress invasive populations**

Authors/organisation: Luke Gierus[28] et al.

Venue/type: Peer-reviewed experimental + modelling paper

Publication date: 2022 (month not consistently displayed in the extracted record)

Link: <https://doi.org/10.1073/pnas.2213308119>

Concrete progress: Demonstrates a mouse gene-drive strategy (tCRISPR) leveraging super-Mendelian transmission; reports engineered mice with biased transmission and Prl mutations at levels argued to support eradication in spatial models (including ~95% transmission and 100% Prl mutation transmission from tCRISPR males as described in the record). Why it matters: Expands gene-drive pest control plausibility beyond insects into vertebrate invasive-species management, while still firmly at lab/prototype stage. [29]

#### 13) **Building an eDNA surveillance toolkit for invasive rodents on islands: can we detect wild-type and gene drive *Mus musculus*?**

Authors/organisation: Antoinette J. Piaggio[30] et al.

Venue/type: Peer-reviewed methodology paper

Publication date: November 2024

Link: <https://doi.org/10.1186/s12915-024-02063-0>

Concrete progress: Develops and demonstrates environmental DNA assays to detect both wild-type and gene-drive-associated mouse signatures and estimate relative abundance from environmental samples. Why it matters: Monitoring/verification is a maturity gate for any release; this is concrete progress toward scalable post-release surveillance without relying solely on trapping/handling individuals. [31]

#### 14) **Modelling daisy quorum drive: A short-term bridge across engineered fitness valleys**

Authors/organisation: Frida J. H. de Haas[32] et al.

Venue/type: Peer-reviewed modelling paper

Publication date: May 2024

Link: <https://doi.org/10.1371/journal.pgen.1011262>

Concrete progress: Models a drive that transitions from a low-threshold “daisy chain” phase to a high-threshold (“quorum”) system, predicting improved spatial confinement after CRISPR elements exhaust, while still enabling local modification. Why it matters: Directly speaks to the ART’s “limit geographic spread / slow propagation” design thread; currently theoretical/modelling support rather than operational proof. [33]

### **Field-trial design, governance, and market-readiness evidence**

#### 15) **Considerations for first field trials of low-threshold gene drive for malaria vector control**

Authors/organisation: John B. Connolly[34] et al.

Venue/type: Peer-reviewed perspective / trial-design paper

Publication date: 2024

Link: <https://doi.org/10.1186/s12936-024-04952-9>

Concrete progress: Specifies design elements and endpoints for initial trials (genetic efficacy and spread, entomological/epidemiological measures, monitoring and adaptive trial design),

explicitly framing the pathway from genetic spread to public-health outcomes and associated uncertainties. Why it matters: Indicates the field is organising around triable, monitorable metrics (a maturity signal), but does not itself demonstrate authorised field trials. [35]

#### 16) **Regulatory and policy considerations for the implementation of gene drive-modified mosquitoes to prevent malaria transmission**

Authors/organisation: Stephanie L. James[36] et al.

Venue/type: Peer-reviewed policy/regulatory analysis

Publication date: 2023

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10102045/>

Concrete progress: States that **no gene drive-modified mosquitoes have yet undergone field testing**, and maps unresolved regulatory questions (product definition, approval/registration, transboundary movement, roles of multinational agreements). Why it matters: This is direct evidence that (as of publication) the ART is pre-field-trial and that non-technical authorisation pathways are dominant near-term maturity constraints. [37]

#### 17) **Sixteenth meeting of the WHO Vector Control Advisory Group**

Authors/organisation: World Health Organization[38]

Venue/type: Authoritative meeting report (public health advisory process)

Publication date: June 2022

Link: <https://www.who.int/publications/i/item/9789240052673>

Concrete progress: WHO's VCAG explicitly includes "reduction of pathogen transmission induced by gene drive" among the intervention classes reviewed, signalling an institutional pathway for evaluating gene-drive-derived vector control concepts. Why it matters: Shows movement toward governance and evaluation infrastructure required for any eventual deployment; it does not imply field authorisation. [39]

#### 18) **Report of the Ad Hoc Technical Expert Group on Risk Assessment on its second meeting**

Authors/organisation: Convention on Biological Diversity[40] (Cartagena Protocol process)

Venue/type: Authoritative international technical report

Publication date: March 2024

Link: <https://www.cbd.int/doc/c/0e44/e702/e4783d74c9e6f262989fbcabc/cp-ra-ahteg-2024-01-03-en.pdf>

Concrete progress: Identifies that engineered gene drive LMOs pose distinctive risk-assessment challenges, including **greater potential for transboundary movement** and the need to consider impacts across larger spatial scales (and uncertainties around ecological function). Why it matters: Confirms that international biosafety governance is actively adapting methodologies—an essential but time-consuming maturity gate for real-world releases. [41]

#### 19) **Guidance for the Use of Genetically Modified Mosquitoes** (West Africa Integrated Vector Management Programme)

Authors/organisation: AUDA-NEPAD[42] (with regional partners)

Venue/type: Authoritative regional guidance / roadmap

Publication date: April 2022

Link: <https://www.nepad.org/file-download/download/public/139454>

Concrete progress: Provides a structured guidance framework explicitly intended to support development/testing/deployment pathways for genetically modified mosquitoes, with stated

focus including gene drive technology and governance/capacity-building considerations. Why it matters: Evidence of region-specific readiness work (policy and institutional capacity), which is necessary for any future trial authorisation and stewardship. [43]

## 20) **Genetically modified mosquitoes: Technology and access landscape report**

Authors/organisation: Unitaaid[44]

Venue/type: Authoritative landscape / market-access report

Publication date: November 2025

Link: <https://unitaid.org/uploads/Genetically-modified-mosquitoes-technology-and-access-landscape.pdf>

Concrete progress: Synthesises current research maturity and outlines access, procurement, and scale-up barriers for genetically modified mosquito approaches, framing development in staged “phase” terms and highlighting constraints across quality, delivery, and adoption.

Why it matters: Supports the maturity assessment that gene-drive-like systems remain largely in R&D/early evaluation rather than late-stage product delivery, even as ecosystem actors plan for eventual pathways. [45]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 3**

#### **Why this rules out lower levels**

- Multiple peer-reviewed studies demonstrate **functional laboratory gene drive systems** that bias inheritance and can **spread through caged populations** (including fixation-level behaviour), satisfying more than a basic “operating principle” demonstration. For example, the mir-184 drive reports near-optimal inheritance and cage fixation dynamics in *Anopheles gambiae*. [9]
- Engineering progress has addressed key previously-blocking sub-problems (at least partially): improved germline promoters and multi-gRNA architectures, and demonstrable controllability via anti-drive constructs in cage environments. [46]

These clearly exceed rubric level **2** (principle verified in lab) because they include integrated, functional prototypes with population-level demonstrations in controlled settings.

#### **Why the evidence does not justify the next higher level**

Rubric **4** requires a PoC that meets commercialisation requirements in functionality and viability for production/deployment. The strongest near-term blockers evident in the last four years include: - **No environmental field testing (for gene-drive mosquitoes) reported in the regulatory analysis**, indicating the ART is still pre-field-trial in the most deployment-relevant category. [37]

- International and regional bodies are still actively developing **risk-assessment guidance** for engineered gene drive organisms, emphasising challenges like transboundary movement and large-scale ecological uncertainty—signals that governance readiness remains incomplete. [41]

- Even within advanced lab systems, papers explicitly highlight unresolved issues: mechanistic/context dependence of inheritance bias, maternal deposition and heterozygote fitness costs, promoter/species dependence, and the ever-present prospect of resistance dynamics. [47]



Collectively, this fits “laboratory prototype demonstrated” (3) rather than PoC-ready deployment (4).

#### Sub-component maturity breakdown (compressed)

- **High-efficiency mosquito homing drives (Anopheles)** → ~3  
Key support: high inheritance + cage fixation and/or strong population effects in controlled settings. [48]
- **Drive control/confinement concepts** → ~2–3  
Key support: anti-drive demonstrated in cage settings (experimental), plus confinement-oriented modelling architectures (theoretical). [49]
- **Design robustness against natural variation/resistance** → ~2–3  
Key support: genomic diversity analysis for target-site selection; mechanistic uncertainty papers reinforcing remaining unpredictability. [50]
- **Monitoring/verification toolchain** → ~2–3  
Key support: proof-of-concept eDNA surveillance for distinguishing wild-type vs gene-drive signatures in environmental samples. [31]
- **Governance/regulatory path to first releases** → ~2  
Key support: WHO VCAG evaluation class recognition, CBD risk-assessment methodology work, and regional guidance frameworks; still not field-authorisation evidence. [51]

Aggregation rationale: the ART’s core functional promise (inheritance bias that self-propagates) is demonstrated at prototype level in multiple species, but the end-to-end “deployable genetic control layer” remains gated by controllability, ecological predictability, and authorisation pathways; thus an overall **3** (prototype demonstrated, pre-PoC for deployment at scale). [52]

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## ART 09.078 Artificial Wombs & Synthetic Embryos

### ART extraction

- **Primary capability (what the ART claims)**
- Controlled *ex vivo* gestational support for defined windows of mammalian development (initially most plausible for very premature “bridge-to-viability” scenarios), using an instrumented liquid environment and a placenta-like gas/nutrient/waste exchange interface. [1]
- “Synthetic embryo” / embryo-model systems grown from stem cells that reproduce selected features of early development (pre-implantation to post-implantation windows) without being identical to conventional embryos, enabling observation and experimentation that is hard or impermissible *in vivo*. [2]
- A protocol-driven platform incorporating dense sensing + imaging + closed-loop control to standardise conditions, detect deviations early, and create auditable, repeatable developmental support processes. [3]
- **Key sub-components / variants (technology bundle)**
- Artificial placenta / extracorporeal life support circuits that connect to umbilical vessels and maintain foetal circulation in a fluid-filled chamber (e.g., sheep and pig models). [1]
- Gas-exchange membranes/oxygenators with improved haemocompatibility (low thrombosis + low bleeding), ideally minimising systemic anticoagulation for fragile premature physiology. [4]
- Transfer/cannulation and perinatal procedures to avoid triggering neonatal transition (e.g., avoiding lung aeration, fast circuit establishment). [5]
- Stem-cell-derived embryo models across stages: blastoids; post-implantation embryoids/SEMs; extra-embryonic tissue models (e.g., amnion models) and primate embryo models pushing later developmental windows. [6]
- Governance/oversight frameworks defining what constitutes an embryo vs an embryo model, permissible culture limits, and prohibitions (e.g., uterine transfer). [7]
- **Maturity indicators that would constitute evidence**
- **Sustained large-animal demonstrations** with stable haemodynamics, low infection, and *normal(ised) growth and organ development* (not only “kept alive”). [8]
- **Repeatability + learning curves:** improving transition/cannulation success, reducing circuit failures (air emboli, thrombosis), and robust protocols transferable across teams/sites. [9]
- **Engineering readiness:** clinically relevant oxygenator performance, low clot formation with minimal anticoagulation, manufacturable sterile disposables, and integrated monitoring/control validated *in vivo*. [4]

- **Regulatory traction:** credible trial-design planning, oversight codes, and regulator positions clarifying legal status of embryo models and boundaries for artificial placenta/womb trials. [10]

## 2. Evidence (10–20 recent, reliable sources)

### 1) An Artificial Placenta Experimental System in Sheep: Critical Issues for Successful Transition and Survival up to One Week

- **Authors/Org:** Elisenda Eixarch[11] et al.
- **Venue/type:** *Biomedicines* (peer-reviewed experimental paper)
- **Publication date:** Mar 2023 (2023-03-01)
- **Link:** <https://www.mdpi.com/2227-9059/11/3/702>
- **Why it matters:** Reports a 28-foetal-sheep series with stepwise survival targets up to **48–168 h**, showing a clear learning curve (e.g., cannulation complications dropped to 0% in later groups) and identifying bottlenecks like air bubbles and thrombosis—strong evidence of *prototype reality* and what is still failing. [12]

### 2) Artificial placenta support of extremely preterm ovine fetuses... for up to 336 hours with maintenance of systemic circulation but reduced somatic and organ growth

- **Authors/Org:** Haruo Usuda[13] et al.
- **Venue/type:** *Frontiers in Physiology* (peer-reviewed experimental paper)
- **Publication date:** Aug 2023 (Published 24 Aug 2023)
- **Link:** <https://www.frontiersin.org/journals/physiology/articles/10.3389/fphys.2023.1219185/full>
- **Why it matters:** Demonstrates **systemic circulation maintained up to 336 h** without infection, but explicitly reports abnormal growth—showing feasibility of long support while spotlighting a decisive maturity blocker: *developmental normalcy*. [14]

### 3) Echocardiographic assessment of cardiovascular physiology of preterm miniature piglets supported with a pumped artificial placenta system

- **Authors/Org:** Henriette Kühle[15] et al.
- **Venue/type:** *Prenatal Diagnosis* (peer-reviewed experimental paper)
- **Publication date:** Jun 2024 (Epub 29 May 2024)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/38809178/>
- **Why it matters:** Provides detailed physiology in a piglet model (closer umbilical anatomy constraints for human translation), finding tachycardia/hypertension, hydrops, and circuit-flow issues—evidence that *haemodynamic matching to the native placenta remains unsolved*. [16]

### 4) Transferring an extremely premature infant to an extra-uterine life support system: a prospective view on the obstetric procedure

- **Authors/Org:** Juliette S. van Haren[17] et al.
- **Venue/type:** *Frontiers in Pediatrics* (peer-reviewed review/clinical-procedure analysis)
- **Publication date:** Feb 2024 (Published 15 Feb 2024)
- **Link:** <https://www.frontiersin.org/journals/pediatrics/articles/10.3389/fped.2024.1360111/full>
- **Why it matters:** Synthesises obstetric/transfer constraints (avoid lung aeration, rapid umbilical cannulation, preserving foetal physiology) and documents EU funding for “Perinatal Life Support System” clinical-translation enabling technologies—evidence of coordinated systems engineering beyond single-lab tinkering. [18]

### 5) Stakeholder Perspectives on the Design of First-In-Human Trials for Artificial Amnion and Placenta Technology: A Qualitative Study

- **Authors/Org:** Angret de Boer[19] et al.
- **Venue/type:** *BJOG* (peer-reviewed qualitative study; trial design readiness)
- **Publication date:** Oct 2025 issue (Received Dec 2024; revised Mar 2025; issue date Oct 2025)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC12411662/>
- **Why it matters:** Shows late-stage translational planning: identifies requirements for human trials (optimise animal model, define stop/success criteria, logistics, parental role), indicating momentum toward clinical experimentation—but still upstream of actual trials. [20]

### 6) A silicon membrane microfluidic oxygenator for use as an artificial placenta with minimal anticoagulation

- **Authors/Org:** David G. Blauvelt[21] et al.
- **Venue/type:** *Bioengineering & Translational Medicine* (peer-reviewed experimental paper; full text in PMC)
- **Publication date:** Jul 2025 (eCollection Sep 2025)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC12478335/>
- **Why it matters:** Reports two prototype generations and concrete metrics: operation with **minimal anticoagulation (ACT 120–180 s)**, **oxygen transfer  $1.51 \pm 0.25$  vol%**, and **6-hour neonatal swine** in vivo testing with minimal clot formation and stable health markers—direct progress on the hardest engineering bottleneck: blood-contacting exchange surfaces. [22]

### 7) An endothelium membrane mimetic antithrombotic coating enables safer and longer extracorporeal membrane oxygenation application

- **Authors/Org:** Rong Li[23] et al.
- **Venue/type:** *Acta Biomaterialia* (peer-reviewed experimental biomaterials paper)
- **Publication date:** Sep 2024 (Epub Aug 2024)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/39103136/>
- **Why it matters:** Demonstrates a coating strategy on polypropylene oxygenator membranes that (per abstract) reduces protein adsorption to **<30 ng/cm<sup>2</sup>** and extends circuit performance to **>15 h in a pig model without systemic anticoagulant**, directly informing the haemocompatibility path needed for artificial placenta/womb circuits. [24]

### 8) Embryo model completes gastrulation to neurulation and organogenesis

- **Authors/Org:** Gianluca Amadei[25] et al.
- **Venue/type:** *Nature*[26] (peer-reviewed experimental paper)
- **Publication date:** Aug 2022 (Published 25 Aug 2022)
- **Link:** <https://www.nature.com/articles/s41586-022-05246-3>
- **Why it matters:** A landmark mouse stem-cell embryo model reaching early organogenesis-like events (e.g., neural tube/somites and a beating heart-like structure), supporting *scientific plausibility* that multi-lineage self-organisation can approximate substantial developmental programs. [27]

### 9) In vitro attachment and symmetry breaking of a human embryo model assembled from primed embryonic stem cells

- **Authors/Org:** Mijo Simunovic[28] et al.
- **Venue/type:** *Cell Stem Cell* (peer-reviewed experimental paper)

- **Publication date:** Jun 2022
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/35659878/>
- **Why it matters:** Demonstrates a human embryo model that attaches in vitro and breaks anteroposterior symmetry to generate early gastrulation-like cell types—direct evidence that “synthetic embryo” constructs can reproduce key early patterning behaviours. [29]

#### 10) Rolling back human pluripotent stem cells to an eight-cell embryo-like stage

- **Authors/Org:** Md Abdul Mazid[30] et al.
- **Venue/type:** Nature (peer-reviewed experimental paper)
- **Publication date:** Mar 2022 (Published 21 Mar 2022)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/35314832/>
- **Why it matters:** Provides a transgene-free method to generate human “8C-like” cells and identifies critical molecular regulators—evidence that stem-cell systems are pushing toward *earlier developmental analogues*, which the ART flags as hardest to support robustly. [31]

#### 11) Pluripotent stem cell-derived model of the post-implantation human embryo

- **Authors/Org:** Emily A. Weatherbee[32] et al.
- **Venue/type:** Nature (peer-reviewed experimental paper)
- **Publication date:** Jun 2023 (Published 27 Jun 2023)
- **Link:** <https://www.nature.com/articles/s41586-023-06368-y>
- **Why it matters:** Establishes a human post-implantation embryoid comprising embryonic and extra-embryonic tissues, directly supporting the ART’s claim that these systems can instrument otherwise hard-to-observe phases and tissue–tissue crosstalk. [33]

#### 12) Complete human day 14 post-implantation embryo models from naive ES cells

- **Authors/Org:** Bernardo Oldak[34] et al.
- **Venue/type:** Nature (peer-reviewed experimental paper)
- **Publication date:** Sep 2023 (Published 06 Sep 2023)
- **Link:** <https://www.nature.com/articles/s41586-023-06604-5>
- **Why it matters:** Reports “complete” integrated human stem-cell embryo models recapitulating organisation of nearly all key compartments/lineages with growth dynamics resembling post-implantation development to ~**13–14 days**—strong plausibility evidence for advanced embryo-like constructs (and a marker of research maturity as a tool). [35]

#### 13) Self-renewing human naïve pluripotent stem cells dedifferentiate in 3D culture and form blastoids spontaneously

- **Authors/Org:** Mingyue Guo[36] et al.
- **Venue/type:** *Nature Communications* (peer-reviewed experimental paper)
- **Publication date:** Jan 2024 (Published 22 Jan 2024)
- **Link:** <https://www.nature.com/articles/s41467-024-44969-x>
- **Why it matters:** Reports spontaneous and efficient formation of blastoids from self-renewing naïve hPSCs in 3D suspension, supporting the ART’s expectation of protocol-driven, repeatable platforms (at least for early-stage embryo models). [37]

#### 14) Cynomolgus monkey embryo model captures gastrulation and early pregnancy

- **Authors/Org:** Jie Li[38] et al.
- **Venue/type:** *Cell Stem Cell* (peer-reviewed experimental paper)
- **Publication date:** Apr 2023 (PubMed indexed; widely reported as published online 6 Apr 2023)



- **Link:** <https://pubmed.ncbi.nlm.nih.gov/37028403/>
- **Why it matters:** Shows primate blastoids that recapitulate gastrulation in vitro and, upon transfer to surrogates, trigger early pregnancy indicators (e.g., progesterone/gestation sacs), demonstrating cross-species developmental potential and sharpening the ethical boundary issues for anything approaching ectogenesis. [39]

#### 15) Post-gastrulation amnioids as a stem cell-derived model of human extra-embryonic development

- **Authors/Org:** Borzo Gharibi[40] et al.
- **Venue/type:** *Cell* (peer-reviewed experimental paper)
- **Publication date:** Jul 2025 (Epub May 2025)
- **Link:** <https://pubmed.ncbi.nlm.nih.gov/40378847/>
- **Why it matters:** Introduces a stem-cell-derived 3D model of post-gastrulation amnion/extra-embryonic development—evidence that “synthetic embryo” work is expanding from embryo-proper features to the *support tissues* that an artificial womb/placenta concept would ultimately need to interface with. [41]

#### 16) Modelling late gastrulation in stem cell-derived monkey embryo models

- **Authors/Org:** Jie Li[42] et al.
- **Venue/type:** *Nature* (peer-reviewed experimental paper)
- **Publication date:** Dec 2025 (Published 03 Dec 2025)
- **Link:** <https://www.nature.com/articles/s41586-025-09831-0>
- **Why it matters:** Reports an optimised 3D suspension culture system advancing a stem-cell-derived monkey blastoid to **day 25**, pushing embryo-model maturity toward later windows that are central to many proposed regulatory debates (e.g., beyond day-14-like limits). [43]

#### 17) Code of practice for the generation and use of human stem cell-based embryo models

- **Authors/Org:** Cambridge Reproduction[44] and Progress Educational Trust[45]
- **Venue/type:** Governance / guidance (UK code of practice; PDF)
- **Publication date:** Jul 2024
- **Link:** [https://www.repro.cam.ac.uk/files/240704\\_scbem\\_code\\_of\\_practice.pdf](https://www.repro.cam.ac.uk/files/240704_scbem_code_of_practice.pdf)
- **Why it matters:** Establishes practical oversight expectations (e.g., governance structures and review) for stem-cell-based embryo models, helping convert a fast-moving technical field into auditable protocols—directly addressing the ART’s “regulatory/ethical boundary” constraint. [46]

#### 18) Human stem cell-based embryo models: a review of ethical and governance questions

- **Authors/Org:** Nuffield Council on Bioethics[47]
- **Venue/type:** Authoritative report (PDF)
- **Publication date:** Nov 2024 (26 Nov 2024)
- **Link:** <https://cdn.nuffieldbioethics.org/wp-content/uploads/NCOB-SCBEM-Full-Report-Final.pdf>
- **Why it matters:** Provides a structured governance analysis and staged recommendations (including distinctions between embryos and SCBEMs and pathways toward regulatory control), evidencing that policy adaptation is occurring in parallel with technical advances. [48]

### 19) Laboratory-based human embryonic stem cell research, embryo research, and related research activities (2025 Guidelines)

- **Authors/Org:** International Society for Stem Cell Research[49]
- **Venue/type:** Standards/guidelines web publication
- **Publication date:** Aug 2025 (11 Aug 2025)
- **Link:** <https://www.isscr.org/guidelines/laboratory-based-human-embryonic-stem-cell-research-embryo-research-and-related-research-activities>
- **Why it matters:** Tightens/clarifies oversight categories and “red lines” (including restrictions around embryo models), which strongly shapes what “mature” looks like: some experiments needed for full ectogenesis are ethically constrained even if technically plausible. [50]

### 20) Annual report and accounts 2024–25

- **Authors/Org:** Human Fertilisation and Embryology Authority[51]
- **Venue/type:** Regulator annual report (UK; PDF)
- **Publication date:** Jul 2025 (17 Jul 2025)
- **Link:** <https://assets.publishing.service.gov.uk/media/688219886a7ea0e1ce1d3610/hfea-annual-report-and-accounts-2024-2025-web-accessible.pdf>
- **Why it matters:** Documents that the regulator recommended SCBEMs (and related technologies) move toward statutory regulation—evidence that governance is being actively positioned for emerging capabilities, influencing timelines to clinical translation. [52]

## 3. Maturity score (1–7) and reasoning

### Final maturity score: 3

This ART is best scored at **Level 3 (laboratory prototype demonstrated)** because multiple core functionalities have been demonstrated in credible experimental settings, but decisive clinical/commercial readiness criteria remain unmet.

- **What evidence rules out Levels 1–2 (theory-only or principle-only)?**

Sustained *in vivo* large-animal artificial placenta/extra-uterine support experiments show that the key operating principle—maintaining foetal circulation via an extracorporeal exchange device while housed in a controlled liquid environment—is not hypothetical. Sheep studies report survival windows reaching up to **one week** with documented transition/cannulation learning curves. [12]

Separately, stem-cell-derived embryo models in multiple top-tier venues achieve structured development across early windows (human post-implantation embryoids; integrated models to ~13–14 days; primate models pushing to day 25), demonstrating the “synthetic embryo model” half is firmly beyond early validation. [53]

- **Why this is not yet Level 4 (PoC meeting commercialisation requirements)?**

The best large-animal support data still show major blockers that would be unacceptable in a commercial/clinical PoC: for example, long support can maintain circulation without infection but with **abnormal somatic/organ growth**, and piglet models reveal haemodynamic failures (afterload shifts → heart failure/hydrops), meaning the system is not yet reliably *development-normal* or physiologically matched to a native placenta. [54]

On the hardware side, there is clear movement toward haemocompatible oxygenators with minimal anticoagulation and strong prototype metrics, but these remain early prototypes (e.g., 6-hour neonatal swine testing) rather than proven long-duration, human-ready disposables integrated into a complete artificial womb platform. [4]

Additionally, governance frameworks explicitly shape what “mature” pathways are permissible (e.g., embryo-model prohibitions/red lines and the need for structured oversight), creating constraints that slow or prevent direct scaling to full ectogenesis even if some engineering hurdles were solved. [55]

### Sub-scores and evidence-to-rubric mapping

- **Ex-vivo gestation support / artificial placenta systems → ~3**
- Long-duration and transition learning curves in sheep (up to one week; improved cannulation success) support “lab prototype demonstrated,” but remaining thrombosis/air bubble/cannulation risks and growth abnormalities block PoC status. [56]
- Piglet physiology studies show the system–foetus coupling is still failing in clinically relevant ways (afterload, hydrops), reinforcing that the prototype does not yet meet clinical requirements. [16]
- **Placenta-like exchange hardware (oxygenators/coatings) → ~3–4 (component-level)**
- Prototype oxygenator work shows concrete advances (minimal anticoagulation operation, quantified oxygen transfer, in vivo swine validation), which is close to PoC at the *component* level but not yet demonstrated as long-duration, production-ready in a full system. [22]
- Biomaterial/coating strategies show meaningful extension of anticoagulant-free operation in animal circuits, relevant to scaling duration, yet not specific to a complete artificial womb platform. [24]
- **Synthetic embryo and embryo-model systems → ~3–4 (research-tool maturity)**
- Human embryo models reaching post-implantation organisation to ~13–14 days, plus primate embryo models reaching day 25, indicate a functional and rapidly advancing research toolkit. [57]
- However, these are not “market-ready” for reproductive use (and are actively constrained by governance), so their maturity is best interpreted as laboratory tool maturity rather than a deployable clinical gestation substitute. [58]

### Aggregation to one score:

Because the ART’s value proposition depends on *combining* (a) extra-uterine gestation support and (b) embryo-like constructs/models—while simultaneously operating within evolving ethical/regulatory constraints—the overall maturity is bounded by the least-ready high-risk subsystem: full-system physiological normalcy and clinical transfer readiness. That keeps the combined ART at **3**, even though some subcomponents (e.g., oxygenator coatings, embryo models as research tools) are approaching **3–4** individually. [59]

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## Group 10 – Space & Aeronautical Engineering

### ART 10.079 Satellite Mega-Constellations & Space Internet

#### ART extraction

- **Primary capability (core claims)**
- Near-global, **low-latency broadband connectivity** delivered by large fleets of **LEO** satellites that behave as a coordinated network (incl. in-space routing).
- “Networked space sensing” at high revisit rates (multi-sensor Earth observation) plus selective **onboard processing (“space-based AI”)** to reduce downlink and speed time-to-insight.
- **Positioning/timing augmentation** (especially in weak/denied terrestrial-signal regions) via dedicated or opportunistic LEO signals.
- **Key sub-components / variants**
- Mass-manufactured small satellites + high-cadence replenishment (production, launch batching, on-orbit lifecycle management).
- **Constellation networking:** gateways + terrestrial backhaul; inter-satellite links (ISLs), especially optical; routing/traffic engineering.
- **User access:** electronically steered phased-array terminals; mobility/harsh-environment variants; integration with terrestrial networks.
- **Optical/laser communications:** space–space and space–ground lasercom terminals; interoperability standards; pointing/acquisition/tracking.

- **Onboard compute / AI:** power/thermal limits; radiation and fault-tolerance; model deployment/updates; edge inference and compression.
- **Earth observation payload mix:** optical multispectral; thermal IR; SAR for structure and all-weather imaging.
- **PNT augmentation:** signals of opportunity (e.g., Doppler) vs dedicated LEO-PNT; receiver architectures and clocking.
- **Governance & sustainability:** spectrum access, cross-border licensing; debris mitigation, disposal reliability, space traffic management.
- **Maturity indicators (what “good evidence” looks like for this ART)**
  - Operational service at scale: measurable latency/throughput, uptime, and geographic coverage; expanding customer segments and terminals.
  - Regulatory authorisations and compliance: licensing, spectrum frameworks, debris/disposal rules, reporting and enforcement.
  - Demonstrated ISL/lasercom capability: high-rate optical downlinks, multi-vendor interoperability standards, and on-orbit network formation.
  - Documented, repeatable delivery of EO products (resolution, revisit, tasking/latency) and evidence of expanding use by institutional buyers.
  - On-orbit demonstrations of onboard AI with clear functional benefit (cloud filtering, detection, compression) and evidence of operationalisation.
  - PNT augmentation evidence: demonstrations or peer-reviewed results showing achievable accuracy/availability, and realistic receiver cost/power pathways.

## 2. Evidence (10–20 recent, reliable sources)

### Evidence dossier

#### 1) A Multifaceted Look at Starlink Performance

- Authors/Org: Nitinder Mohan et al. (multi-institution academic team; studies the Starlink[1] network operated by SpaceX[2])
- Venue/type: Peer-reviewed conference paper (ACM Web Conference / WWW '24)
- Date: **May 2024**
- Link: <https://mediatum.ub.tum.de/doc/1742995/document.pdf>
- What it reports / why it matters: Large-scale, multi-method measurement of real-world Starlink performance across many countries (crowdsourced tests + active probes + controlled terminals), supporting the **plausibility and maturity** of low-latency LEO broadband as delivered service rather than a lab claim. [3]

#### 2) Measuring a Low-Earth-Orbit Satellite Network

- Authors/Org: Jianping Pan, Jinwei Zhao, Lin Cai (University of Victoria)
- Venue/type: Preprint (arXiv)
- Date: **July 2023**
- Link: <https://arxiv.org/pdf/2307.06863>
- What it reports / why it matters: Ongoing measurement campaign focused on Starlink's access network, gateways/PoPs, and Internet connectivity, providing evidence that “mega-constellation internet” includes a **complex, evolving terrestrial+space architecture** consistent with scalable ISP-like operations. [4]



### 3) Kuiper Systems LLC Request for Modification... Order and Authorization (DA 24-224)

- Authors/Org: Federal Communications Commission[5]; Kuiper Systems LLC[6]
- Venue/type: Authoritative government licensing decision (order/authorisation)
- Date: **March 2024**
- Link: <https://docs.fcc.gov/public/attachments/DA-24-224A1.pdf>
- What it reports / why it matters: Confirms a major competitor's licensed NGSO system parameters and operational authorisations (incl. Ka-band use and LEOP/testing/deorbit operations), evidencing **multi-actor race conditions** and regulatory readiness beyond a single operator. [7]

### 4) Regulation (EU) 2023/588 establishing the Union Secure Connectivity Programme (IRIS<sup>2</sup>)

- Authors/Org: European Union[8] (European Parliament and Council)
- Venue/type: Authoritative legal act / programme establishment
- Date: **March 2023**
- Link: <https://eur-lex.europa.eu/eli/reg/2023/588/oj/eng>
- What it reports / why it matters: Formalises an EU-level multi-orbit secure connectivity programme, signalling long-horizon institutional commitment and funding frameworks for sovereign/strategic “space internet” as infrastructure, not just commercial experimentation. [9]

### 5) Single Network Future: Supplemental Coverage from Space — Report and Order / Fact Sheet

- Authors/Org: Federal Communications Commission[5]
- Venue/type: Government rulemaking (spectrum/regulatory framework enabling satellite-terrestrial collaboration)
- Date: **February 2024**
- Link: <https://docs.fcc.gov/public/attachments/DOC-400678A1.pdf>
- What it reports / why it matters: Establishes a formal domestic framework for satellite-to-handset “supplemental coverage” using terrestrial spectrum via leasing/arrangements—direct evidence that **integration with mainstream telecom regulation** is moving from concept to implementable rules. [10]

### 6) On-orbit demonstration of 200-Gbps laser communication downlink from the TBIRD CubeSat

- Authors/Org: C. Schieler et al.; NASA[11] / MIT Lincoln Laboratory and partners
- Venue/type: Peer-reviewed conference paper (SPIE; NASA NTRS record)
- Date: **2023** (meeting timeframe includes **Jan–Feb 2023** for SPIE Photonics West presentation context)
- Link: <https://ntrs.nasa.gov/api/citations/20230000434/downloads/Schieler%20paper%20spie2023-tbird-v4.pdf>
- What it reports / why it matters: Demonstrates **100–200 Gbps** lasercom downlinks from a 6U LEO CubeSat with **>1 TB error-free transfer in a single pass**, directly supporting feasibility of high-throughput optical links that reduce RF spectrum bottlenecks for sensing and comms constellations. [12]

### 7) SDA Optical Communications Terminal Standard v3.0.1 (signed)

- Authors/Org: Space Development Agency[13]

- Venue/type: Authoritative interoperability standard (government programme standard)
- Date: **2024** (posted; standard version v3.0.1)
- Link: <https://www.sda.mil/wp-content/uploads/2024/08/SDA-OCT-Standard-v3.0.1-signed.pdf>
- What it reports / why it matters: Specifies interoperability requirements for free-space optical comms including **space-to-space OISLs**, enabling multi-vendor optical mesh networking—evidence of maturation from bespoke demos to **standardised, scalable procurement**. [14]

#### 8) SDA Successfully Launches Tranche 0 of Proliferated Warfighter Space Architecture

- Authors/Org: U.S. Department of Defense / Space Development Agency[13] (public release)
- Venue/type: Authoritative programme milestone report (government announcement with deployment details)
- Date: **April 2023**
- Link: <https://www.defense.gov/News/Releases/Release/Article/3350680/sda-successfully-launches-tranche-0-of-proliferated-warfighter-space-arch/>
- What it reports / why it matters: Documents launch of an initial tranche including **data transport satellites intended for an optical mesh** and sensor satellites for tracking, demonstrating “constellation-as-a-system” deployment beyond commercial broadband alone. [15]

#### 9) Laser Communications — GAO-25-106838

- Authors/Org: U.S. Government Accountability Office[16]
- Venue/type: Authoritative government oversight report
- Date: **February 2025**
- Link: <https://www.gao.gov/assets/gao-25-106838.pdf>
- What it reports / why it matters: Assesses progress, remaining technical and programme risks for proliferated lasercom (incl. SDA efforts), helping evaluate maturity constraints (e.g., interoperability, demonstrations, schedule risk) that affect scaling of optical crosslink networks. [17]

#### 10) FCC Adopts New “5-Year Rule” for Deorbiting Satellites — Fact Sheet (DOC-387720A1)

- Authors/Org: Federal Communications Commission[5]
- Venue/type: Authoritative rule adoption summary (orbital debris mitigation)
- Date: **September 2022**
- Link: <https://docs.fcc.gov/public/attachments/DOC-387720A1.pdf>
- What it reports / why it matters: Requires LEO-region satellites (below 2,000 km) to deorbit **no later than five years** after mission completion, directly evidencing that mega-constellation economics and design now incorporate **hard disposal constraints**, shaping feasibility and cost. [18]

#### 11) IADC Report on the Status of the Space Debris Environment

- Authors/Org: Inter-Agency Space Debris Coordination Committee[19] (hosted via UN/space sustainability portal)
- Venue/type: Authoritative international technical report
- Date: **February 2025**
- Link: [https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC\\_report\\_on\\_status\\_of](https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC_report_on_status_of)

\_space\_debris\_environment.pdf

- What it reports / why it matters: Provides an international technical baseline on the evolving debris environment and mitigation context—critical for evaluating whether mega-constellation scaling is compatible with sustainable operations, insurance, licensing, and long-term feasibility. [20]

#### 12) **Φsat-2 mission page**

- Authors/Org: European Space Agency[21]

- Venue/type: Authoritative mission description (on-orbit AI demonstration)

- Date: **August 2024** (launch date stated)

- Link: [https://www.esa.int/Applications/Observing\\_the\\_Earth/Phsat-2](https://www.esa.int/Applications/Observing_the_Earth/Phsat-2)

- What it reports / why it matters: States Φsat-2 launched **16 Aug 2024** and is designed to demonstrate onboard AI applications (e.g., cloud filtering, vessel detection/classification, map conversion), supporting **plausibility and early maturity** of “space-based AI” workflows. [22]

#### 13) **Current AI Technology in Space (v4 briefing)**

- Authors/Org: Justin Goodwill et al.; NASA[11] (Goddard Space Flight Center)

- Venue/type: Authoritative technical briefing (NASA NTRS)

- Date: **2024** (briefing revision marked 07/23 in-file)

- Link:

<https://ntrs.nasa.gov/api/citations/20240001139/downloads/Current%20Technology%20in%20Space%20v4%20Briefing.pdf>

- What it reports / why it matters: Summarises current drivers, applications, and constraints for onboard AI in space systems (latency, autonomy, resource limits), useful as a grounded reality-check on what “space AI” can do today versus aspirational model sizes/operations. [23]

#### 14) **Deciphering the Enigma of Satellite Computing with COTS Devices: Measurement and Analysis**

- Authors/Org: Ruolin Xing et al.

- Venue/type: Preprint (arXiv) + (published venue link exists elsewhere; core evidence here is measurement study)

- Date: **January 2024**

- Link: <https://arxiv.org/abs/2401.03435>

- What it reports / why it matters: Presents a measurement study of **thermal control, power management, and performance** of commercial off-the-shelf compute devices on satellites—direct evidence for the ART’s stated bottlenecks (power/cooling) and for what limits onboard AI/in-orbit compute scaling. [24]

#### 15) **Review on Hardware Devices and Software Techniques for AI-Based Onboard Space Applications**

- Authors/Org: L. Diana et al.

- Venue/type: Peer-reviewed review article (MDPI Remote Sensing)

- Date: **2024**

- Link: <https://www.mdpi.com/2072-4292/16/21/3957>

- What it reports / why it matters: Surveys hardware accelerators and software techniques suitable for onboard neural-network inference, including discussion of radiation tolerance

testing and mission use—evidence that a toolchain is emerging, but also that “space AI” remains constrained and heterogeneous in hardware maturity. [25]

#### 16) Planet Imagery Product Specifications (Combined Specs)

- Authors/Org: Planet Labs[26]

- Venue/type: Vendor technical documentation (specification guide; hosted by ESA Earth Online gateway)

- Date: **May 2022**

- Link:

[https://earth.esa.int/eogateway/documents/20142/37627/Planet\\_Combined\\_Imagery\\_Product\\_Specs\\_May\\_2022.pdf](https://earth.esa.int/eogateway/documents/20142/37627/Planet_Combined_Imagery_Product_Specs_May_2022.pdf)

- What it reports / why it matters: Provides concrete product specifications for smallsat EO imagery products (incl. product structure/attributes), supporting the maturity of optical smallsat constellations as **standardised, spec-driven services**. [27]

#### 17) Commercial Satellite Data Acquisition Program — Capella evaluation report

- Authors/Org: NASA[11] (CSDA) evaluating Capella Space[28] data

- Venue/type: Authoritative government technical evaluation report

- Date: **July 2025**

- Link: [https://earthdata.nasa.gov/s3fs-public/2025-](https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report_Final.pdf)

[07/CSDA%20Capella%20Evaluation%20PI%20Report\\_Final.pdf](https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report_Final.pdf)

- What it reports / why it matters: Independent assessment noting strengths such as very fine SAR spatial resolution (e.g., **0.5 m-class** referenced) and tasking/usability characteristics—evidence that commercial SAR constellations are delivering **operational, evaluated products**. [29]

#### 18) Accurate, near real-time Earth monitoring with SAR data (ICEYE SAR Data Brochure)

- Authors/Org: ICEYE[30]

- Venue/type: Vendor technical brochure with performance metrics

- Date: **2025**

- Link:

[https://www.iceye.com/hubfs/Downloadables/SAR\\_Data\\_Brochure\\_ICEYE.pdf](https://www.iceye.com/hubfs/Downloadables/SAR_Data_Brochure_ICEYE.pdf)

- What it reports / why it matters: Claims operational constellation capability including **daily/sub-daily revisits** and modes including **up to 25 cm** resolution in certain collections—directly supports the plausibility of “see structure through clouds” (SAR) at high cadence in a constellation model. [31]

#### 19) LEO-PNT Workshop — Xona Space Systems presentation

- Authors/Org: Xona Space Systems[32]

- Venue/type: Technical workshop slides (hosted by UN/UNOOSA event page; practical demo claims)

- Date: **June 2023**

- Link: [https://www.unoosa.org/documents/pdf/icg/2023/LEO-PNT-](https://www.unoosa.org/documents/pdf/icg/2023/LEO-PNT-workshop/S2_Xona.pdf)  
[workshop/S2\\_Xona.pdf](https://www.unoosa.org/documents/pdf/icg/2023/LEO-PNT-workshop/S2_Xona.pdf)

- What it reports / why it matters: Describes a dedicated LEO-PNT approach and reports early on-orbit transmission/demonstration milestones (including stated residual performance in slides), supporting **plausibility** while also highlighting that dedicated LEO-PNT is at an earlier commercial maturity stage than broadband. [33]

## 20) NAVISP — Navigation and Timing in the Future – Vision 2035 (NAVAC White Paper)

- Authors/Org: European Space Agency[21] (NAVISP/NAVAC)

- Venue/type: Authoritative roadmap / white paper

- Date: **May 2024**

- Link:

<https://navisp.esa.int/uploads/files/documents/NAVAC%20White%20Paper%20May%202024.pdf>

- What it reports / why it matters: Discusses LEO constellations primarily built for communications where PNT may be ancillary, plus “signals of opportunity” approaches (e.g., Doppler) and expected limitations—this is roadmap-grade evidence that PNT augmentation from LEO is plausible but **not yet equivalent to dedicated GNSS** and may start with opportunistic methods. [34]

### 3. Maturity score (1–7) and reasoning

**Final maturity score**

**Maturity score: 6**

**Evidence-to-rubric mapping**

- **Why the evidence rules out scores 1–5 (i.e., why this is beyond lab prototype/PoC):**
- Multiple independent measurement programmes analyse real, deployed LEO broadband as an operational service (e.g., multi-country Starlink measurement results), which implies **customer-delivered capability** rather than a prototype. [35]
- Major regulators have issued detailed authorisations and frameworks for NGSO broadband systems and satellite–terrestrial integration (Kuiper licensing modifications; “Supplemental Coverage from Space”), indicating the ecosystem is operating at **commercial deployment and scaling governance** levels. [36]
- High-rate optical space links are not merely conceptual: TBIRD reports **100–200 Gbps** LEO-to-ground demonstrations with terabyte-class downlinks, showing a key enabling thread (optical links to relieve RF downlink constraints) is experimentally validated at system-relevant rates. [12]
- EO constellations deliver specification-driven optical products and operational SAR capabilities, with third-party evaluation of commercial SAR data through NASA CSDA, demonstrating **routine productisation** in at least one core value stream of the ART (sensing). [37]
- **Why the evidence does not yet justify score 7 for the ART as a whole:**
- The ART description bundles **broadband + EO + PNT augmentation + onboard AI** into a single integrated capability package. Some components (broadband access; EO products) look “7-like” in isolation, but other elements are earlier:
  - **PNT augmentation from LEO** is acknowledged in roadmap literature as plausible but typically inferior to dedicated systems when opportunistic, and still emerging in dedicated form; current evidence supports early demonstrations and roadmap positioning, not clearly widespread competitive product delivery at mass scale. [38]

- **Onboard AI** has credible on-orbit demonstrations (Φsat-2) and NASA technical assessments, but the constraint evidence (power/thermal limits; COTS behaviour in orbit) suggests the field is still in active transition from demos to robust, standardised fleet-wide operations. [39]
- Governance and sustainability constraints remain a decisive scaling gate: the FCC's 5-year disposal requirement and IADC debris-environment reporting reflect a tightening operational regime. That is consistent with scaling, but also indicates the "hard requirements" side of the ART is still evolving and can materially affect roll-out pace and cost. [40]

#### **Sub-score breakdown and aggregation**

- **LEO broadband mega-constellation internet access** → 7
- Evidence: operational performance measurement studies and evidenced global deployment as an ISP-like system. [35]
- **Optical links / in-space routing and mesh networking (laser ISLs + standards)** → 5–6
- Evidence: TBIRD shows very high-rate optical downlink feasibility; SDA standardisation and DoD tranche deployment indicate movement toward scaled interoperable optical networking, while GAO still frames lasercom as an area with continuing risk/immaturity in large programmes. [41]
- **Earth observation constellations (optical + SAR as exemplar)** → 6–7
- Evidence: Planet specs (productised optical EO), ICEYE performance claims (high revisit SAR), and NASA CSDA evaluation of Capella data (independent assessment) together indicate mature service delivery with expanding institutional use. [42]
- **Onboard AI / "space-based AI" (edge inference, filtering, compression)** → 4–5
- Evidence: Φsat-2 is explicitly positioned as an in-orbit AI demonstration mission; NASA briefing and computing measurement study emphasise constraints and the still-evolving nature of reliable onboard AI stacks at scale. [39]
- **LEO PNT augmentation (signals of opportunity + dedicated LEO-PNT)** → 3–4
- Evidence: ESA roadmap frames LEO PNT largely as ancillary/opportunistic with limitations; Xona workshop materials describe early demo progress, but broad commercial scaling is not yet strongly evidenced in the same way as broadband/EO. [38]

**Aggregation method:** Average-based, because the ART's promised benefits are materially split across different application lines (broadband, EO, PNT augmentation, onboard AI) with different maturity levels. Averaging these sub-scores yields a result centred around ~6, hence **Maturity Score = 6**. [43]

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[1] [9] <https://eur-lex.europa.eu/eli/reg/2023/588/oj/eng>

<https://eur-lex.europa.eu/eli/reg/2023/588/oj/eng>



[2] [8] [12] [30] [41]

<https://ntrs.nasa.gov/api/citations/20230000434/downloads/Schieler%20paper%20spie2023-tbird-v4.pdf>

<https://ntrs.nasa.gov/api/citations/20230000434/downloads/Schieler%20paper%20spie2023-tbird-v4.pdf>

[3] [13] [35] [43] <https://mediatum.ub.tum.de/doc/1742995/document.pdf>

<https://mediatum.ub.tum.de/doc/1742995/document.pdf>

[4] <https://arxiv.org/pdf/2307.06863>

<https://arxiv.org/pdf/2307.06863>

[5] [22] [28] [39] [https://www.esa.int/Applications/Observing\\_the\\_Earth/Phsat-2](https://www.esa.int/Applications/Observing_the_Earth/Phsat-2)

[https://www.esa.int/Applications/Observing\\_the\\_Earth/Phsat-2](https://www.esa.int/Applications/Observing_the_Earth/Phsat-2)

[6] [18] [40] <https://docs.fcc.gov/public/attachments/DOC-387720A1.pdf>

<https://docs.fcc.gov/public/attachments/DOC-387720A1.pdf>

[7] [11] [36] <https://docs.fcc.gov/public/attachments/DA-24-224A1.pdf>

<https://docs.fcc.gov/public/attachments/DA-24-224A1.pdf>

[10] [21] <https://docs.fcc.gov/public/attachments/DOC-400678A1.pdf>

<https://docs.fcc.gov/public/attachments/DOC-400678A1.pdf>

[14] <https://www.sda.mil/wp-content/uploads/2024/08/SDA-OCT-Standard-v3.0.1-signed.pdf>

<https://www.sda.mil/wp-content/uploads/2024/08/SDA-OCT-Standard-v3.0.1-signed.pdf>

[15] <https://www.war.gov/News/Releases/Release/Article/3348974/space-development-agency-successfully-launches-tranche-0-satellites/>

<https://www.war.gov/News/Releases/Release/Article/3348974/space-development-agency-successfully-launches-tranche-0-satellites/>

[16] [27] [37] [42]

[https://earth.esa.int/eogateway/documents/20142/37627/Planet\\_Combined\\_Imagery\\_Product\\_Specs\\_May\\_2022.pdf](https://earth.esa.int/eogateway/documents/20142/37627/Planet_Combined_Imagery_Product_Specs_May_2022.pdf)

[https://earth.esa.int/eogateway/documents/20142/37627/Planet\\_Combined\\_Imagery\\_Product\\_Specs\\_May\\_2022.pdf](https://earth.esa.int/eogateway/documents/20142/37627/Planet_Combined_Imagery_Product_Specs_May_2022.pdf)

[17] <https://www.gao.gov/assets/gao-25-106838.pdf>

<https://www.gao.gov/assets/gao-25-106838.pdf>

[19] [25] <https://www.mdpi.com/2072-4292/16/21/3957>

<https://www.mdpi.com/2072-4292/16/21/3957>

[20]

[https://www.unoosa.org/res/oosadoc/data/documents/2025/aac\\_105c\\_12025crp/aac\\_105c\\_12025crp\\_10\\_0\\_html/AC105\\_C1\\_2025\\_CRP10E.pdf](https://www.unoosa.org/res/oosadoc/data/documents/2025/aac_105c_12025crp/aac_105c_12025crp_10_0_html/AC105_C1_2025_CRP10E.pdf)

[https://www.unoosa.org/res/oosadoc/data/documents/2025/aac\\_105c\\_12025crp/aac\\_105c\\_12025crp\\_10\\_0\\_html/AC105\\_C1\\_2025\\_CRP10E.pdf](https://www.unoosa.org/res/oosadoc/data/documents/2025/aac_105c_12025crp/aac_105c_12025crp_10_0_html/AC105_C1_2025_CRP10E.pdf)

[23]

<https://ntrs.nasa.gov/api/citations/20240001139/downloads/Current%20Technology%20in%20Space%20v4%20Briefing.pdf>

<https://ntrs.nasa.gov/api/citations/20240001139/downloads/Current%20Technology%20in%20Space%20v4%20Briefing.pdf>

[24] <https://arxiv.org/abs/2401.03435>

<https://arxiv.org/abs/2401.03435>

[26] [34] [38]

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<https://navisp.esa.int/uploads/files/documents/NAVAC%20White%20Paper%20May%202024.pdf>

[29] [32] [https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report\\_Final.pdf](https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report_Final.pdf)

[https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report\\_Final.pdf](https://earthdata.nasa.gov/s3fs-public/2025-07/CSDA%20Capella%20Evaluation%20PI%20Report_Final.pdf)

[31] [https://www.iceye.com/hubfs/Downloadables/SAR\\_Data\\_Brochure\\_ICEYE.pdf](https://www.iceye.com/hubfs/Downloadables/SAR_Data_Brochure_ICEYE.pdf)

[https://www.iceye.com/hubfs/Downloadables/SAR\\_Data\\_Brochure\\_ICEYE.pdf](https://www.iceye.com/hubfs/Downloadables/SAR_Data_Brochure_ICEYE.pdf)

[33] [https://www.unoosa.org/documents/pdf/icg/2023/ICG\\_WG-S\\_LEO-PNT\\_Workshop\\_June\\_2023/ICG\\_LEO-PNT\\_Workshop\\_2023\\_04.pdf](https://www.unoosa.org/documents/pdf/icg/2023/ICG_WG-S_LEO-PNT_Workshop_June_2023/ICG_LEO-PNT_Workshop_2023_04.pdf)

[https://www.unoosa.org/documents/pdf/icg/2023/ICG\\_WG-S\\_LEO-PNT\\_Workshop\\_June\\_2023/ICG\\_LEO-PNT\\_Workshop\\_2023\\_04.pdf](https://www.unoosa.org/documents/pdf/icg/2023/ICG_WG-S_LEO-PNT_Workshop_June_2023/ICG_LEO-PNT_Workshop_2023_04.pdf)

## ART 10.080 Space Resource Utilization (SRU)

### ART extraction

#### Primary capability the ART claims

- End-to-end **space resource utilization aimed at returning high-value material from asteroids to Earth**, emphasizing high-grade concentrates (kilograms to tons) rather than bulk rock (thousands of tons). [1]
- A **pipeline architecture**: (i) remote reconnaissance/prospecting, (ii) rendezvous + anchoring + low-force collection/extraction in microgravity, (iii) on-site “mass-reduction” processing to concentrate value, (iv) **Earth return in hardened capsules** plus tracking and controlled recovery/assay chain-of-custody. [2]

## Key sub-components and variants

- **Target identification & prospecting:** spectral/radar methods, elemental inference, and/or in situ instruments capable of discriminating metal-rich vs silicate-rich bodies (plus estimation of spin/shape/roughness for operations). [3]
- **Proximity ops, station-keeping, and autonomy** under deep-space communication delay, including onboard planning/scheduling and navigation updates. [4]
- **Anchoring and excavation/collection in microgravity** (e.g., drills/anchors, force-closure schemes, rubble/regolith handling). [5]
- **On-site beneficiation / concentration** (mechanical sorting, magnetic/electrostatic separation, thermal treatment, chemical leaching in closed loops). [6]
- **Earth-return capsule + EDL prediction/verification**, including trajectory targeting/orbit determination, high-fidelity entry simulations, and robustness to off-nominal events. [7]
- **Contamination control and chain-of-custody** (portable cleanrooms, monitoring, nitrogen purge transfer, curated handling and assay readiness). [8]
- **Governance & ownership claims** (international work toward principles for space resource activities, informing regulatory expectations and dispute risk). [9]

## Maturity indicators that would constitute strong evidence

- A **flight demonstration** of asteroid rendezvous + controlled interaction with surface material at meaningful mass throughput (beyond gram-scale scientific sampling). [10]
- A **closed-loop in-space processing demo** that measurably concentrates a target metal fraction (e.g., enrichment factor, yield, energy per kg processed) in relevant conditions (vacuum, low gravity, limited power). [11]
- A demonstrated **Earth-return logistics and safety case** for a cargo product (tracking, landing corridor control, recovery procedures, contamination/handling controls), plus repeatability. [12]
- **Multiple actors** converging on interoperable/standardized approaches (interfaces, capsules, processing modules), and early industrial scaling signals (repeat missions, higher cadence). [13]

## 2. Evidence (10–20 recent, reliable sources)

### 1) **Spacecraft sample collection and subsurface excavation of asteroid (101955) Bennu**

- Authors/Org: Multi-institution OSIRIS-REx science/engineering team (journal article listing via PubMed)
- Venue/type: Peer-reviewed paper (Science)
- Publication date: **July 2022** (Epub July 7; issue July 15)
- Link: <https://pubmed.ncbi.nlm.nih.gov/35857591/>
- Why it matters: Reports real spacecraft–asteroid surface interaction where the sampling event excavated a ~9 m-scale crater and captured **250 ± 101 g** of material—strong evidence that low-force collection in microgravity/rubble-like regolith is feasible (but still far from “mining” throughput). [10]

### 2) **Curation planning and facilities for asteroid Bennu samples returned by OSIRIS-REx**

- Authors/Org: NASA[14] (Johnson Space Center curation team and partners)
- Venue/type: NASA technical paper / curation implementation report (publicly released via

NTRS; NASA technical review noted)

- Publication date: **March 2023** (NTRS-hosted revision)

- Link: <https://ntrs.nasa.gov/api/citations/20230005897/downloads/Curation-OREX-paper-rev1-4-noTC.pdf>

- Why it matters: Describes concrete contamination-control and handling infrastructure sized for asteroid return (mentions design intent for up to kilogram-class returns) and operational planning from field recovery into curated cleanrooms—directly relevant to the ART’s chain-of-custody and assay-readiness claims. [15]

### 3) **OSIRIS-REx Earth Return & Entry: Navigation Operations & Lessons Learned**

- Authors/Org: NASA Goddard Space Flight Center[16] / KinetX team (conference paper via NTRS)

- Venue/type: Conference paper (AAS GN&C; NASA NTRS)

- Publication date: **February 2024** (conference dates in NTRS record)

- Link:

[https://ntrs.nasa.gov/api/citations/20240000800/downloads/O\\_REx\\_Earth\\_Return\\_Entry\\_Na v\\_Ops\\_LL\\_v4.pdf](https://ntrs.nasa.gov/api/citations/20240000800/downloads/O_REx_Earth_Return_Entry_Na v_Ops_LL_v4.pdf)

- Why it matters: Provides detailed Earth-return targeting/operations (trajectory correction strategy, SRC release criteria, interfaces with recovery teams), supporting feasibility of a tracked reentry corridor and recovery concept—core to any Earth-return SRU logistics pipeline. [17]

### 4) **OSIRIS-REx Earth Return Orbit Determination Analysis and Performance**

- Authors/Org: KinetX + NASA Goddard Space Flight Center[16] (conference paper via NTRS)

- Venue/type: Conference paper (AAS GN&C; NASA NTRS)

- Publication date: **February 2024** (meeting dates in NTRS record)

- Link:

[https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx\\_Earth\\_Return\\_OD\\_Analysis\\_and\\_Performance.pdf](https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx_Earth_Return_OD_Analysis_and_Performance.pdf)

- Why it matters: Shows the navigation/orbit-determination rigor used to deliver a capsule to an entry interface corridor (including quantified EFPA corridor and tracking assumptions), strengthening the “predictable landing corridors + telemetry tracking” aspect of the ART. [18]

### 5) **Entry, Descent, and Landing Analysis for the OSIRIS-REx Sample Return Capsule**

- Authors/Org: Lockheed Martin + NASA Langley Research Center[19] (conference paper via NTRS)

- Venue/type: Conference paper (AAS GN&C; NASA NTRS)

- Publication date: **February 2024** (meeting dates in NTRS record)

- Link:

[https://ntrs.nasa.gov/api/citations/20240000629/downloads/OREX\\_EDL\\_paper\\_011124\\_afternoon.pdf](https://ntrs.nasa.gov/api/citations/20240000629/downloads/OREX_EDL_paper_011124_afternoon.pdf)

- Why it matters: Documents use of high-fidelity EDL simulation (POST-architecture) to bound landing predictions and compare to observed outcomes—evidence that Earth-return EDL risk can be engineered and audited, a key maturity prerequisite for any commercial return stream. [20]

### 6) **Portable Cleanroom for NASA OSIRIS-REx Mission Deintegration**

- Authors/Org: NASA Johnson Space Center[21] curation/infrastructure team (presentation via NTRS)

- Venue/type: Technical presentation (contamination control / cleanroom engineering; NASA NTRS)
- Publication date: **May 2024** (meeting dates in NTRS record)
- Link: <https://ntrs.nasa.gov/api/citations/20240004308/downloads/ES24-McQuillan.pdf>
- Why it matters: Describes a field-deployable cleanroom workflow (ISO-class target, nitrogen purge transfer) used to move a returned capsule into controlled handling rapidly—directly analogous to “tamper-evident tracked capsule → rapid chain-of-custody.” [22]

#### 7) **2023 Cleanroom Monitoring for OSIRIS-REx**

- Authors/Org: NASA Johnson Space Center[21] curation/monitoring team (NTRS record)
- Venue/type: Technical poster/presentation (microbial monitoring; NASA NTRS)
- Publication date: **2024** (NTRS record; monitoring conducted July–Sept 2023)
- Link: <https://ntrs.nasa.gov/citations/20240000196>
- Why it matters: Reports measurable microbial monitoring results in a temporary field cleanroom vs lab environments, illustrating the operational reality (and solvable constraints) of contamination control during recovery operations—relevant to SRU product provenance and handling credibility. [23]

#### 8) **Geophysical Observations of the 24 September 2023 OSIRIS-REx Sample Return Capsule Re-Entry**

- Authors/Org: Multi-institution observational team (arXiv)
- Venue/type: Preprint (arXiv; clearly labeled)
- Publication date: **July 2024**
- Link: <https://arxiv.org/abs/2407.02420>
- Why it matters: Uses a well-characterized capsule entry with known timing/trajectory as an instrumented event, supporting the ART’s emphasis on tracked reentry and independently verifiable flight/landing reconstruction for custody assurance. [24]

#### 9) **Simulations of Hayabusa2 Atmospheric Entry and Comparisons with Data from the Imaging Campaign**

- Authors/Org: NASA Ames Research Center[25] and partners (NTRS-hosted AIAA paper)
- Venue/type: Conference paper (AIAA; aerothermodynamics modeling vs observations; NASA NTRS)
- Publication date: **2022** (AIAA Aviation 2022 paper as hosted on NTRS)
- Link: [https://ntrs.nasa.gov/api/citations/20220006454/downloads/AIAA-Aviation2022\\_v5.pdf](https://ntrs.nasa.gov/api/citations/20220006454/downloads/AIAA-Aviation2022_v5.pdf)
- Why it matters: Presents detailed flow/radiation simulations and comparison to measured irradiance for a deep-space return capsule, showing that entry environments can be modeled and compared to flight data—key to licensing, safety, and capsule design margins for any return-to-Earth SRU product. [26]

#### 10) **Post-Flight Analysis of Recovered Components of Hayabusa2 Sample Return Capsule**

- Authors/Org: JAXA[27] / ISAS team (open-access via J-STAGE)
- Venue/type: Peer-reviewed/open-access proceedings paper (Journal of Evolving Space Activities; provides PDF)
- Publication date: **June 2023** (available on J-STAGE June 7, 2023)
- Link: [https://www.jstage.jst.go.jp/article/jesa/1/0/1\\_16/\\_article/-char/ja/](https://www.jstage.jst.go.jp/article/jesa/1/0/1_16/_article/-char/ja/)
- Why it matters: Summarizes reentry at ~12 km/s and post-flight inspection methods

(trajectory reconstruction, flight-data analysis, nonintrusive inspection like X-ray CT), evidencing mature engineering feedback loops for capsule design validation—relevant for scaling return-capsule reliability. [28]

#### 11) **First asteroid gas sample delivered by the Hayabusa2 mission: A treasure box from Ryugu**

- Authors/Org: Multi-institution team led by Japanese curation/science groups (PubMed/PMC entry for Sci Adv)
- Venue/type: Peer-reviewed paper (Science Advances; open access on PMC)
- Publication date: **November 2022** (Epub Nov 16; issue Nov 18)
- Link: <https://pubmed.ncbi.nlm.nih.gov/36264781/>
- Why it matters: Describes a **metal-sealed sample container** and rapid post-recovery gas extraction/measurement, demonstrating that sealed containment and post-landing volatile/contamination-sensitive handling are feasible—directly relevant to “sealed, tracked capsule + verifiable contents.” [29]

#### 12) **Arecibo Planetary Radar Observations of Near-Earth Asteroids: 2017 December–2019 December**

- Authors/Org: University of Helsinki[30] / Arecibo radar collaboration (paper text hosted on ResearchGate; original journal: Planetary Science Journal)
- Venue/type: Peer-reviewed paper (The Planetary Science Journal; CC BY noted on the hosted version)
- Publication date: **September 2022** (published Sept 22, 2022 per hosted full text)
- Link: [https://www.researchgate.net/publication/363775247\\_Arecibo\\_Planetary\\_Radar\\_Observations\\_of\\_Near-Earth\\_Asteroids\\_2017\\_December-2019\\_December](https://www.researchgate.net/publication/363775247_Arecibo_Planetary_Radar_Observations_of_Near-Earth_Asteroids_2017_December-2019_December)
- Why it matters: Reports radar characterization at scale (191 NEAs; including radar cross sections, circular polarization ratios, and delay-Doppler imaging down to ~75 m range resolution for selected targets), which supports the plausibility of pre-mission target screening for composition/structure relevant to SRU feasibility and risk. [31]

#### 13) **The Psyche Gamma-Ray and Neutron Spectrometer**

- Authors/Org: NASA Jet Propulsion Laboratory[32] mission instrument team and partners (Springer open access)
- Venue/type: Peer-reviewed paper (Space Science Reviews)
- Publication date: **September 2025**
- Link: <https://link.springer.com/article/10.1007/s11214-025-01201-6>
- Why it matters: Provides concrete instrument design/performance context for **elemental composition measurement** (including Fe/Ni measurement drivers, HPGe sensor approach, expected accumulation times and detection limits as a design basis), relevant to the ART’s prospecting step for metal-rich targets and grade inference. [33]

#### 14) **Study the influence of anchoring parameters on asteroid drilling anchoring with discrete element simulation**

- Authors/Org: University-based robotics/mechanics team (journal listing via ScienceDirect)
- Venue/type: Peer-reviewed paper (Advances in Space Research; simulation + experiment validation described in abstract)
- Publication date: **2022** (DOI indicates 2022; online publication timing implied by journal listing)



- Link: <https://www.sciencedirect.com/science/article/abs/pii/S0273117722009887>

- Why it matters: Addresses a central physical blocker—**how to generate reliable anchoring forces in granular “asteroid soil”**—and reports parameterized effects (configuration, material strength, force direction; with an example optimal anchoring angle under assumed conditions), supporting plausibility of engineered anchoring rather than “Earth-like mining.” [\[34\]](#)

#### 15) **Precious and structural metals on asteroids: Composition, geology, and an approach to practical mining**

- Authors/Org: Planetary science / resource utilization researchers (journal page via ScienceDirect)

- Venue/type: Peer-reviewed paper (Planetary and Space Science)

- Publication date: **January 2023**

- Link: <https://www.sciencedirect.com/science/article/pii/S0032063322001615>

- Why it matters: Provides a technically grounded discussion of asteroid metal occurrence and mining approaches (including what constitutes “ore” in an asteroid context and constraints on extractability), directly informing plausibility of the ART’s “concentrate-first” logic and the difficulty of reliably high-grade targets. [\[35\]](#)

#### 16) **A novel method for extracting metals from asteroids using non-aqueous deep eutectic solvents**

- Authors/Org: University of Leicester[\[36\]](#) + collaborators (paper on nature.com)

- Venue/type: Peer-reviewed experimental paper (Scientific Reports)

- Publication date: **October 2023** (published Oct 8, 2023)

- Link: <https://www.nature.com/articles/s41598-023-44152-0>

- Why it matters: Demonstrates catalytic dissolution of metals from meteorite proxies using a deep eutectic solvent (DES), providing experimental evidence that “closed-loop chemical leaching” is chemically plausible for metal-rich feedstocks under conditions compatible with low vapor pressure solvents—relevant to in-space beneficiation concepts. [\[37\]](#)

#### 17) **Magnetic Separation of Lunar Regolith as its Beneficiation for Construction Effort on the Moon**

- Authors/Org: Polish university + space research institute collaboration (paper PDF)

- Venue/type: Peer-reviewed/open-access paper (Artificial Satellites)

- Publication date: **2023**

- Link: <https://sciendo.com/2/v2/download/article/10.2478/arsa-2023-0023.pdf>

- Why it matters: Reports lab beneficiation experiments across **10 regolith simulants** with measured ferromagnetic fraction outcomes, giving practical evidence that low-complexity physical separation can concentrate useful fractions—conceptually transferable to asteroid regolith “mass reduction” steps (though not yet tested in relevant microgravity operations). [\[38\]](#)

#### 18) **Mineral Processing... In Space**

- Authors/Org: NASA Glenn Research Center[\[39\]](#) + academic partner (NTRS-hosted IMPC paper)

- Venue/type: Authoritative technical report / conference paper (IMPC; NASA NTRS)

- Publication date: **September 2024** (conference schedule in NTRS record)

- Link: [https://ntrs.nasa.gov/api/citations/20240001733/downloads/Gertsch-Pierce\\_IMPC2024\\_STRIVES.pdf](https://ntrs.nasa.gov/api/citations/20240001733/downloads/Gertsch-Pierce_IMPC2024_STRIVES.pdf)

- Why it matters: Summarizes constraints unique to mineral processing off-Earth (gravity effects, autonomy needs under communication delay, subsystem integration) and enumerates credible candidate processing methods; it supports plausibility while implicitly underscoring that integrated, production-like SRU processing remains a major R&D challenge. [40]

#### 19) **Autonomous Small Body Science Operations Using Reinforcement Learning**

- Authors/Org: University of Colorado Boulder[41] (journal paper PDF hosted by author)  
 - Venue/type: Peer-reviewed paper (Journal of Aerospace Information Systems)  
 - Publication date: **October 2024** (publication date in institutional record)  
 - Link: <https://hanspeterschaub.info/PapersPrivate/Herrmann2024a.pdf>  
 - Why it matters: Demonstrates RL-based decision-making for small-body operations under resource constraints (power, storage, downlink, navigation updates) in simulation, directly supporting the ART’s assumption that autonomy can absorb minutes-to-hours delays—while still not equivalent to a flight-proven mining autonomy stack. [42]

#### 20) **Working Group on Space Resources (UN COPUOS Legal Subcommittee)**

- Authors/Org: United Nations Office for Outer Space Affairs[43]  
 - Venue/type: Authoritative international governance documentation hub (official UN office webpage collecting draft principles and state submissions)  
 - Publication date: **Updated through 2025–2026** (page lists dated drafts/updates)  
 - Link: <https://www.unoosa.org/oosa/en/ourwork/copuos/lsc/space-resources/index.html>  
 - Why it matters: Shows active multilateral work toward “recommended principles for space resource activities,” which is relevant to the ART’s acknowledged ownership/claims uncertainty and suggests that governance is still evolving—a maturity drag for commercial Earth-return SRU even if engineering progresses. [9]

### 3. Maturity score (1–7) and reasoning

#### Final maturity score

**Maturity score: 3**

#### Why this score fits the rubric

Evidence rules out **levels 1–2** because several core enabling elements of Earth-return SRU have progressed beyond theory and lab-only demonstrations:

- **Asteroid material acquisition in microgravity** has been demonstrated in an actual deep-space mission context (including excavating and collecting hundreds of grams), not merely as a ground prototype. [10]
- **Earth return via reentry capsule** has been executed with modern, instrumented mission operations and validated against high-fidelity navigation/EDL analysis workflows, with mature contamination-control handling and recovery infrastructure. [44]

However, the evidence does **not** justify **level 4 (PoC meeting commercialization requirements)** for the ART as stated (“returning high-value space-mined materials to Earth” via a prospect→extract→process→return pipeline), because key missing demonstrations remain:

- There is **no recent evidence (within the window) of an end-to-end flight PoC** that performs **on-asteroid beneficiation/refining** into “dense ingots/pellets” (or comparable product) followed by Earth return and third-party assay at commercially meaningful mass flows. The strongest processing evidence is still at **lab/materials-proxy level** (e.g., solvent extraction on meteorite proxies) and systems-level discussion/roadmapping rather than in-space, integrated throughput demonstrations. [\[45\]](#)
- **Target certainty / grade assurance** remains a gating uncertainty: radar and spectroscopy can characterize many objects and future instruments target elemental inference (e.g., Ni/Fe measurement drivers for a metal-rich asteroid mission), but reliably selecting “high-concentration” ore-grade targets for economic Earth-return SRU is not yet demonstrated as an operationally bankable pipeline. [\[46\]](#)
- The governance environment is still being actively shaped through international processes, which increases commercialization risk and can delay scaling even if the engineering works. [\[9\]](#)

These gaps align best with **level 3**: a collection of laboratory prototypes and flight-demonstrated subfunctions exists (sampling, capsule return, recovery/curation), but the ART’s distinctive value proposition—**industrial-like extraction + mass-reduction processing + Earth return of high-value concentrates**—is not yet shown in an integrated, production-credible prototype. [\[47\]](#)

#### Sub-component maturity estimates and aggregation

Because the ART is a bundle with uneven component maturity, the overall score is set using a **bottleneck-weighted average** (heavier weight on the least-mature, mission-critical steps: beneficiation/processing + reliable target selection), rather than the maximum sub-score. [\[48\]](#)

- **Earth return capsule + navigation/EDL + recovery/curation chain** → ~4–5  
Supporting evidence: modern navigation/OD/EDL analysis papers and operational cleanroom/curation infrastructure show repeated, engineering-grade capability for returning sensitive payloads and handling them in contamination-controlled workflows. [\[49\]](#)
- **Microgravity interaction: sampling/collection + anchoring concepts** → ~4 (collection demonstrated) / ~3 (anchoring for sustained mining)  
Supporting evidence: Bennu sampling is flight-demonstrated at hundreds of grams, but anchoring remains largely in simulation/experiment-driven optimization rather than flight-proven “mining-grade” anchoring for continuous operations. [\[5\]](#)
- **Prospecting & characterization for metal-rich targets** → ~3–4  
Supporting evidence: radar surveys provide broad physical characterization capability for many NEAs; future elemental instruments (e.g., Psyche GRNS) are intended to quantify elemental abundances relevant to metal fraction inference, supporting plausibility but not yet proving “ore-grade certainty” at operational decision thresholds. [\[3\]](#)
- **On-site beneficiation / mass-reduction processing (mechanical, thermal, chemical)** → ~2–3  
Supporting evidence: experimental chemistry exists for extracting metals from asteroid-analog materials in lab conditions; physical separation methods exist for regolith simulants; but

integrated, power/thermal/autonomy-constrained processing in relevant space conditions is not yet demonstrated as a flight PoC. [50]

- **Autonomy for delayed operations & exception handling** → ~3

Supporting evidence: RL planning/scheduling work shows feasibility in simulation for resource-constrained small-body operations, but it is not yet equivalent to flight-proven autonomous mining supervision/execution at industrial reliability. [4]

**Aggregation to one score:** The highest-maturity pieces (capsule return + recovery chain) could suggest 4–5 in isolation, but the **mission-critical differentiators** for SRU Earth-return economics—(i) reliable high-grade target selection, and especially (ii) in-space beneficiation/refining into a concentrate product—remain at ~2–3. Weighting those bottlenecks most heavily yields an overall **3**. [51]

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[1] [6] [35] [41] [43] [48] [51] <https://pmc.ncbi.nlm.nih.gov/articles/PMC10560668/>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC10560668/>

[2] [5] [10] [32] [47] <https://pubmed.ncbi.nlm.nih.gov/35857591/>

<https://pubmed.ncbi.nlm.nih.gov/35857591/>

[3] [31] [46]

[https://www.researchgate.net/publication/363775247\\_Arecibo\\_Planetary\\_Radar\\_Observations\\_of\\_Near-Earth\\_Asteroids\\_2017\\_December-2019\\_December](https://www.researchgate.net/publication/363775247_Arecibo_Planetary_Radar_Observations_of_Near-Earth_Asteroids_2017_December-2019_December)

[https://www.researchgate.net/publication/363775247\\_Arecibo\\_Planetary\\_Radar\\_Observations\\_of\\_Near-Earth\\_Asteroids\\_2017\\_December-2019\\_December](https://www.researchgate.net/publication/363775247_Arecibo_Planetary_Radar_Observations_of_Near-Earth_Asteroids_2017_December-2019_December)

[4] [30] [42] <https://hanspeterschaub.info/PapersPrivate/Herrmann2024a.pdf>

<https://hanspeterschaub.info/PapersPrivate/Herrmann2024a.pdf>

[7] [12] [14] [17] [44] [49] AAS 24-151 OSIRIS-REX EARTH RETURN & ENTRY

[https://ntrs.nasa.gov/api/citations/20240000800/downloads/O\\_REx\\_Earth\\_Return\\_Entry\\_Nav\\_Ops\\_LL\\_v4.pdf?utm\\_source=chatgpt.com](https://ntrs.nasa.gov/api/citations/20240000800/downloads/O_REx_Earth_Return_Entry_Nav_Ops_LL_v4.pdf?utm_source=chatgpt.com)

[8] [15] [36] <https://ntrs.nasa.gov/api/citations/20230005897/downloads/Curation-OREX-paper-rev1-4-noTC.pdf>

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[9] [13] [21] Working Group on Space Resources

<https://www.unoosa.org/oosa/en/ourwork/copuos/lsc/space-resources/index.html>

[11] [16] [37] [45] [50] <https://www.nature.com/articles/s41598-023-44152-0>

<https://www.nature.com/articles/s41598-023-44152-0>

[18]

[https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx\\_Earth\\_Return\\_OD\\_Analysis\\_and\\_Performance.pdf](https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx_Earth_Return_OD_Analysis_and_Performance.pdf)

[https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx\\_Earth\\_Return\\_OD\\_Analysis\\_and\\_Performance.pdf](https://ntrs.nasa.gov/api/citations/20240000806/downloads/OREx_Earth_Return_OD_Analysis_and_Performance.pdf)

[19] [23] <https://ntrs.nasa.gov/citations/20240000196>

<https://ntrs.nasa.gov/citations/20240000196>

[20] <https://ntrs.nasa.gov/citations/20240000629>

<https://ntrs.nasa.gov/citations/20240000629>

[22] <https://ntrs.nasa.gov/citations/20240004308>

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[24] <https://arxiv.org/abs/2407.02420>

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[26] [39] [https://ntrs.nasa.gov/api/citations/20220006454/downloads/AIAA-Aviation2022\\_v5.pdf](https://ntrs.nasa.gov/api/citations/20220006454/downloads/AIAA-Aviation2022_v5.pdf)

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[27] [33] The Psyche Gamma-Ray and Neutron Spectrometer | Space Science Reviews | Springer Nature Link

<https://link.springer.com/article/10.1007/s11214-025-01201-6>

[29] <https://pubmed.ncbi.nlm.nih.gov/36264781/>

<https://pubmed.ncbi.nlm.nih.gov/36264781/>

[34] <https://www.sciencedirect.com/science/article/abs/pii/S0273117722009887>

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[38] <https://sciendo.com/2/v2/download/article/10.2478/arsa-2023-0023.pdf>

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[40] <https://ntrs.nasa.gov/citations/20240001733>

<https://ntrs.nasa.gov/citations/20240001733>

## ART 10.081 Closed-Loop Life Support System

### ART extraction

### Primary capability the ART claims

- Provide a **high-reliability, long-duration “utility plant”** for off-Earth habitats that **continuously maintains breathable air and potable water** while handling wastes with minimal resupply.
- Achieve **high closure of key resource loops** (especially water; progressively also oxygen/CO<sub>2</sub>) by combining **bioregenerative modules** (plants/algae/microbes) with **physico-chemical processing** (reactors, sorbents, filters).
- Enable **safe, low-crew-time operations** via pervasive sensing (air, water, microbial load) and **adaptive control / anomaly detection** with remote diagnostics.

### Key sub-components or variants

- **Water loop closure**
- Urine processing + brine processing; humidity condensate capture; potable water polishing; biofilm/contamination management.
- Partial-gravity variants (lunar/Mars) that exploit gravity to reduce complexity.
- **Air revitalisation + oxygen generation**
- CO<sub>2</sub> removal (molecular sieves, amine scrubbing, etc.), humidity control, trace contaminant control (activated carbon + catalytic oxidation).
- O<sub>2</sub> generation (electrolysis) and integration with CO<sub>2</sub> reduction.
- **CO<sub>2</sub> reduction / “air loop closure” extensions**
- Sabatier-based architectures ( $\text{CO}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{CH}_4$ ) plus add-ons to recover H<sub>2</sub> from CH<sub>4</sub> (e.g., methane pyrolysis / carbon vapour deposition) for higher O<sub>2</sub> recovery.
- Alternative CO<sub>2</sub> capture concepts (e.g., ionic liquid + membrane contactors) for continuous operation and easier integration.
- **Bioregenerative modules**
- Photobioreactors (cyanobacteria/microalgae) for CO<sub>2</sub> removal + O<sub>2</sub> production + biomass; higher-plant growth chambers; microbial nutrient loops (e.g., urine nitrification).
- **Environmental monitoring + control software**
- Trace-gas measurement, water quality sensing, microbial/biofouling surveillance; digital twins and automated fault detection/isolation/recovery (FDIR).

### Maturity indicators that would constitute good evidence

- **On-orbit operation** (months/years) of regenerative subsystems with measured closure (e.g., % water recovered), maintainability, and fault history.
- **Integrated end-to-end loop tests** (air + water + waste handling), at least at pilot scale, showing stable control and acceptable safety margins.
- **Performance metrics under relevant environments** (microgravity, partial gravity analogue, vibration/launch loads) including biofouling resistance, contamination control, and reliability/MTBF.
- **Commercialisation signals**: multiple well-capitalised actors building and testing production-like hardware; standardised interfaces; vendor procurement and acceptance testing; ground qualification campaigns for commercial stations.

### Evidence (10–20 recent, reliable sources)



## Operational physico-chemical subsystems (flight heritage, measurable closure)

### 1) Environmental Control and Life Support System (ECLSS) (fact sheet PDF)

- **Organisation:** NASA[1]
- **Venue/type:** Agency technical fact sheet (PDF)
- **Publication date:** Aug 2025
- **Link:** <https://www.nasa.gov/wp-content/uploads/2025/08/g-657270-59-hp-environmental-control-and-life-support-system-eclss.pdf>
- **Why it matters:** Describes the regenerative ECLSS architecture on the International Space Station[2] and states the water recovery system is capable of recovering and recycling **~98% of water on station**, demonstrating high-maturity physico-chemical closure for a continuously crewed platform. [3]

### 2) Status of ISS Water Management and Recovery (ICES-2023-097)

- **Organisation:** NASA (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2023
- **Link:** <https://ntrs.nasa.gov/api/citations/20230006217/downloads/ICES%202023-097%20Status%20of%20ISS%20Water%20Management%20and%20Recovery.pdf>
- **Why it matters:** Reports that the on-orbit Brine Processor Assembly achieves **~98% water recovery** (using membrane distillation + forced convection) and provides concrete operational evidence (e.g., **14 dewatering cycles since Feb 2022, ~305 L brine processed, ~260 L water returned**), which is directly relevant to proving feasibility and durability of closed-loop water recovery. It also documents real ops constraints (odour mitigation, ORU lifetimes) that matter for maturity assessment. [4]

### 3) Status of ISS Water Management and Recovery (ICES-2024-317)

- **Organisation:** NASA (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2024
- **Link:** [https://ntrs.nasa.gov/api/citations/20240005472/downloads/ICES%202024-317%20Status%20of%20ISS%20Water\\_Final.pdf](https://ntrs.nasa.gov/api/citations/20240005472/downloads/ICES%202024-317%20Status%20of%20ISS%20Water_Final.pdf)
- **Why it matters:** Updates the ISS water-recovery status and explicitly notes the brine-processing demonstration enabling **>95% water recovered**, while also documenting an important *non-closure* constraint: the Sabatier reactor “has not been in service since Oct 2017” and replacement hardware is intended, illustrating how “closed-loop” is still bounded by reliability and spares/top-ups. [5]

### 4) Development and Testing of a New Partial Gravity Urine Processor Design and Urine Pretreatment (ICES-2023-100)

- **Organisation:** NASA (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2023
- **Link:** <https://ntrs.nasa.gov/api/citations/20230006219/downloads/ICES%202023-100%20Planetary%20Urine%20Processor%20%28PUP%29%20Development.pdf>
- **Why it matters:** Proposes a planetary (lunar/Mars) urine processor that exploits **local**

**gravity** to reduce complexity and targets **>96% water reclamation**, addressing a core feasibility bound in the ART (reliability/maintainability in partial gravity) and providing prototype-development evidence beyond ISS-optimised microgravity designs. [6]

#### 5) NASA Environmental Control and Life Support Technology Development for Exploration: 2022–2023 Status (ICES-2023-312)

- **Organisation:** NASA (conference paper via NTRS)
- **Venue/type:** Technical roadmap/status paper (ICES), PDF via NTRS
- **Publication date:** Jul 2023
- **Link:** <https://ntrs.nasa.gov/api/citations/20230008504/downloads/ICES-2023-312%20Final.pdf>
- **Why it matters:** Summarises the active maturation pipeline (air, water, waste, monitoring) and documents that the ISS Sabatier CO<sub>2</sub> reduction assembly accumulated **~2 years runtime** before failure due to contamination, plus an ongoing “Sabatier 2.0” upgrade programme—important evidence that the science is feasible but engineering maturity hinges on contamination tolerance and maintainability. [7]

#### 6) NextSTEP Appendix A Modular ECLSS Effort Lessons Learned (ICES-2023-321)

- **Organisation:** NASA + industry partners (conference paper via NTRS)
- **Venue/type:** Programme lessons-learned / technical report (ICES), PDF via NTRS
- **Publication date:** Jul 2023
- **Link:** [https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321\\_Final\\_230525.pdf](https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321_Final_230525.pdf)
- **Why it matters:** Captures system-integration maturity work (integrated control architecture, ECLSS standards & habitat interface, intelligent systems, and a functional air revitalisation prototype including a “full capacity thermal amine scrubber”), showing movement from component R&D toward integrated, modular designs relevant to future habitats. [8]

#### 7) Development and Performance Test Results of the Starlab Alternative Urine Processor Ground Test Unit (ICES 2025)

- **Organisation:** Starlab LLC[9] + Paragon Space Development Corporation[10] (conference paper entry on ResearchGate)
- **Venue/type:** Technical conference paper (ICES); public abstract on ResearchGate (full text not shown)
- **Publication date:** Jul 2025
- **Link:** [https://www.researchgate.net/publication/398343667\\_Development\\_and\\_Performance\\_Test\\_Results\\_of\\_the\\_Starlab\\_Alternative\\_Urine\\_Processor\\_Ground\\_Test\\_Unit](https://www.researchgate.net/publication/398343667_Development_and_Performance_Test_Results_of_the_Starlab_Alternative_Urine_Processor_Ground_Test_Unit)
- **Why it matters:** Reports a full-scale ground test unit designed/built/tested to process urine for **4 crew** (1.8 L/person/day input) and to recover **>95% of available water**, aiming to match the combined recovery of ISS urine+brine processing with lower mass/volume—direct commercial-station evidence that closed-loop water processing is moving toward production-relevant form factors. [11]

**Toward fuller air-loop closure and safer atmospheres (CO<sub>2</sub> utilisation, contaminants)**

#### 8) Integrated Simulations of the Sabatier and Carbon Vapor Deposition Reactor to Understand Its Impacts to Operations and Performance (ICES-2024-156)

- **Organisation:** NASA + Honeywell Aerospace[12] context (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2024
- **Link:** <https://ntrs.nasa.gov/api/citations/20240004053/downloads/ICES-2024-156-Final.pdf>
- **Why it matters:** Quantifies a fundamental closure limit—Sabatier venting CH<sub>4</sub> limits maximum O<sub>2</sub> recovery to ~50%—and analyses methane pyrolysis (CVD) as a path to **near-100% O<sub>2</sub> recovery** by recovering H<sub>2</sub> from CH<sub>4</sub>. This is strong plausibility evidence for tighter closed loops while also highlighting operational/thermal challenges (e.g., >1000 °C pyrolysis) relevant to practical maturity. [13]

#### 9) Carbon Dioxide Removal by Ionic Liquid System for Mobility (CDRILS-M) for Mars Exploration Extravehicular Mobility Unit (mxEMU) (ICES-2025-150 record)

- **Organisation:** Honeywell + NASA (NTRS record)
- **Venue/type:** Technical conference paper (ICES) record on NTRS; downloadable docx listed
- **Publication date:** Feb 2025 (record acquired); conference Jul 2025
- **Link:** <https://ntrs.nasa.gov/citations/20250001226>
- **Why it matters:** Describes a continuously recirculated **ionic-liquid sorbent + hollow-fibre membrane contactors** approach and states the technology is working toward an ISS **flight demonstration in 2028**, showing credible engineering momentum (but not yet flight maturity) for lower-complexity CO<sub>2</sub>/humidity control and integration into closed-loop architectures. [14]

#### 10) A membrane Sabatier system for water recovery and rocket propellant production

- **Organisation:** Academic research team (peer-reviewed)
- **Venue/type:** Peer-reviewed paper (Nature Communications, open PDF)
- **Publication date:** 2025 (month not indicated in the PDF excerpt above)
- **Link:** <https://www.nature.com/articles/s41467-025-63667-w.pdf>
- **Why it matters:** Demonstrates an integrated catalytic reactor + **water-vapour permselective membrane** approach that improves CO<sub>2</sub> conversion and long-term stability by in-situ water removal, and explicitly discusses robustness under **intermittent power**—a key feasibility constraint for habitat utility plants limited by variable energy supply. [15]

#### 11) ECLSS Trace Contaminant Control Testing (ICES-2025-465)

- **Organisation:** Vast Space, LLC[16] + NASA collaboration (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2025
- **Link:** <https://ntrs.nasa.gov/api/citations/20250004962/downloads/ICES-2025-465%20-%20Copyright%20added.pdf>
- **Why it matters:** Provides rare commercial-station evidence: describes subscale and system-level testing of a **commercial trace contaminant control (TCC) system**, including offgassing tests and planned closed-hatch offgassing per NASA standards, and states results demonstrate the system can maintain safe atmosphere for designed loads—directly relevant to maturity toward deployable habitat air loops. [17]

#### 12) ANITA2 – Multicomponent Air Analyser for ISS – 2 Years of Operation, Hardware Behaviour and Possible Improvements for Future Versions

- **Organisation:** SINTEF[18] with European Space Agency[19] and OHB SE[20] involvement (as described on the publication page)

- **Venue/type:** Technical conference lecture write-up / proceedings entry (ICES 2024)
- **Publication date:** Jul 2024
- **Link:** <https://www.sintef.no/en/publications/publication/2350263/>
- **Why it matters:** Reports ANITA2 has operated since early 2022 providing real-time analysis for **>40 gases every 6 minutes**, running **24/7/365** and producing **>130,000 data points per gas**, with downtime driven by operational constraints rather than instrument failures—strong maturity evidence for continuous, low-consumables atmospheric sensing needed for closed-loop control. [21]

#### **Bioregenerative modules (oxygen, carbon, nutrients) under space-relevant conditions**

##### **13) Space Algae-2 Ground and Lunar Analog Studies in Preparation for Long-Duration Propagation of Cyanobacteria in Spaceflight (ICES-2024-184)**

- **Organisation:** NASA-linked research team (conference paper via NTRS)
- **Venue/type:** Technical conference paper (ICES), PDF via NTRS
- **Publication date:** Jul 2024
- **Link:** [https://ntrs.nasa.gov/api/citations/20240005724/downloads/ICES\\_184-SpaceAlgae2\\_20240506\\_Revision.pdf](https://ntrs.nasa.gov/api/citations/20240005724/downloads/ICES_184-SpaceAlgae2_20240506_Revision.pdf)
- **Why it matters:** States that a **50 mL membrane photobioreactor** of *Limnospira indica* was flown for **four weeks** on the ISS and microgravity had **no significant effect on oxygen production rate**, supporting plausibility of bioregenerative oxygen production in space while also motivating longer-duration, multi-cycle validation. [22]

##### **14) Development and implementation of a simulated microgravity setup for edible cyanobacteria**

- **Organisation:** Academic research team (peer-reviewed)
- **Venue/type:** Peer-reviewed paper (npj Microgravity)
- **Publication date:** 2024 (month not indicated in the displayed excerpt)
- **Link:** <https://www.nature.com/articles/s41526-024-00436-x>
- **Why it matters:** Introduces and validates a ground analogue using a random positioning machine to test edible, oxygenic cyanobacteria under microgravity-like conditions—directly addressing feasibility risks around reduced gravity effects on bioregenerative modules before scaling toward integrated life support. [23]

##### **15) Whole transcriptome analysis highlights nutrient limitation of nitrogen cycle bacteria in simulated microgravity**

- **Organisation:** Academic/government-affiliated research team (peer-reviewed, open via PMC)
- **Venue/type:** Peer-reviewed experimental paper (open full text)
- **Publication date:** 2024 (accepted Jan 2024)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC10781756/>
- **Why it matters:** Demonstrates that simulated microgravity alters fluid dynamics enough to induce **nutrient and O<sub>2</sub> limitation signals** in urine-conversion/nitrification-relevant bacteria, which is a concrete engineering constraint for closing the nutrient loop: bioreactors must be designed for mass transfer and bubble management under reduced gravity to maintain stable conversion. [24]

##### **16) The influence of different storage conditions on *Limnospira indica*, a promising candidate for air revitalization in space**

- **Organisation:** Academic research team (peer-reviewed, open via PMC)
- **Venue/type:** Peer-reviewed experimental paper (open full text)
- **Publication date:** 2025 (month not indicated in the displayed excerpt)
- **Link:** <https://pmc.ncbi.nlm.nih.gov/articles/PMC12529360/>
- **Why it matters:** Shows practical operational constraints for bioregenerative modules: *L. indica* can be stored **2 weeks at 4°C in the dark without biomass loss**, and simulated microgravity does not worsen storage—evidence that logistics and standby modes (launch delays, dormancy) can be engineered rather than assumed away. [25]

#### 17) Reliability and lifetime estimation of bioregenerative life support system based on 370-day closed human experiment of Lunar Palace 1[26] and Monte Carlo simulation

- **Organisation:** Academic research team (peer-reviewed)
- **Venue/type:** Peer-reviewed paper (Acta Astronautica, open via ScienceDirect)
- **Publication date:** Jan 2023
- **Link:** <https://www.sciencedirect.com/science/article/abs/pii/S0094576522006294>
- **Why it matters:** Uses a **370-day closed human BLSS dataset** to estimate reliability distributions and reports a modelled mean lifetime (~**19,112 days**) under normal operation/maintenance, giving rare quantitative reliability evidence for long-duration bioregenerative habitat operation (and highlighting which subsystems dominate reliability sensitivity). [27]

#### 18) Surface fungal diversity and several mycotoxin-related genes' expression profiles during the Lunar Palace 365 experiment

- **Organisation:** Academic research team (peer-reviewed, open access)
- **Venue/type:** Peer-reviewed paper (Microbiome, open access)
- **Publication date:** Oct 2022
- **Link:** <https://link.springer.com/article/10.1186/s40168-022-01350-8>
- **Why it matters:** Provides hard evidence for a key feasibility bound in bioregenerative closed habitats—**bio-contamination and health risk management**—by characterising fungal communities and mycotoxin-gene markers over long isolation, finding plants as a major source and occupant turnover as a perturbation driver; this informs the monitoring/sanitation burden that must be engineered into mature closed-loop systems. [28]

### Monitoring and autonomy (control-software path to “utility plant” operations)

#### 19) Digital Twin Technologies for Autonomous Environmental Control and Life Support Systems

- **Organisation:** Academic/industry research team (peer-reviewed)
- **Venue/type:** Peer-reviewed journal article (AIAA Journal of Aerospace Computing, Information, and Communication; access via ResearchGate page)
- **Publication date:** Jan 2024
- **Link:** [https://www.researchgate.net/publication/383959968\\_Digital\\_Twin\\_Technologies\\_for\\_Autonomous\\_Environmental\\_Control\\_and\\_Life\\_Support\\_Systems](https://www.researchgate.net/publication/383959968_Digital_Twin_Technologies_for_Autonomous_Environmental_Control_and_Life_Support_Systems)
- **Why it matters:** Surveys and structures “digital twin” approaches that fuse physics models, ground testbeds, and flight data to support more autonomous ECLSS operations—highly relevant to the ART’s adaptive control/dashboards claim, but largely still at research/prototyping maturity rather than deployed autonomy. [29]

## 20) Status and Challenges of ECLSS Air Revitalization System in a Microgravity Environment

- **Organisation:** Japan Aerospace Exploration Agency[30] (conference paper PDF)
- **Venue/type:** Technical conference paper/extended abstract (Japanese conference proceedings PDF)
- **Publication date:** Sep 2025
- **Link:** <https://www.jasma.info/jasmac-37/wp-content/uploads/sites/18/2025/09/OS1-1.pdf>
- **Why it matters:** Offers an additional agency viewpoint on maturity blockers, explicitly emphasising **gas–liquid separation under microgravity** as a continuing key factor and describing planned/ongoing developments (e.g., CO<sub>2</sub> removal demonstrations) and the need for system integration test environments—directly aligned with the ART’s feasibility bounds around phase separation, reliability, and operational maintenance. [31]

### Maturity score (1–7) and reasoning

**Final maturity score: 4**

Closed-loop life support **as a full hybrid system** (physico-chemical + bioregenerative + automated monitoring/control) best fits **Level 4 (PoC)**.

### Why the evidence rules out lower levels

Level 1–3 are too low because multiple subsystems have moved beyond lab principle/prototype into **operational demonstration and iterative improvement in a real spacecraft environment**:

- **High-closure water recovery is not hypothetical:** ISS-class systems have measured, sustained performance—e.g., NASA reporting **~98% water recovery capability** on station and operational brine processing achieving ~98% water recovery with multiple on-orbit cycles and quantified volumes recovered. [32]
- The evidence base includes **detailed operational realities** (odor mitigation, ORU lifetimes, failures, spares, maintenance approaches), which is characteristic of post-prototype maturity rather than laboratory-only demonstrations. [33]
- For bioregenerative elements, there are **space-relevant demonstrations** (e.g., small photobioreactors flown on ISS with oxygen production not significantly degraded by microgravity) and controlled ground analogues to test reduced-gravity compatibility. [34]

Collectively, this exceeds Level 3 (“laboratory prototype”) because key functions have been demonstrated in **relevant environments** (on-orbit operation; long-duration closed human ground experiments) and with **quantitative performance/reliability results**. [35]

### Why the evidence does not yet justify Level 5

Level 5 would require clear evidence that **multiple well-capitalised actors are competing to build production prototypes** of the *integrated* closed-loop habitat utility plant (including biological loops + automation), or that a production prototype is in a finishing phase with rapid launch-to-production progress.



The evidence shows **strong subsystems and multiple actors**, but also highlights missing pieces that keep the *integrated* ART at PoC:

- **Full “air-loop closure” is still not operationally mature.** Sabatier-based CO<sub>2</sub> reduction is constrained by reliability/contamination history and, without methane processing, is fundamentally limited (≈50% O<sub>2</sub> recovery when CH<sub>4</sub> is vented). Advanced closure concepts (e.g., methane pyrolysis/CVD integration or ionic-liquid CO<sub>2</sub> removal architectures) are under development and modelling, with future flight demonstrations planned, but not yet widely fielded. [36]
- **Bioregenerative modules remain scale- and operations-limited.** There is credible feasibility evidence (ISS and ground analog results), yet engineering constraints like mass transfer and nutrient/O<sub>2</sub> limitations under reduced gravity are still active research topics—suggesting that scaling to habitat-throughput, multi-month reliability remains pre-production. [37]
- **Contamination/biofouling and biosafety are not “solved problems” for biological loops.** Long-duration habitat studies show that occupant turnover and plant integration perturb microbial/fungal communities, implying ongoing needs for monitoring, cleaning protocols, and fault responses—features expected in mature systems but not yet standardised at habitat scale. [28]
- Some commercial efforts exist (e.g., commercial trace contaminant system testing for a planned station, and commercial urine processor ground tests), but the corpus does not yet show **multiple routinely delivered, competing integrated closed-loop habitat products** with growing customer deployment—required for Levels 6–7. [38]

#### Sub-component maturity breakdown and aggregation

Because this ART is a **bundle** with materially different maturity across sub-components, an average-based score is appropriate.

- **Physico-chemical water-loop closure (ISS-class WRS / brine processing): ~6**
- Flight operations with quantified closure (~98% water recovery capability; multi-year operational data and maintenance cycles). [32]
- **Atmosphere management + trace contaminant monitoring/control: ~5–6**
- High-frequency multi-gas monitoring running continuously for years (ANITA2), plus commercial TCC testing aligned to station deployment. [39]
- **Air-loop closure beyond baseline (Sabatier upgrades, methane pyrolysis/CVD, ionic liquid CO<sub>2</sub> removal): ~3–4**
- Strong engineering analysis and clear pathways, but still largely in upgrade development / modelling / future flight demo planning (e.g., CDRILS flight demo targeted 2028). [36]
- **Bioregenerative oxygen + nutrient loops (cyanobacteria PBRs, nitrification, storage/dormancy): ~3–4**
- Space-relevant oxygen-production demonstration at small scale and substantial ground/omics evidence of microgravity-sensitive constraints; long-duration closed-habitat work supports plausibility but not yet production-readiness at habitat scale. [40]
- **Autonomous, adaptive control (digital twins / learning-based operations): ~3**

- Active research framing and early system concepts, but limited evidence of mature, certified autonomy running integrated life support without heavy ground-in-the-loop operations. [29]

**Aggregation to one score:** With major functionality depending on the least-mature elements (bioregenerative scaling + autonomy + fully closed air loop), the bundle as a whole is best characterised as **Level 4 (PoC)**: credible, functional prototypes exist for many key loops; however, integrated, production-prototype readiness for long-duration off-Earth habitats is not yet consistently demonstrated across the full hybrid stack. [41]

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[1] [13] <https://ntrs.nasa.gov/api/citations/20240004053/downloads/ICES-2024-156-Final.pdf>

<https://ntrs.nasa.gov/api/citations/20240004053/downloads/ICES-2024-156-Final.pdf>

[2] [27] [35] <https://www.sciencedirect.com/science/article/abs/pii/S0094576522006294>

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[3] [32] <https://www.nasa.gov/wp-content/uploads/2025/08/g-657270-59-hp-environmental-control-and-life-support-system-eclss.pdf?emrc=a8506e>

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[4] [16] [33] [41] <https://ntrs.nasa.gov/api/citations/20230006217/downloads/ICES%202023-097%20Status%20of%20ISS%20Water%20Management%20and%20Recovery.pdf>

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[https://ntrs.nasa.gov/api/citations/20240005472/downloads/ICES%202024-317%20Status%20of%20ISS%20Water\\_Final.pdf](https://ntrs.nasa.gov/api/citations/20240005472/downloads/ICES%202024-317%20Status%20of%20ISS%20Water_Final.pdf)

[6] <https://ntrs.nasa.gov/api/citations/20230006219/downloads/ICES%202023-100%20Planetary%20Urine%20Processor%20%28PUP%29%20Development.pdf>

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[7] [36] <https://ntrs.nasa.gov/api/citations/20230008504/downloads/ICES-2023-312%20Final.pdf>

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[8] [https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321\\_Final\\_230525.pdf](https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321_Final_230525.pdf)

[https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321\\_Final\\_230525.pdf](https://ntrs.nasa.gov/api/citations/20230010384/downloads/ICES-2023-321_Final_230525.pdf)

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[https://www.researchgate.net/publication/398343667\\_Development\\_and\\_Performance\\_Test\\_Results\\_of\\_the\\_Starlab\\_Alternative\\_Urine\\_Processor\\_Ground\\_Test\\_Unit](https://www.researchgate.net/publication/398343667_Development_and_Performance_Test_Results_of_the_Starlab_Alternative_Urine_Processor_Ground_Test_Unit)

[10] [29]

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[https://www.researchgate.net/publication/377247318\\_Digital\\_Twin\\_Technologies\\_for\\_Autonomous\\_Environmental\\_Control\\_and\\_Life\\_Support\\_Systems](https://www.researchgate.net/publication/377247318_Digital_Twin_Technologies_for_Autonomous_Environmental_Control_and_Life_Support_Systems)

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[14] <https://ntrs.nasa.gov/citations/20250001226>

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[15] [18] [26] <https://www.nature.com/articles/s41467-025-63667-w.pdf>

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[17] [38] <https://ntrs.nasa.gov/api/citations/20250004962/downloads/ICES-2025-465%20-%20Copyright%20added.pdf>

<https://ntrs.nasa.gov/api/citations/20250004962/downloads/ICES-2025-465%20-%20Copyright%20added.pdf>

[19] [22] [34] [37] [40]

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[https://ntrs.nasa.gov/api/citations/20240005724/downloads/ICES\\_184-SpaceAlgae2\\_20240506\\_Revision.pdf](https://ntrs.nasa.gov/api/citations/20240005724/downloads/ICES_184-SpaceAlgae2_20240506_Revision.pdf)

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[21] [39] <https://www.sintef.no/en/publications/publication/2350263/>

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[31] <https://www.jasma.info/jasmac-37/wp-content/uploads/sites/18/2025/09/OS1-1.pdf>

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## ART 10.082 High-Altitude Platforms & Balloons

### ART extraction

**A) Primary capability claimed (what the ART does)** - Persistent “pseudo-satellite” presence in/near the stratosphere ( $\approx 60,000$  ft /  $\sim 18$  km and above) for weeks to months, providing wide-area **communications relay** and/or **remote sensing**. [1]

- Recoverable, upgradable, and redeployable aerial infrastructure (vs. non-recoverable orbital assets), with operations resembling cloud-managed services (service areas, performance targets, updates, APIs). *(From ART text; operational style is a claim rather than a measured result.)* - Autonomy-heavy station-keeping/managed corridors using wind-field forecasting, cooperative control, and robust power management under extreme stratospheric conditions (UV, cold, pressure cycling). [2]

**B) Key sub-components / variants (sub-threads to evaluate)** - Stratospheric **balloons** (zero-pressure, super-pressure, steerable/altitude-controlled) for long duration flights and (sometimes) limited station-keeping. [3]

- Solar-electric **fixed-wing HALE aircraft** (“pseudo-satellites”) targeting multi-week endurance and payload testing. [4]

- Stratospheric **airships** (powered flight, relocation, heavier payload potential) with iterative flight-test maturation programmes. [5]

- **Station-keeping & navigation**: wind-layer exploitation, forecast models, planning/control algorithms, and performance variability by season/latitude. [6]

- **Comms payloads and network integration**: LTE/5G relay, gateways/backhaul, spectrum sharing constraints, and standards alignment (NTN/HAPS/HIBS). [7]

- **Payload + data handling**: EO/IR/radio payload integration, onboard power limits, recoverable storage, and operational recovery logistics. [8]

- **Regulatory/airspace pathway**: evolution of higher-airspace governance, certification expectations, and cross-border coordination. [9]

**C) Maturity indicators that would count as evidence** - **Multi-week/month endurance in relevant flight regimes**, with documented mission outcomes (not just design intent). [10]

- **Station-keeping performance with quantified tolerance** (distance-to-target / time-on-station), across seasons/latitudes, and with validated wind models/forecasting. [6]

- **Field demonstrations of comms services** (e.g., LTE coverage delivered to users) and/or operational sensing outputs, in realistic conditions. [11]

- **Repeatability and operational workflows**: launch cadence, command-and-control robustness, recovery, refurbishment, redeployment. [12]

- **Standards and spectrum pathway**: explicit inclusion in cellular/NTN standards; regulatory conditions enabling HIBS/HAPS deployments. [13]

- **Progress on airspace and higher-airspace governance** at international/regulatory bodies for safe integration. [14]

### 2. Evidence (10–20 recent, reliable sources)

## **ETSI TS 138 300 V17.1.0 (3GPP TS 38.300) – “NR and NG-RAN Overall description; Stage-2”**

Authors/organisation: ETSI[15] / 3GPP[16]

Venue/type: Standards specification (Release 17)

Publication date: Aug 2022

Link:

[https://www.etsi.org/deliver/etsi\\_ts/138300\\_138399/138300/17.01.00\\_60/ts\\_138300v170100p.pdf](https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/17.01.00_60/ts_138300v170100p.pdf)

Defines “High Altitude Platform Station” as an NTN payload platform at ~8–50 km altitude, anchoring HAPS as a recognised element in the 5G architectural vocabulary (important for plausibility of standard-aligned integration). [17]

## **Non-Terrestrial Networks (NTN) overview page**

Authors/organisation: 3GPP[16]

Venue/type: Standards-body technical overview / definitions and framing

Publication date: May 2024

Link: <https://www.3gpp.org/technologies/ntn-overview>

Defines NTN concepts including HAPS/airborne vehicles and regenerative payload terminology, supporting the ART’s claim that HAPS can be operated as network nodes with gateways and payload processing concepts analogous to “cloud-managed infrastructure”. [18]

## **Resolution 213 (WRC-23) – “Use of high-altitude platform stations as IMT base stations in 694–960 MHz”**

Authors/organisation: International Telecommunication Union[19]

Venue/type: Authoritative radiocommunication regulatory text (WRC resolution)

Publication date: 2023 (WRC-23), published in Radio Regulations 2024 compilation

Link: [https://www.itu.int/dms\\_pub/itu-r/oth/0C/0A/R0C0A0000110066PDFE.pdf](https://www.itu.int/dms_pub/itu-r/oth/0C/0A/R0C0A0000110066PDFE.pdf)

Specifies conditions (including coordination and power-flux-density limits) for HIBS, and explicitly frames HIBS as part of terrestrial IMT networks—strong evidence that spectrum governance is actively being adapted for HAPS-like deployments (maturity enabler). [20]

## **Proposal for a Roadmap on Higher Airspace Operations (HAO)**

Authors/organisation: European Union Aviation Safety Agency[21]

Venue/type: Regulator roadmap/report (EU-level)

Publication date: Mar 2023

Link: <https://www.easa.europa.eu/en/document-library/general-publications/proposal-roadmap-higher-airspace-operations-hao>

Positions HAPS among higher-airspace vehicle categories needing regulatory adaptation and recommends studies/tests/demonstrators and “regulatory sandboxes,” indicating active movement from concept to governed operations (but acknowledging they do not yet exist at large scale in Europe). [22]

## **ICAO Assembly Working Paper A42-WP/63 (Rev. 1) – “Higher Airspace Operations”**

Authors/organisation: International Civil Aviation Organization[23] (paper presented by Oman[24])

Venue/type: International aviation governance working paper (Assembly, Technical Commission)

Publication date: Aug 2025 (revision)

Link:

[https://www.icao.int/sites/default/files/Meetings/a42/Documents/WP/wp\\_063\\_rev1\\_en.pdf](https://www.icao.int/sites/default/files/Meetings/a42/Documents/WP/wp_063_rev1_en.pdf)

Explicitly includes “High Altitude Platform Systems (HAPS)” as a driver of the growing higher-airspace domain, showing that HAPS are now treated as a policy-relevant operational class at the global aviation-governance level. [25]

### **Overview of the DLR High Altitude Platform and scientific potential of the technology demonstrator HAP-alpha**

Authors/organisation: Florian Nikodem[26]; German Aerospace Center[27]

Venue/type: Conference paper (DLRK 2023; research institution engineering programme)

Publication date: Sep 2023

Link: <https://elib.dlr.de/198509/>

Provides concrete engineering parameters (e.g., aircraft mass, wingspan, payload capacity, comms link and ground segment concept) for a solar HAP demonstrator, supporting feasibility at the system-engineering level (not merely conceptual). [28]

### **General design considerations for solar-electric high-altitude long-endurance aircraft**

Authors/organisation: Andreas Bierig[29] et al.; German Aerospace Center[27]

Venue/type: Conference proceedings paper (ICAS Congress)

Publication date: Sep 2024

Link:

[https://www.icas.org/icas\\_archive/icas2024/data/papers/icas2024\\_0910\\_paper.pdf](https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0910_paper.pdf)

Derives operational-limit diagrams from environmental and performance modelling and argues that advances in solar cells, batteries and lightweight materials enable solar-electric stratospheric aircraft deployment—useful plausibility evidence for multi-day to multi-week HALE concepts. [30]

### **Recent Developments from the NASA Balloon Program Office**

Authors/organisation: Sarah Roth[31]; NASA[32]

Venue/type: Conference presentation (ESA Symposium on European Rocket & Balloon Programmes)

Publication date: May 2022

Link:

<https://ntrs.nasa.gov/api/citations/20220006293/downloads/NASA%20Program%20Overview%20ESA%20Symposium%2004-2022%20%281%29.pdf>

Summarises NASA balloon platform classes, typical durations and payload envelopes, and an explicit technology roadmap seeking ~100+ day diurnal super-pressure flights—evidence of mature operational infrastructure and a scaling agenda for long-duration balloons. [33]

### **Super Pressure Balloon fact sheet**

Authors/organisation: NASA

Venue/type: Government fact sheet / technical overview

Publication date: Sep 2022

Link: <https://www.nasa.gov/wp-content/uploads/2023/03/super-pressure-balloon-fact-sheet.pdf>

States the goal of lifting “a ton of science” to ~33.5 km (~110,000 ft) with altitude stability at



mid-latitudes, supporting the plausibility of high-payload, long-duration stratospheric balloon platforms as persistent sensing/relay hosts. [34]

### **Data Downloaded via Parachute from a NASA Super-Pressure Balloon**

Authors/organisation: Ellen L. Sirks[35] et al.

Venue/type: Peer-reviewed paper (MDPI Aerospace)

Publication date: Nov 2023

Link: <https://www.mdpi.com/2226-4310/10/11/960>

Reports a real stratospheric super-pressure balloon mission in Apr 2023 with ~40 days aloft and a recoverable data-capsule system (multi-terabyte storage with parachute recovery), directly supporting the ART's "recoverable/upgradeable" lifecycle advantage claim. [36]

### **Seasonal and geographic viability of high altitude balloon navigation**

Authors/organisation: David Brown[37] et al.; Harvard University[38] + Urban Sky[39]

Venue/type: Peer-reviewed paper (Scientific Reports)

Publication date: Sep 2024

Link: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11413015/>

Uses ERA5 winds and search-based control to quantify "time within 50 km of target," finding strong season/latitude dependence and highlighting that balloon station-keeping is not uniformly feasible—directly relevant to the ART's station-keeping precision constraint. [40]

### **Station-Keeping Control of Stratospheric Balloons Based on Simultaneous Optimistic Optimization in Dynamic Wind**

Authors/organisation: Yuanqiao Fan[41] et al.; National University of Defense Technology[42]

Venue/type: Peer-reviewed paper (MDPI Electronics)

Publication date: Oct 2024

Link: <https://www.mdpi.com/2079-9292/13/20/4032>

Proposes a receding-horizon controller using learned short-term wind forecasts (neural networks) and reports simulation-based performance gains versus greedy/A\* baselines—evidence for plausibility of "wind-field forecasting + autonomous control" as a key enabler, while also indicating much remains simulation-heavy. [43]

### **Aerostar provides cellular connectivity from the stratosphere via Thunderhead Balloon System**

Authors/organisation: Aerostar[44] (via Raven Industries[45] announcement) with Abside Networks[46]

Venue/type: Industry technical press release (contains concrete demo claim)

Publication date: Apr 2022

Link: <https://aerostar.com/news/aerostar-provides-cellular-connectivity-from-the-stratosphere-via-thunderhead-balloon-system>

Reports a series of test flights demonstrating **4G LTE connectivity "from the stratosphere"** using the Thunderhead balloon system and a HAPS-RAN product—direct evidence that LTE relay payloads have been field-demonstrated on high-altitude balloons. [47]

### **Aerostar Thunderhead Balloon System achieves 200 days of flight in the stratosphere**

Authors/organisation: Aerostar

Venue/type: Industry press release (contains explicit endurance/navigation metrics)

Publication date: Oct 2024

Link: <https://aerostar.com/news/aerostar-thunderhead-balloon-system->

### achieves-200-days-of-stratospheric-flight

Claims a specific balloon (HBAL 676) reached 200 days aloft after a March 2024 launch and reports distance travelled plus use of ML-enabled wind models/software—strong maturity evidence for long-duration balloon operations and navigation workflow, albeit self-reported. [\[48\]](#)

### Improving Firefighter Safety with STRATO (Flight Summary)

Authors/organisation: NASA (with partners including Aerostar and the U.S. Forest Service, among others)

Venue/type: Government programme flight summary (field test results)

Publication date: Page last updated Jan 2026 (describes Aug 2024 flight and results)

Link: <https://www.nasa.gov/stmd-flight-opportunities/flight-summaries/improving-firefighter-safety-with-strato/>

Describes an Aug 2024 stratospheric balloon flight test providing persistent LTE coverage and infrared fire imaging, with stated test duration and outcomes—direct evidence of real operational use cases (disaster response / remote connectivity) beyond lab prototypes. [\[49\]](#)

### Zephyr sets world-record for longest continuous flight, flying 67 days in stratosphere

Authors/organisation: AALTO HAPS Ltd.[\[50\]](#) (an Airbus[\[51\]](#) subsidiary)

Venue/type: Industry press release PDF (contains detailed flight timeline/claims)

Publication date: May 2025

Link: <https://www.aaltohaps.com/wp-content/uploads/2025/05/Zephyr-sets-world-record-for-longest-continuous-flight-flying-67-days-in-stratosphere.pdf>

Reports a 67-day continuous stratospheric flight ending 28 Apr 2025 and notes connectivity payload testing and multi-region flight management—strong evidence that solar HAPS aircraft can achieve multi-month endurance and operate under real airspace/regulatory coordination. [\[52\]](#)

### AALTO secures UK's first HAPS Design Organisation Approval (DOA) from the UK Civil Aviation Authority

Authors/organisation: AALTO (statement includes a quoted manager from the UK CAA)

Venue/type: Industry announcement tied to a regulatory milestone

Publication date: Jul 2024

Link: <https://www.aaltohaps.com/aalto-achieves-milestone-haps-regulation-with-design-organisation-approval-from-uk-civil-aviation-authority/>

Documents a specific regulatory step (DOA) described as prerequisite progress toward type certification and targeted entry-into-service timing—important maturity evidence on the “airworthiness/certification bottleneck”. [\[53\]](#)

### Sceye's Flight Program: “A journey from iterative development to market acceptance”

Authors/organisation: Sceye[\[54\]](#) (slides hosted by EUROCONTROL[\[55\]](#) event materials)

Venue/type: Industry technical presentation (flight-test milestones; pre-commercial claims)

Publication date: Nov 2024

Link: <https://www.eurocontrol.int/sites/default/files/2024-11/eurocontrol-2024-echo2-event-roundtable2-sceye-flight-program.pdf>

Summarises >20 test flights and lists 2023–2024 flight-program achievements (e.g., diurnal capability, relocation, payload tests up to ~200 lb, BLOS/automation tests), providing concrete evidence of iterative maturation for the stratospheric airship branch. [\[5\]](#)

### **Navy demonstrates multi-day solar UAS flight**

Authors/organisation: Naval Air Warfare Center Aircraft Division[56] via Defense Visual Information Distribution Service[57]; partner: Skydweller Aero[58]

Venue/type: Government field-trial story (public-domain release)

Publication date: Jul 2025

Link: <https://www.dvidshub.net/news/544139/navy-demonstrates-multi-day-solar-uas-flight>

Reports a 73-hour continuous solar-powered unmanned flight validating comms links and autonomous real-time decision-making (including adaptation to turbulence)—evidence that pseudo-satellite-like solar UAV concepts are progressing in operationally relevant trials (even if not always at stratospheric altitudes). [59]

### **An update of the CNES stratospheric balloon activities**

Authors/organisation: CNES[60] (V. Dubourg et al.)

Venue/type: Conference paper (EUCASS 2023)

Publication date: 2023

Link: <https://www.eucass.eu/doi/EUCASS2023-267.pdf>

Describes an institutional-scale balloon infrastructure (multiple balloon types; regular campaigns; stated operational tempo such as dozens of balloons per year at a French operations centre), supporting maturity of stratospheric balloon logistics and repeatable operations. [61]

## **3. Maturity score (1–7) and reasoning**

### **Final maturity score: 5**

This ART is beyond laboratory prototypes because multiple platform variants have demonstrated **functional, operationally relevant prototypes** in the field (including multi-day to multi-month endurance and real comms/sensing use cases). Examples include self-reported but detailed multi-month endurance for steerable high-altitude balloons and multi-month stratospheric solar-aircraft endurance, as well as government-documented multi-day solar-UAS test flights and a government-described wildfire-response communications use case. [62]

At the same time, the evidence does not yet support “products delivered to customers in increasing amounts” (rubric 6) across the ART as a whole: the strongest material is still dominated by flight trials, programme roadmaps, and regulatory/standards progress rather than broad, routine deployments with disclosed customer counts, production rates, and economics. [63]

### **Evidence-to-rubric mapping**

**What evidence rules out lower levels (1–4)** - Level 1–2 (theory/lab verification) is ruled out by **field operations**:

- A solar HAPS aircraft flown continuously for **67 days** in the stratosphere (reported with specific dates and operational notes). [52]
- A high-altitude balloon reported to have achieved **200 days** of stratospheric flight (with launch date and operational navigation tooling described). [48]
- A government-described stratospheric balloon trial delivering **LTE coverage + IR imaging** to support wildfire operations, with multi-day testing results described. [49]

- A government-reported **73-hour** solar-UAS flight validating comm links and autonomous decision-making—evidence of a functioning autonomy/power stack in relevant conditions. [\[59\]](#)

- Level 3–4 (lab prototype / single PoC) is ruled out because there is evidence of **repeatable programmes, institutional infrastructure, and enabling governance**:
- NASA and CNES documentation shows balloon programmes with defined platform classes, telemetry/recovery systems, and multi-year roadmaps. [\[64\]](#)
- Cellular/NTN standards explicitly define HAPS as an NTN platform class and provide canonical terminology for payload/gateway concepts (enabler for telecom integration). [\[65\]](#)
- ITU WRC-23 regulatory text sets explicit technical coordination conditions for HIBS/HAPS-style IMT base stations in sub-1 GHz spectrum (critical maturity enabler). [\[20\]](#)
- Aviation regulators and ICAO-level processes explicitly categorise HAPS within “higher airspace operations,” signalling active governance work rather than purely experimental activity. [\[14\]](#)

**Why this maps best to level 5 (not 4, not 6)** - Level 5 requires *either* several well-capitalised actors competing post-PoC *or* a production prototype clearly in the finishing phase with investments made to launch production.

- Evidence of multiple active lines (balloons, solar fixed-wing, airships, solar UAS) and sustained test programmes supports the “post-PoC competing actors” interpretation, and AALTO’s DOA milestone is consistent with an aircraft entering a certification pathway (a typical marker of readiness work rather than basic R&D). [\[66\]](#)

- Level 6 would require clear evidence of **products delivered in increasing amounts** and financed production expansion. The sources available in the last four years (meeting the strict window) do not provide strong, auditable data on scaling (unit deliveries, production capacity, recurring revenue, broad customer adoption), so level 6 is not justified for the ART “as a whole.” [\[67\]](#)

#### Sub-scores and aggregation

Because this ART bundles multiple platform types with similar end functionality (persistent wide-area comms/sensing from high altitude), a **weighted average** is more defensible than taking the maximum.

- **Stratospheric balloons (incl. comm relay / limited station-keeping)** → maturity estimate **5–6**  
Key evidence: 4G LTE-from-stratosphere demo claim (Apr 2022), 200-day endurance claim (Oct 2024), and NASA-described STRATO operational testing (Aug 2024 flight described on NASA page). [\[68\]](#)  
Caution: some of the most “market-like” metrics here are from company press releases (credible but not independently audited in these sources). [\[48\]](#)
- **Solar fixed-wing stratospheric HAPS aircraft** → maturity estimate **5**  
Key evidence: 67-day stratospheric flight report and a regulator-facing certification milestone (DOA) indicating movement toward certified operations. [\[69\]](#)
- **Stratospheric airships** → maturity estimate **4–5**  
Key evidence: Scye’s documented test programme milestones (including diurnal capability

and relocation) suggest a pre-commercial prototype stage, but customer delivery/scale is not evidenced in the cited material. [5]

- **Solar long-endurance “pseudo-satellite role” UAVs (not always stratospheric)** → maturity estimate **4–5**  
Key evidence: government release of a 73-hour continuous solar powered unmanned flight validating comms and autonomy indicates strong PoC and ongoing maturation, but not broad operations. [59]
- **Station-keeping algorithms / wind-field forecasting research** → maturity estimate **2–3**  
Key evidence: peer-reviewed work demonstrates feasibility via modelling/simulation and quantifies constraints (season/latitude dependence), but remains far from validated commercial autonomy stacks across all operational regimes. [70]

**Aggregation to one score:** The platform layer (balloons + solar aircraft + emerging airships) shows multiple field-tested prototypes and regulatory/standardisation progress—consistent with **level 5** overall—while the autonomy/control stack and global station-keeping reliability remain uneven across conditions and are still research-intensive in the recent peer-reviewed literature. [71]

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[1] [13] [17] [19] [65]

[https://www.etsi.org/deliver/etsi\\_ts/138300\\_138399/138300/17.01.00\\_60/ts\\_138300v170100p.pdf](https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/17.01.00_60/ts_138300v170100p.pdf)

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[2] [43] <https://www.mdpi.com/2079-9292/13/20/4032>

<https://www.mdpi.com/2079-9292/13/20/4032>

[3] [12] [33] [46] [55] [64]

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[4] [10] [21] [29] [31] [38] [39] [50] [52] [67] [69] [71] <https://www.aaltohops.com/wp-content/uploads/2025/05/Zephyr-sets-world-record-for-longest-continuous-flight-flying-67-days-in-stratosphere.pdf>

<https://www.aaltohops.com/wp-content/uploads/2025/05/Zephyr-sets-world-record-for-longest-continuous-flight-flying-67-days-in-stratosphere.pdf>

[5] <https://www.eurocontrol.int/sites/default/files/2024-11/eurocontrol-2024-echo2-event-roundtable2-sceye-flight-program.pdf>

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[7] [11] [15] [16] [47] [68] <https://aerostar.com/news/aerostar-provides-cellular-connectivity-from-the-stratosphere-via-thunderhead-balloon-system>

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[8] [49] <https://www.nasa.gov/stmd-flight-opportunities/flight-summaries/improving-firefighter-safety-with-strato/>

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[9] [14] [22] [41] [45] [57] [63] <https://www.easa.europa.eu/en/document-library/general-publications/proposal-roadmap-higher-airspace-operations-hao>

<https://www.easa.europa.eu/en/document-library/general-publications/proposal-roadmap-higher-airspace-operations-hao>

[18] <https://www.3gpp.org/technologies/ntn-overview>

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[20] [23] [60] [https://www.itu.int/dms\\_pub/itu-r/oth/0C/0A/R0C0A0000110066PDFE.pdf](https://www.itu.int/dms_pub/itu-r/oth/0C/0A/R0C0A0000110066PDFE.pdf)

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[28] <https://elib.dlr.de/198509/>

<https://elib.dlr.de/198509/>

[30] [https://www.icas.org/icas\\_archive/icas2024/data/papers/icas2024\\_0910\\_paper.pdf](https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0910_paper.pdf)

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[32] [53] [66] <https://www.aaltohaps.com/aalto-achieves-milestone-haps-regulation-with-design-organisation-approval-from-uk-civil-aviation-authority/>



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[34] [54] <https://www.nasa.gov/wp-content/uploads/2023/03/super-pressure-balloon-fact-sheet.pdf>

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[36] [37] <https://www.mdpi.com/2226-4310/10/11/960>

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[61] <https://www.eucass.eu/doi/EUCASS2023-267.pdf>

<https://www.eucass.eu/doi/EUCASS2023-267.pdf>

## Group 11 - Digital Platforms & Collective-Intelligence Systems

### ART11.083 Decentralized Trust Networks (Web3 & Blockchain)

#### ART extraction

##### A) Primary capability (claimed)

- Enable many independent parties to **coordinate transactions and shared records** without a single “source-of-truth” operator, using cryptographic verification and distributed consensus.
- Provide **tamper-evident / hard-to-retroactively-edit audit trails** and programmable rule enforcement (smart contracts) that reduce reconciliation and disputes.
- Support **selective disclosure and cross-ecosystem interoperability** (identity proofs, credential sharing, cross-network proofs/assets) so users can interact through familiar apps/API patterns.

##### B) Key sub-components / sub-threads (technology bundle)

- **Base ledgers & consensus** (permissionless and permissioned DLTs; event ordering; finality; throughput/latency engineering).
- **Smart-contract runtimes** (EVM-like VMs; upgradeability; composability; formal methods; auditing/monitoring).
- **Layer-2 scaling & data availability** (rollups, state channels; “data availability” guarantees; fee/cost dynamics).
- **Privacy-preserving mechanisms** (zero-knowledge proofs; selective disclosure; unlinkability trade-offs; key-binding).
- **Decentralised identity** via **DIDs** and **Verifiable Credentials** (issuer–holder–verifier model; revocation/status; wallet interoperability).
- **Interoperability / cross-network bridges** (light clients, relays, bridges; security models and failure modes).
- **Key management & recovery** (hardware/software wallets; MPC/threshold schemes; governance for credential/key lifecycle).

- **Governance, compliance, and auditability** (regulatory constraints; liability; operational controls; transparency requirements).

### C) Maturity indicators (what “good evidence” looks like for this ART)

- **Standards reached Recommendation/RFC/International Standard** status for identity, credential formats, and selective disclosure; signs of multi-vendor interoperability.
- **Field pilots** and **multi-party deployments** (eg, cross-border or cross-organisation trials) with concrete artefacts (transaction hashes, testnets, deployment specs).
- **Measured performance results** (throughput, latency, scalability limits) for both permissioned and public-chain contexts.
- **Scaling mechanisms already live** (eg, rollups + protocol upgrades) with clear, recent engineering progress.
- **Security evidence**: published analyses of bridge risk, formal verification progress, and/or empirical incident datasets mapping real failures to vulnerabilities.
- **Regulatory frameworks** in force or actively implemented that shape operational/governance requirements for real deployments.

## 2. Evidence (10–20 recent, reliable sources)

### Ethereum protocol scaling and operational feasibility

#### 1) Dencun Mainnet Announcement

- **Organisation**: Ethereum Foundation[1]
- **Type**: Technical protocol announcement (core network upgrade)
- **Date**: Feb 2024
- **Link**: <https://blog.ethereum.org/2024/02/27/dencun-mainnet-announcement>
- **Why it matters**: Confirms ongoing, production-grade protocol evolution to improve scalability and costs (notably via EIP-4844 “blobs” aimed at rollup data). This is direct evidence that the “layered trust fabric” model (L1 + L2 scaling) is not speculative but actively shipped on a major network. [2]

#### 2) Impact of EIP-4844 on Ethereum: Consensus Security, Blockspace Markets, and Developer Considerations

- **Authors**: (arXiv preprint; authors listed in the paper)
- **Type**: Preprint with technical analysis (labelled *preprint*)
- **Date**: May 2024
- **Link**: <https://arxiv.org/abs/2405.03567>
- **Why it matters**: Provides a research-level examination of proto-danksharding’s implications (security and market dynamics), supporting plausibility (engineering feasibility) while highlighting maturity constraints (new fee markets, operational considerations) that still need validation at scale.

#### 3) Ethereum Energy Consumption

- **Organisation**: [ethereum.org](https://ethereum.org)[3]
- **Type**: Vendor/technical documentation page (network energy estimates and methodology pointers)
- **Date**: Nov 2025 (page date)
- **Link**: <https://ethereum.org/energy-consumption/>
- **Why it matters**: Directly supports the ART’s claim that energy use “is likely manageable” for

major proof-of-stake deployments, providing an explicit network-level energy estimate and framing energy as a design variable rather than a blocker for most non-PoW deployments. [4]

## **Layer-2 scaling, rollups, data availability, and privacy tech**

### **4) Analyzing and Benchmarking ZK-Rollups**

- **Authors:** Antonis Chaliasos[5] et al.
- **Venue/type:** Peer-reviewed conference paper (LIPIcs / AFT 2024)
- **Date:** 2024
- **Link:** <https://www.dagstuhl.de/dagpub/978-3-95977-341-6>
- **Why it matters:** Empirically benchmarks real ZK-rollup systems (including performance/overheads), showing that advanced privacy/scalability techniques are beyond theory and can be compared as engineered systems—supporting both plausibility and “post-PoC” maturity for ZK rollups.

### **5) A Survey on Data Availability in Layer 2 Blockchain Rollups: Open Challenges and Future Improvements**

- **Authors:** Muhammad Bin Saif[6] et al.
- **Venue/type:** Peer-reviewed survey (Future Internet, open access)
- **Date:** Aug 2024
- **Link:** <https://www.mdpi.com/1999-5903/16/9/315>
- **Why it matters:** Treats data availability as a concrete, current bottleneck for rollups (a key constraint in the ART) and maps deployed approaches plus open engineering gaps, helping assess how close rollup-centric scaling is to robust, general-purpose enterprise reliability. [7]

### **6) On cryptographic mechanisms for the selective disclosure of verifiable credentials**

- **Authors:** Andrea Flamini[8] et al.
- **Venue/type:** Peer-reviewed paper (Journal of Information Security and Applications, open access)
- **Date:** Jun 2024
- **Link:** <https://www.sciencedirect.com/science/article/pii/S2214212624000929>
- **Why it matters:** Surveys and experimentally evaluates selective disclosure mechanisms used in modern credential systems (including ZK-proof-based approaches like BBS signatures), explicitly connecting privacy claims to measurable trade-offs (credential/presentation size; generation/verification time), which is critical for maturity assessment. [9]

## **Decentralised identity, credential standards, and interoperability plumbing**

### **7) Decentralized Identifiers (DIDs) v1.0**

- **Organisation:** World Wide Web Consortium[10]
- **Type:** Standard (W3C Recommendation)
- **Date:** Jul 2022
- **Link:** <https://www.w3.org/TR/did-1.0/>
- **Why it matters:** Establishes a stable, standardised identifier layer for decentralised identity and cross-organisation authentication/authorisation flows, supporting the ART’s claim that identity and permissioning can be handled through decentralised identifiers. [11]

### **8) Verifiable Credentials Data Model v2.0**

- **Organisation:** W3C (Recommendation)

- **Type:** Standard (W3C Recommendation)
- **Date:** May 2025
- **Link:** <https://www.w3.org/TR/vc-data-model-2.0/>
- **Why it matters:** Provides a widely deployable, standard data model for verifiable credentials and presentations—core to “prove specific attributes without exposing full underlying data”—signalling maturation from competing formats toward interoperable credential ecosystems. [12]

#### 9) RFC 9901: Selective Disclosure for JSON Web Tokens (SD-JWT)

- **Organisation:** Internet Engineering Task Force [13]
- **Type:** Standard (IETF RFC, Proposed Standard)
- **Date:** Nov 2025
- **Link:** <https://datatracker.ietf.org/doc/rfc9901/>
- **Why it matters:** Standardises a practical selective-disclosure mechanism compatible with existing JWT tooling (including optional key binding), making “selective disclosure with widely available cryptographic tools” materially more deployable in mainstream identity stacks. [14]

#### 10) OpenID for Verifiable Presentations 1.0 (OpenID4VP)

- **Organisation:** OpenID Foundation [15]
- **Type:** Standard (Final specification)
- **Date:** Jul 2025
- **Link:** [https://openid.net/specs/openid-4-verifiable-presentations-1\\_0-final.html](https://openid.net/specs/openid-4-verifiable-presentations-1_0-final.html)
- **Why it matters:** Shows convergence toward familiar web/app integration patterns (OAuth-style flows) for credential presentation, directly matching the ART claim that end-users will interact via standard sign-in/authorisation flows rather than bespoke blockchain UX. [16]

#### 11) OpenID for Verifiable Credential Issuance 1.0 (OpenID4VCI)

- **Organisation:** OpenID Foundation
- **Type:** Standard (Final specification)
- **Date:** Sept 2025
- **Link:** [https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0.html)
- **Why it matters:** Defines an interoperable issuance API for credentials, helping move decentralised identity from isolated pilots to scalable issuer ecosystems integrated with existing OAuth/OpenID Connect deployments. [17]

#### 12) ISO/TR 23644:2023 — Blockchain and distributed ledger technologies — Trust anchors for DLT based identity management

- **Organisation:** International Organization for Standardization [18]
- **Type:** International standard / technical report
- **Date:** May 2023
- **Link:** <https://www.iso.org/standard/83094.html>
- **Why it matters:** Indicates international-standard attention to “trust anchors” in DLT identity management—evidence that governance and trust bootstrapping are being formalised beyond single-vendor ecosystems. [19]

#### 13) ISO 22739:2024 — Blockchain and distributed ledger technologies — Vocabulary

- **Organisation:** ISO
- **Type:** International standard
- **Date:** Jan 2024

- **Link:** <https://www.iso.org/standard/86618.html>
- **Why it matters:** Mature markets standardise language and definitions; a shared vocabulary reduces integration friction, audit ambiguity, and procurement risk for multi-party trust networks. [20]

### Security, key management, and bridge risk concentration

#### 14) NISTIR 8214C (Second Public Draft): NIST First Call for Multi-Party Threshold Schemes

- **Organisation:** National Institute of Standards and Technology[21]
- **Type:** Authoritative roadmap/call (government lab technical report; draft)
- **Date:** Mar 2025
- **Link:** <https://nvlpubs.nist.gov/nistpubs/ir/2025/NIST.IR.8214C.2pd.pdf>
- **Why it matters:** Directly addresses a core operational bottleneck in decentralised networks—key compromise and recovery—by pushing towards standardisable threshold cryptography (relevant to MPC wallets, institutional key management, and resilient signing infrastructures). [22]

#### 15) SoK: Security and Privacy of Blockchain Interoperability (extended version)

- **Authors:** André Augusto[23] et al.
- **Venue/type:** Security & privacy systematic study (extended version of IEEE S&P work; label as *preprint/extended technical version*)
- **Date:** May 2024 (conference timing)
- **Link:** <https://www.dpss.inesc-id.pt/~mpc/pubs/augusto2024.pdf>
- **Why it matters:** Provides a structured security model and an incident-grounded dataset showing cross-chain bridge hacks on the order of ~\$3.1B and mapping exploits to concrete vulnerability classes—strong evidence that “bridge components” are a concentrated risk and remain a maturity limiter. [24]

### Performance, deployment, and multi-party operational evidence

#### 16) On the performance and scalability of consensus mechanisms in privacy-enabled decentralized renewable energy marketplace

- **Authors:** Roman-Valentyn Tkachuk[25] et al.
- **Venue/type:** Peer-reviewed paper (Annals of Telecommunications; open access)
- **Date:** Sept 2023 (version of record)
- **Link:** <https://link.springer.com/article/10.1007/s12243-023-00973-8>
- **Why it matters:** Reports concrete throughput/latency figures in a permissioned Ethereum-client environment (eg, ~200 TPS in baseline configuration and read throughput on the order of ~1440 RPS with latency behaviour reported), illustrating real engineering trade-offs between BFT-style security, privacy features, and performance—central to plausibility and scaling constraints. [26]

#### 17) Project Mariana: Cross-border exchange of wholesale CBDCs using automated market-makers (Final report)

- **Organisations:** Bank for International Settlements[27] / Banque de France[28] (with partners including Swiss National Bank[29] and Monetary Authority of Singapore[30])
- **Type:** Authoritative central-bank / international consortium PoC report
- **Date:** Sept 2023
- **Link:** <https://www.banque-france.fr/system/files/2023->

09/20230928%20Mariana%20final%20report.pdf

- **Why it matters:** Demonstrates a real multi-party architecture combining smart contracts (AMM), token standards, and **bridges** across networks, including publishable transaction hashes on a public test network—high-value evidence that multi-institution trust networks can be engineered and tested end-to-end, while also explicitly noting out-of-scope gaps (eg, full non-functional privacy/performance). [31]

#### 18) European Blockchain Services Infrastructure (EBSI) — Home

- **Organisation:** European Blockchain Services Infrastructure[32]
- **Type:** Technical deployment documentation (EU-scale infrastructure documentation hub)
- **Date:** Feb 2026 (page “last updated”)
- **Link:** <https://hub.ebsi.eu/home>
- **Why it matters:** Evidence of a concrete, multi-country public-sector deployment effort with published documentation and operational governance artefacts—strong maturity signal beyond lab PoCs. [33]

#### 19) EBSI — Standards Versions

- **Organisation:** EBSI
- **Type:** Technical deployment documentation (spec versioning and compatibility)
- **Date:** Feb 2026 (page “last updated”)
- **Link:** <https://hub.ebsi.eu/specs/standards-versions>
- **Why it matters:** Versioned standards tracking is a practical “scaling-to-production” marker: it indicates active compatibility management across evolving DID/VC/OIDC-related standards rather than one-off demonstrations. [34]

#### 20) Regulation (EU) 2023/1114 on markets in crypto-assets (MiCA) — EUR-Lex

- **Organisation:** European Union[35]
- **Type:** Authoritative legal text (regulatory framework)
- **Date:** May 2023
- **Link:** <https://eur-lex.europa.eu/eli/reg/2023/1114/oj/eng>
- **Why it matters:** Direct evidence that governance/liability/auditability constraints are not hypothetical; a major jurisdiction has a unified regime for crypto-asset activities, shaping how trust networks can be operated and commercialised (compliance, disclosure, and service-provider controls). [36]

#### 21) FATF: Updated Guidance / Targeted Update on virtual assets and VASPs

- **Organisation:** Financial Action Task Force[37]
- **Type:** Authoritative international policy/implementation update
- **Date:** Jul 2024
- **Link:** <https://www.fatf-gafi.org/en/publications/Fatfrecommendations/targeted-update-virtual-assets-vasps-2024.html>
- **Why it matters:** Shows the evolving global compliance pressure (AML/CFT, “travel rule” implementation), which is a real-world maturity constraint for decentralised trust networks when used for value transfer and multi-party workflows involving regulated actors. [38]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 6



## B) Why level 6 is justified (explicit mapping to the rubric)

Level 6 requires that products are being delivered to customers in increasing amounts, application areas are expanding, and scaling/production expansion is ongoing and financed. This is supported by multiple independent signals across the stack:

- **Operational deployments and large multi-party programmes exist**, not just lab demos: the EU’s EBSI documentation hub and active standards/version management indicate a sustained, multi-stakeholder deployment trajectory rather than a one-off pilot. [\[39\]](#)
- **Central-bank / international consortium PoCs demonstrate functional end-to-end architectures** using token standards, smart contracts, and bridges, with concrete artefacts (eg, transaction hashes) and explicit engineering architecture for cross-network mobility. [\[31\]](#)
- **Major public smart-contract platforms continue shipping core upgrades aimed at scaling** (eg, rollup-centric data improvements), consistent with an ecosystem in active production evolution and investment rather than early-stage research. [\[40\]](#)
- **Standardisation of identity/credentials and selective disclosure is now at “final” (Recommendation/RFC/Final spec) status in multiple standards bodies**, which is a strong maturity signal for interoperability and ecosystem formation (W3C DID/VC, IETF SD-JWT, OpenID4VP/OID4VCI). [\[41\]](#)
- **Measured performance trade-offs** (throughput/latency under BFT and privacy constraints, plus rollup data-availability bottlenecks) are being quantified in peer-reviewed venues, indicating engineering maturity with known limits rather than unknown feasibility. [\[42\]](#)

These collectively rule out levels 1–5: the evidence is not merely theoretical (1) or lab-only (2–3) or isolated PoCs (4); instead, there are **deployments, standards, and continuous upgrades** with multiple capitalised actors and public-sector programmes, consistent with level 6.

## C) What is still missing to confidently claim level 7

Level 7 implies broad, competitive “competing products” delivery with rising demand and well-understood, scalable product-property improvements. While many components of decentralised trust networks already meet parts of that description, two maturity-limiting gaps repeatedly appear in the most technical evidence:

- **Interoperability/bridge risk is still a major systemic weakness**, with large, incident-grounded losses and recurring vulnerability classes; this indicates that cross-network trust fabrics still have “sharp edges” that constrain broad enterprise-grade adoption without heavy risk controls. [\[43\]](#)
- **Key management and recovery is still an active standardisation frontier**, as reflected by ongoing NIST work toward threshold-cryptography criteria—suggesting that reliable, standardisable operational security for keys (especially for institutions) is still being formalised. [\[22\]](#)
- **Regulatory constraints remain complex and evolving** (especially for value-transfer use cases), which can slow scaling and force asymmetric architectures (permissioned layers, governance “hooks,” or trusted operators) that partially undermine “fully decentralised” operation. [\[44\]](#)

### Sub-score breakdown (bundle) and aggregation approach

Because the ART is explicitly a **bundle** (ledger + smart contracts + identity + privacy + interoperability), the most defensible approach is an **average-weighted score** rather than taking the maximum.

- **Shared ledgers + smart-contract execution (core platforms): ~7** — Continuous mainnet upgrades and broad operational usage patterns indicate mature production technology. [45]
- **Layer-2 scaling + data availability: ~6** — Deployed rollups exist and are benchmarked, while data availability is still an active constraint. [46]
- **Decentralised identity + credentials interoperability: ~6** — Multiple “final” standards (W3C/IETF/OpenID, and ISO technical reports) exist, enabling real interoperable integration work. [47]
- **Privacy-preserving selective disclosure: ~5–6** — Mechanisms are mature enough for experimental evaluation and standardisation, but real-world deployment patterns and performance trade-offs still vary by mechanism and use case. [48]
- **Cross-network interoperability/bridges: ~4–5** — Well-studied, clearly valuable, but still disproportionately failure-prone, limiting “trust fabric” maturity. [43]
- **Key management & recovery infrastructure: ~5** — Strong progress and formalisation underway, but still in active standardisation and not uniformly solved for end users/institutions. [22]

**Aggregation:** Taking a conservative average across the above yields **~6**, reflecting that core ledgers and many standards are mature, while cross-chain security and operational key management remain the principal bottlenecks preventing a confident “7” for the entire ART bundle.

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[1] [13] [24] [30] [32] [43] <https://www.dpss.inesc-id.pt/~mpc/pubs/augusto2024.pdf>

<https://www.dpss.inesc-id.pt/~mpc/pubs/augusto2024.pdf>

[2] [40] [45]

[https://www.researchgate.net/publication/398691435\\_A\\_systematic\\_review\\_of\\_academic\\_literature\\_for\\_blockchain\\_application\\_in\\_government\\_and\\_public\\_service](https://www.researchgate.net/publication/398691435_A_systematic_review_of_academic_literature_for_blockchain_application_in_government_and_public_service)

[https://www.researchgate.net/publication/398691435\\_A\\_systematic\\_review\\_of\\_academic\\_literature\\_for\\_blockchain\\_application\\_in\\_government\\_and\\_public\\_service](https://www.researchgate.net/publication/398691435_A_systematic_review_of_academic_literature_for_blockchain_application_in_government_and_public_service)

[3] [11] [41] [47] <https://www.w3.org/TR/did-core/>

<https://www.w3.org/TR/did-core/>

[4] <https://ethereum.org/energy-consumption/>

<https://ethereum.org/energy-consumption/>

[5] [15] [33] [39] <https://ec.europa.eu/digital-building-blocks/sites/spaces/EBSI/pages/447687044/Home>

<https://ec.europa.eu/digital-building-blocks/sites/spaces/EBSI/pages/447687044/Home>

[6] [8] [36] [44] <https://eur-lex.europa.eu/eli/reg/2023/1114/oj/eng>

<https://eur-lex.europa.eu/eli/reg/2023/1114/oj/eng>

[7] [27] [29] [46] <https://www.mdpi.com/1999-5903/16/9/315>

<https://www.mdpi.com/1999-5903/16/9/315>

[9] [48] <https://www.sciencedirect.com/science/article/pii/S2214212624000929>

<https://www.sciencedirect.com/science/article/pii/S2214212624000929>

[10] [34] <https://digital-strategy.ec.europa.eu/en/policies/european-blockchain-services-infrastructure>

<https://digital-strategy.ec.europa.eu/en/policies/european-blockchain-services-infrastructure>

[12] [18] Verifiable Credentials Data Model v2.0

<https://www.w3.org/TR/vc-data-model-2.0/>

[14] <https://datatracker.ietf.org/doc/rfc9901/>

<https://datatracker.ietf.org/doc/rfc9901/>

[16] [21] [35] [https://openid.net/specs/openid-4-verifiable-presentations-1\\_0-final.html](https://openid.net/specs/openid-4-verifiable-presentations-1_0-final.html)

[https://openid.net/specs/openid-4-verifiable-presentations-1\\_0-final.html](https://openid.net/specs/openid-4-verifiable-presentations-1_0-final.html)

[17] [23] [37] [https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0.html)

[https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0.html)

[19] <https://www.iso.org/standard/81773.html>

<https://www.iso.org/standard/81773.html>

[20] <https://www.iso.org/standard/82208.html>

<https://www.iso.org/standard/82208.html>

[22] [25] [28] NISTIR 8214C 2pd: NIST First Call for Multi-Party Threshold Schemes

<https://nvlpubs.nist.gov/nistpubs/ir/2025/NIST.IR.8214C.2pd.pdf>

[26] [42] <https://link.springer.com/article/10.1007/s12243-023-00973-8>

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[31] <https://www.banque-france.fr/system/files/2023-09/20230928%20Mariana%20final%20report.pdf>

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[38] <https://www.fatf-gafi.org/en/publications/Fatfrecommendations/targeted-update-virtual-assets-vasps-2024.html>

<https://www.fatf-gafi.org/en/publications/Fatfrecommendations/targeted-update-virtual-assets-vasps-2024.html>

## ART 11.084 Platform Cooperatives & Fair Work

### Platform cooperatives and fair work evidence dossier and maturity score

#### ART extraction

#### Primary capability

- A worker- or user-owned digital marketplace “stack” (apps + payments + identity) that can run at scale while embedding **shared economic rights** (revenue share), **data rights**, and **decision rights** into day-to-day platform operations.
- A configurable “co-op operating system” for marketplaces that supports onboarding, credentialing, scheduling, dispute resolution, pooled benefits, and audited payouts, with governance embedded in the UI (proposals, voting, admin elections, rule/algorithm visibility).
- A verifiable, contestable rules layer (audit trails for ranking/fees/penalties; privacy controls) enabling members and regulators to check how decisions were applied.

#### Sub-components and variants

- **Marketplace core:** listings/ordering, matching, scheduling/dispatch, commissions/fees, refunds, disputes.
- **Co-op governance UI:** member proposals, voting, role/election workflows, policy/fee changes, meeting participation, delegation/anti-capture mechanics.
- **Algorithmic transparency & accountability:** clear explanations of ranking/matching, monitoring/penalties, appeal pathways, and logging for audit.
- **Identity, credentialing & compliance:** KYC/ID checks, role-based access control, portable credentials (skills, licences), fraud prevention.
- **Payments & audited payouts:** payout calculation, fee splits, payroll/tax artefacts (where relevant), traceability and reconciliation.
- **Plug-in architecture:** APIs for external services (payments, insurance, training, compliance) without giving plug-ins control over the “core relationship”.
- **Tamper-evident logs / provenance:** cryptographic attestations or verifiable records to support auditability (not necessarily blockchain).

#### What maturity indicators would constitute evidence

- Functioning **real-world deployments** of platform co-ops (not just proposals), including sustained operations, revenue flows, and member governance in practice.
- Existence of **reusable software modules** (open-source or commercial) that cover significant parts of the co-op OS bundle (dispatch/scheduling, pricing, payments, governance, auditability), with evidence of iterative releases and operational usage.

- Evidence that governance features and algorithmic rules are **legible and contestable** (documented processes, transparency tools, appeal or dispute resolution).
- **Regulatory harmonisation signals** for platform work and algorithmic management (e.g., workforce classification presumptions, human oversight and transparency duties).
- **Scaling signals:** multiple independent co-ops using the same stack, cross-region diffusion, and evidence of support ecosystems (public procurement, dedicated funding instruments, co-op federations).

#### **Evidence (10–20 recent, reliable sources)**

##### **1) Platform cooperatives and employment: an alternative for platform work**

Authors/Org: OECD[1]

Venue/type: Authoritative report (policy/market analysis with case studies)

Publication date: September 2023 (25 Sep 2023)

Link:

[https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment\\_8e8a1d61/3eab339f-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment_8e8a1d61/3eab339f-en.pdf)

Concrete finding/progress: Documents operational platform co-ops (e.g., [Entity](#)["organization", "Up & Go", "worker-owned cleaning platform nyc"][\[2\]](#)) with measurable economics (workers receive 95% of fees; average USD 22.25/hour, ~USD 5 above the local average) and identifies capital/legal constraints and supportive levers like social procurement and public–private collaboration. [\[2\]](#)

##### **2) Realizing decent work in the platform economy (ILC.113/Report V(1))**

Authors/Org: International Labour Organization[\[3\]](#) (International Labour Office)

Venue/type: Authoritative international report supporting standard-setting (law/practice survey + questionnaire)

Publication date: 2024 (first published 2024)

Link: <https://www.ilo.org/sites/default/files/2024-07/ILC113-V%281%29-%5BWORKQ-231121-002%5D-Web-EN.pdf>

Concrete finding/progress: Provides a structured, comparative view of platform-work regulation and explicitly frames transparency, monitoring, and employment-status determination as core issues—directly relevant to co-op OS requirements for compliant algorithmic management, data protection, and dispute processes across jurisdictions. [\[4\]](#)

##### **3) Reference document for the Meeting of experts on decent work in the platform economy (MEDWPE/2022)**

Authors/Org: International Labour Office (ILO)

Venue/type: Authoritative technical/reference document for an expert meeting

Publication date: 2022 (document code MEDWPE/2022)

Link: [https://wfuna.org/wp-content/uploads/2023/10/wcms\\_855048.pdf](https://wfuna.org/wp-content/uploads/2023/10/wcms_855048.pdf)

Concrete finding/progress: Defines platform typologies (in-situ vs online, P2P/B2B/B2P) and outlines governance and labour-market challenges that a co-op OS must handle (classification, control, and diverse operational models), strengthening feasibility arguments by clarifying the operational design space. [\[5\]](#)

##### **4) Digital platform work: the benefits of platform cooperativism (case study)**

Authors/Org: European Agency for Safety and Health at Work[\[6\]](#) (EU-OSHA)

Venue/type: Authoritative case study report (occupational safety and health focus)

Publication date: 2024 (© EU-OSHA 2024)

Link: [https://healthy-](https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism_EN.pdf)

[workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism\\_EN.pdf](https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism_EN.pdf)

Concrete finding/progress: Summarises concrete mechanisms by which platform co-ops can improve transparency and accountability (including algorithm scrutiny by worker-owners) but also flags financial sustainability as a recurring constraint—key for assessing both plausibility and near-term scaling limits of a co-op OS. [7]

#### **5) Platform workers: Council adopts new rules to improve their working conditions (press release)**

Authors/Org: Council of the European Union[8]

Venue/type: Authoritative government/institution communication (regulatory milestone)

Publication date: October 2024 (14 Oct 2024)

Link: [https://www.consilium.europa.eu/en/press/press-](https://www.consilium.europa.eu/en/press/press-releases/2024/10/14/platform-workers-council-adopts-new-rules-to-improve-their-working-conditions/)

[releases/2024/10/14/platform-workers-council-adopts-new-rules-to-improve-their-working-conditions/](https://www.consilium.europa.eu/en/press/press-releases/2024/10/14/platform-workers-council-adopts-new-rules-to-improve-their-working-conditions/)

Concrete finding/progress: States that EU rules will make algorithmic HR management more transparent, require qualified human monitoring, and grant workers rights to contest automated decisions—raising the compliance bar that co-op marketplaces must meet, and making “governance + explainability + contestability” product features more market-relevant. [9]

#### **6) Working group preparing the national implementation of the Platform work Directive**

Authors/Org: Finnish Government[10]

Venue/type: Government programme/project page (implementation readiness signal)

Publication date: January 2025 (29 Jan 2025)

Link: <https://valtioneuvosto.fi/en/projects-and-legislation/project?tunnus=TEM092%3A00%2F2024>

Concrete finding/progress: Explicitly lists the Directive’s aims (status determination, algorithmic transparency/fairness/human control, data protection) and provides a concrete transposition deadline (2 Dec 2026), evidencing that regulatory harmonisation is progressing but still incomplete—matching the ART’s stated constraint. [11]

#### **7) Addressing platform workers’ employment misclassification: legal frameworks, enforcement strategies and the new Platform Work Directive**

Authors/Org: European Labour Authority[12]

Venue/type: Authoritative study / enforcement-oriented report

Publication date: April 2025 (manuscript completed April 2025)

Link: [https://www.ela.europa.eu/sites/default/files/2025-06/UDW\\_Study\\_Misclassification\\_of\\_work\\_final\\_clean.pdf](https://www.ela.europa.eu/sites/default/files/2025-06/UDW_Study_Misclassification_of_work_final_clean.pdf)

Concrete finding/progress: Provides quantified scale context (28.3 million people in the EU estimated to source work through platforms in 2021; 5.5 million estimated under platform control, with likely misclassification) and shows concrete enforcement/tooling approaches (e.g., self-assessment tools, guidance, training) that a co-op OS could implement as built-in compliance workflows. [13]



## 8) Mapping Platform Cooperatives: Identities, Dimensions and Challenges (Working Paper No. 138/25)

Authors/Org: Euricse[14]; author Stefano Tortorici[15]

Venue/type: Research institute working paper (survey-based mapping)

Publication date: December 2025 (paper citation: 2025; file dated 2025-12)

Link: [https://euricse.eu/wp-content/uploads/2025/12/WP-138\\_Tortorici\\_2025.12.18\\_FV.pdf](https://euricse.eu/wp-content/uploads/2025/12/WP-138_Tortorici_2025.12.18_FV.pdf)

Concrete finding/progress: Presents an aggregate mapping based on an international survey (86 businesses across six continents; identifies 27 active platform cooperatives) and quantifies movement breadth via the Platform Cooperativism Consortium directory (643 initiatives in 53 countries as of Nov 2025), supporting plausibility while highlighting persistent legal/financial/governance/market barriers that impede “level-6/7” scaling. [16]

## 9) Silicon law of oligarchy: patterns of member participation in the decision-making of platform cooperatives

Authors/Org: Damion J. Bunders[17]

Venue/type: Peer-reviewed journal article (Socio-Economic Review, open access PDF)

Publication date: July 2024

Link: <https://research-portal.uu.nl/ws/files/236328782/mwad058.pdf>

Concrete finding/progress: Empirically shows that platform co-ops can still develop participation inequalities (“participation elites”), implying that UI voting tools alone do not solve capture/coercion risks—directly relevant to the ART’s constraint about “voting blocs” and the need for robust governance processes. [18]

## 10) Platform cooperatives and the dilemmas of platform worker-member participation

Authors/Org: Morshed Mannan[19]; Simon Pek[20]

Venue/type: Peer-reviewed journal article (New Technology, Work and Employment; repository PDF)

Publication date: July 2024 (journal vol. 39, no. 2)

Link:

<https://www.pure.ed.ac.uk/ws/portalfiles/portal/479663173/MannanMPekS2024NTWEPlatformCooperatives.pdf>

Concrete finding/progress: Based on interviews with 21 leaders/founders, identifies four structural features (multihoming, untethered work, scale pressures, low initial member investment) that shape participation and governance outcomes—useful design constraints for a co-op OS aiming to scale without undermining member control. [21]

## 11) The Transformative Potential of Platform Cooperativism: The Case of CoopCycle

Authors/Org: Vangelis Papadimitropoulos[22]; Haris Malamidis[23]

Venue/type: Peer-reviewed open-access journal article (tripleC 22(1))

Publication date: January 2024 (published 4 Jan 2024)

Link: <https://www.triple-c.at/index.php/tripleC/article/view/1418/1504>

Concrete finding/progress: Provides a detailed case study of CoopCycle[24] as a federated model that combines shared software infrastructure with workplace democracy, evidencing that a reusable platform layer can support multiple co-ops across countries (a partial realisation of “co-op OS”). [25]

## 12) CoopCycle administrator guide: platform architecture and operational capabilities

Authors/Org: CoopCycle (official documentation)

Venue/type: Open-source technical documentation (operator/admin manual)

Publication date: November 2024 (documentation updated in repo on 18 Nov 2024)

Link: <https://docs.coopcycle.org/en/admin/intro/>

Concrete finding/progress: Documents concrete “marketplace OS” functions—task-based dispatch, real-time courier tracking, configurable pricing logic, and role-specific interfaces—showing that core scheduling/pricing/logistics components are already implemented in production-used software. [26]

### 13) CoopCycle Data Analytics module documentation

Authors/Org: CoopCycle (official documentation)

Venue/type: Open-source technical documentation (operations analytics features)

Publication date: February 2024 (module created in repo on 23 Feb 2024; subsequent updates through 2025)

Link: <https://docs.coopcycle.org/en/admin/data-analytics/>

Concrete finding/progress: Describes dashboards for income/volume and shift-planning proxies (e.g., average income per hour vs labour cost), illustrating how an operational “co-op OS” can surface legible metrics to support collective decisions about staffing and profitability rather than opaque algorithmic control. [27]

### 14) CoopCycle Pricing configuration documentation

Authors/Org: CoopCycle (official documentation)

Venue/type: Open-source technical documentation (pricing rules + integrations)

Publication date: March 2025 (pricing docs updated in repo on 18 Mar 2025)

Link: <https://docs.coopcycle.org/en/admin/pricing/>

Concrete finding/progress: Shows configurable pricing rules and integration points (APIs/webhooks; payment processors such as Stripe/MercadoPago), supporting the ART claim that co-op marketplaces can remain compatible with mainstream payments while retaining co-op control of fee logic. [28]

### 15) Decidim: open source digital infrastructure for participatory democracy

Authors/Org: Decidim[29]; Eurocities[30] (presentation/report)

Venue/type: Technical/report deck (public-sector FLOSS governance infrastructure)

Publication date: 2024 (month not stated in file header)

Link: [https://living-in.eu/sites/default/files/files/decidim\\_2024\\_eurocities\\_nil\\_0.pdf](https://living-in.eu/sites/default/files/files/decidim_2024_eurocities_nil_0.pdf)

Concrete finding/progress: Provides scaling evidence for governance UX: reports Decidim use by “+450 democratic organisations” across “30 countries”, and emphasises values like transparency/traceability/integrity defined in code—highly relevant to embedding proposal/vote/audit functions into a co-op OS UI. [31]

### 16) Decentralized Identifiers (DIDs) v1.0 becomes a W3C Recommendation

Authors/Org: World Wide Web Consortium[32]

Venue/type: Standards body announcement (Recommendation milestone)

Publication date: July 2022 (19 Jul 2022)

Link: <https://www.w3.org/press-releases/2022/did-rec/>

Concrete finding/progress: Establishes a mature, privacy-respecting identity primitive that does not require a central registry; relevant to co-op OS needs for secure onboarding and consent-based data sharing without ceding control to a dominant platform. [33]

**17) Verifiable Credentials Data Model v1.1 (W3C Recommendation)**

Authors/Org: W3C (Recommendation)

Venue/type: Standards specification (cryptographically verifiable credentials)

Publication date: March 2022 (03 Mar 2022)

Link: <https://www.w3.org/TR/vc-data-model-1.1/>

Concrete finding/progress: Specifies interoperable, cryptographically secure, machine-verifiable credentials—directly enabling the ART’s “credentialing” requirement (skills/licences/role proofs) and supporting tamper-evident auditability for member entitlements and access rules. [34]

**18) Artificial Intelligence Risk Management Framework (AI RMF 1.0)**

Authors/Org: National Institute of Standards and Technology[35]

Venue/type: Government standards/roadmap framework

Publication date: January 2023

Link: <https://nvlpubs.nist.gov/nistpubs/ai/nist.ai.100-1.pdf>

Concrete finding/progress: Provides a widely referenced governance framework for trustworthy AI (risk identification, measurement, monitoring), supporting the feasibility of “plain-language dashboards” and auditable governance around ranking/matching/penalty algorithms in marketplace platforms. [36]

**19) IRIS Special 2023-2: Algorithmic transparency and accountability of digital services**

Authors/Org: Council of Europe[37]; European Audiovisual Observatory[38]

Venue/type: Authoritative report (regulatory/standards landscape synthesis)

Publication date: 2023 (issue 2023-2; month not specified)

Link: <https://rm.coe.int/iris-special-2023-02en/1680aeda48>

Concrete finding/progress: Frames the EU Digital Services Act (entered into force in 2022; fully applicable Feb 2024) as a “turning point” for platform transparency obligations—relevant to the ART’s claim that marketplace power depends on opaque ranking/access rules and that transparency requirements are strengthening. [39]

**20) Platform workers case study and scaling challenge evidence (Drivers Cooperative)**

Authors/Org: Internet Policy Review; author Stefano Tortorici[15] (case study paper)

Venue/type: Peer-reviewed journal analysis (case study; Internet Policy Review)

Publication date: 2026 (within the last 4 years; month not shown in snippet)

Link: <https://policyreview.info/articles/analysis/drivers-cooperative-new-york-city>

Concrete finding/progress: Provides a detailed case study of The Drivers Cooperative[40] showing that scaling pressures can fracture the relationship between co-op membership and platform infrastructure—directly informing maturity assessment (operational viability exists, but scaling and governance/tech alignment remain hard). [41]

**Maturity score (1–7) and reasoning****Final maturity score**

**Maturity score: 4 (Proof of Concept).**

**Evidence-to-rubric mapping**

The evidence rules out levels 1–3 because multiple sources document **operational, functioning platform cooperatives and enabling software components in real use**, not just theory or lab prototypes. The OECD[1] report describes live platform co-op operations with measurable payout structures and real funding pathways (e.g., Up & Go paying 95% of fees to worker-owners and sustaining a specific maintenance reinvestment model). [42] The CoopCycle[24] documentation demonstrates implemented, deployable modules for dispatch/scheduling, pricing rules, payments integration, and analytics—core components of a marketplace OS. [43]

Score **4** (PoC) is justified because the ecosystem shows **functional prototypes meeting real operational requirements** in specific verticals (delivery, cleaning, ride-hailing) and because modular building blocks for governance and identity are mature enough to integrate (e.g., DID/VC standards). [44] Regulatory developments are also making transparency/human oversight requirements more explicit, increasing the maturity relevance of governance-embedded UI and audit tools (EU platform work rules and supporting enforcement studies). [45]

However, the evidence still falls short of levels **5–7**. The next higher level (5) would require clear signs that **multiple well-capitalised actors** are racing to industrialise a broadly reusable co-op OS (or that a production prototype is close to mass launch with major investment for scaling). Instead, multiple sources emphasise persistent constraints: access to capital without diluting member control, sustainability limits versus VC-subsidised incumbents, and governance participation/capture challenges (participation elites, scale-driven tensions). [46] Empirical mapping suggests breadth of initiatives globally but does not demonstrate mass-market standardisation of a single modular stack across sectors at scale. [47]

#### Sub-score breakdown and aggregation

This ART is a **bundle** whose sub-components differ in maturity; the overall score is therefore an **average constrained by the least mature “integration-to-market” layer**.

- **Marketplace operations stack (dispatch/scheduling/pricing/payments/analytics)** → **4** → Supported by CoopCycle’s implemented admin, pricing, and analytics modules and ongoing updates. [48]
- **Co-op governance processes and participation at scale** → **3–4** → Governance is feasible but remains a blocking risk: empirical work finds participation elites and scale/participation tensions that a co-op OS must actively mitigate. [49]
- **Governance UI tooling (proposal/vote/traceability platforms)** → **6** → Decidim shows large-scale adoption (+450 organisations across 30 countries) and code-embedded traceability values, indicating mature components that could be adapted into co-op marketplaces. [31]
- **Identity & credentialing primitives** → **6–7** → DID and VC standards are mature web standards and enable privacy-respecting, verifiable onboarding/credentialing foundations. [44]
- **Algorithmic transparency/accountability and compliance drivers** → **5** → EU policy direction and enforcement tooling are crystallising requirements (human oversight,

contestability, misclassification enforcement), pushing productisation but still mid-transition for harmonised implementation. [50]

**Aggregation logic:** Although some sub-components (identity and governance tooling) are already high maturity, the ART's *distinctive promise* is an **integrated, modular co-op operating system for marketplaces** that can be deployed widely while preserving member control and resisting capture. The core integration layer remains at “proven in operational PoCs, not yet industrialised to broad cross-sector scaling,” so the overall maturity is best represented as **4** rather than being pulled upward by mature enabling standards alone. [51]

[1] [18] [35] [49] <https://research-portal.uu.nl/ws/files/236328782/mwad058.pdf>

<https://research-portal.uu.nl/ws/files/236328782/mwad058.pdf>

[2] [30] [37] [42] [51]

[https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment\\_8e8a1d61/3eab339f-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment_8e8a1d61/3eab339f-en.pdf)

[https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment\\_8e8a1d61/3eab339f-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/09/platform-cooperatives-and-employment_8e8a1d61/3eab339f-en.pdf)

[3] [5] [19] [23] [https://wfuna.org/wp-content/uploads/2023/10/wcms\\_855048.pdf](https://wfuna.org/wp-content/uploads/2023/10/wcms_855048.pdf)

[https://wfuna.org/wp-content/uploads/2023/10/wcms\\_855048.pdf](https://wfuna.org/wp-content/uploads/2023/10/wcms_855048.pdf)

[4] <https://www.ilo.org/sites/default/files/2024-07/ILC113-V%281%29-%5BWORKQ-231121-002%5D-Web-EN.pdf>

<https://www.ilo.org/sites/default/files/2024-07/ILC113-V%281%29-%5BWORKQ-231121-002%5D-Web-EN.pdf>

[6] [12] [15] [33] [44] <https://www.w3.org/press-releases/2022/did-rec/>

<https://www.w3.org/press-releases/2022/did-rec/>

[7] [24] [32] [46] [https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism\\_EN.pdf](https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism_EN.pdf)

[https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism\\_EN.pdf](https://healthy-workplaces.osha.europa.eu/sites/hwc/files/hwc/publication/Digital-platform-work-benefits-platform-cooperativism_EN.pdf)

[8] [28] <https://docs.coopcycle.org/en/admin/pricing/>

<https://docs.coopcycle.org/en/admin/pricing/>

[9] [10] [29] [45] [50] <https://www.consilium.europa.eu/en/press/press-releases/2024/10/14/platform-workers-council-adopts-new-rules-to-improve-their-working-conditions/>

<https://www.consilium.europa.eu/en/press/press-releases/2024/10/14/platform-workers-council-adopts-new-rules-to-improve-their-working-conditions/>

[11] <https://valtioneuvosto.fi/en/projects-and-legislation/project?tunnus=TEM092%3A00%2F2024>

<https://valtioneuvosto.fi/en/projects-and-legislation/project?tunnus=TEM092%3A00%2F2024>

[13] [https://www.ela.europa.eu/sites/default/files/2025-06/UDW\\_Study\\_Misclassification\\_of\\_work\\_final\\_clean.pdf](https://www.ela.europa.eu/sites/default/files/2025-06/UDW_Study_Misclassification_of_work_final_clean.pdf)

[https://www.ela.europa.eu/sites/default/files/2025-06/UDW\\_Study\\_Misclassification\\_of\\_work\\_final\\_clean.pdf](https://www.ela.europa.eu/sites/default/files/2025-06/UDW_Study_Misclassification_of_work_final_clean.pdf)

[14] [41] <https://policyreview.info/articles/analysis/drivers-cooperative-new-york-city>

<https://policyreview.info/articles/analysis/drivers-cooperative-new-york-city>

[16] [https://euricse.eu/wp-content/uploads/2025/12/WP-138\\_Tortorici\\_2025.12.18\\_FV.pdf](https://euricse.eu/wp-content/uploads/2025/12/WP-138_Tortorici_2025.12.18_FV.pdf)

[https://euricse.eu/wp-content/uploads/2025/12/WP-138\\_Tortorici\\_2025.12.18\\_FV.pdf](https://euricse.eu/wp-content/uploads/2025/12/WP-138_Tortorici_2025.12.18_FV.pdf)

[17] [47] [https://github.com/coopcycle/coopcycle-docs/commits/master/docs/\\_admin/intro.md](https://github.com/coopcycle/coopcycle-docs/commits/master/docs/_admin/intro.md)

[https://github.com/coopcycle/coopcycle-docs/commits/master/docs/\\_admin/intro.md](https://github.com/coopcycle/coopcycle-docs/commits/master/docs/_admin/intro.md)

[20] [34] <https://www.w3.org/TR/vc-data-model-1.1/>

<https://www.w3.org/TR/vc-data-model-1.1/>

[21] [40]

<https://www.pure.ed.ac.uk/ws/portalfiles/portal/479663173/MannanMPekS2024NTWEPlatformCooperatives.pdf>

<https://www.pure.ed.ac.uk/ws/portalfiles/portal/479663173/MannanMPekS2024NTWEPlatformCooperatives.pdf>

[22] [26] [43] [48] <https://docs.coopcycle.org/en/admin/intro/>

<https://docs.coopcycle.org/en/admin/intro/>

[25] <https://www.triple-c.at/index.php/tripleC/article/view/1418/1504>

<https://www.triple-c.at/index.php/tripleC/article/view/1418/1504>

[27] <https://docs.coopcycle.org/en/admin/data-analytics/>

<https://docs.coopcycle.org/en/admin/data-analytics/>

[31] [https://living-in.eu/sites/default/files/files/decidim\\_2024\\_eurocities\\_nil\\_0.pdf](https://living-in.eu/sites/default/files/files/decidim_2024_eurocities_nil_0.pdf)

[https://living-in.eu/sites/default/files/files/decidim\\_2024\\_eurocities\\_nil\\_0.pdf](https://living-in.eu/sites/default/files/files/decidim_2024_eurocities_nil_0.pdf)

[36] [38] <https://nvlpubs.nist.gov/nistpubs/ai/nist.ai.100-1.pdf>

<https://nvlpubs.nist.gov/nistpubs/ai/nist.ai.100-1.pdf>

[39] <https://rm.coe.int/iris-special-2023-02en/1680aeda48>



<https://rm.coe.int/iris-special-2023-02en/1680aeda48>

## ART 11.085 Open Data Sharing Marketplaces

### ART extraction

- **A) Primary capability**
- Create repeatable, scalable cross-organisation data exchange via marketplace-style “listings” (discoverability + pricing/terms + onboarding) rather than bespoke integrations.
- Enforce **programmable permissions** (who/what/purpose/time), plus logging for audit and billing, so data sharing becomes a governed, automatable workflow.
- Enable **data access without raw-data handoffs** where needed (e.g., “compute-to-data”, secure processing environments, privacy-preserving analytics).
- **B) Key sub-components / variants**
- **Data cataloguing & discovery:** machine-readable dataset descriptions, metadata, schema, and listing mechanisms (including private/public exchanges).
- **Identity, authentication, and authorisation:** participant onboarding, roles, cross-domain trust signals, and policy decision points.
- **Usage-control policies:** purpose limits, duration, onward-sharing constraints; machine-readable “data contracts” and negotiable agreements.
- **Secure delivery patterns:** zero-copy sharing, linked datasets, controlled exports, API-mediated access, and event-driven notifications.
- **Compute-to-data / privacy-enhancing tech:** secure processing environments, confidential computing/TEEs, federated analytics, differential privacy, and other safeguards.
- **Interoperability layer:** common protocols/specs, connector ecosystems, compliance test suites, and (ideally) certification regimes.
- **Governance & legal layer:** standard terms/templates, dispute mechanisms, registries/oversight (especially for neutral intermediaries), provenance/traceability expectations.
- **Commercial settlement:** subscription, pay-per-query, revenue share, usage metering, and billing integration.
- **C) Maturity indicators that would count as evidence**
- **Shipping “marketplace/exchange” products** with self-service listings, role-based controls, usage metrics, and operational audit logging.
- **Large-scale operational adoption** (e.g., thousands of enterprises, multi-vendor support) rather than isolated pilots.
- **Standardised interop protocols** that define catalogue/contract negotiation/access workflows, plus published compliance tooling (e.g., TCKs).
- **Multiple independent connector implementations** that demonstrably interoperate (test output, compatibility claims, deployments).
- **Documented production deployments** in cross-organisation ecosystems (e.g., sector data spaces), not only lab PoCs.

- **Institutional/legal scaffolding** that makes “trusted intermediaries” and governed sharing enforceable (registries, guidance, applicable regulations).
- **Demonstrated safeguards** against misuse (privacy-by-design guidance, concrete engineering patterns to reduce re-identification risk, secure execution approaches).

## 2. Evidence (10–20 recent, reliable sources)

### Shipping platforms that already look like “data exchanges”

#### 1) Delta Sharing: An Open Protocol for Cross-Platform Data Sharing

- Authors/organisation: Krishna Puttaswamy[1] et al. (Databricks[2])
- Venue/type: Peer-reviewed paper (PVLDB)
- Publication date: **2025** (Vol. 18(12))
- Link: <https://www.vldb.org/pvldb/vol18/p5197-puttaswamy.pdf>
- Reports an open, HTTP-API-based protocol (built on open formats) for secure “live” sharing across heterogeneous systems and describes a **large-scale study of production data-sharing workloads**, directly evidencing feasibility and operational scaling; it also reports **enterprise adoption at multi-thousand scale** (as of the paper), which is unusually strong maturity evidence for an “open sharing” layer. [3]

#### 2) Share data using the Delta Sharing open sharing protocol (for providers)

- Authors/organisation: Databricks documentation
- Venue/type: Vendor technical doc
- Publication date: **March 2025** (page “Last updated”)
- Link: <https://docs.databricks.com/aws/en/delta-sharing/share-data-open>
- Documents operational mechanics for cross-platform sharing (recipient objects, shares, grants) and explicit authentication options (bearer tokens or **OIDC federation**), showing that “programmable permissions + identity integration” is implemented as product functionality rather than a conceptual aspiration. [4]

#### 3) Introduction to BigQuery sharing (formerly Analytics Hub)

- Authors/organisation: Google Cloud[5] documentation
- Venue/type: Vendor technical doc
- Publication date: **February 2026** (page “Last updated”)
- Link: <https://docs.cloud.google.com/bigquery/docs/analytics-hub-introduction>
- Describes a publish/subscribe **data exchange platform** with **listings**, granular IAM roles, usage metrics, and “zero-copy”/in-place sharing via linked datasets—core marketplace mechanics (discover → subscribe → govern → measure) aligned with the ART’s “interoperable exchange” form factor. [6]

#### 4) Document history for AWS Data Exchange – AWS Data Exchange User Guide

- Authors/organisation: Amazon Web Services[7] documentation
- Venue/type: Vendor technical doc (change log / release history)
- Publication date: **October 2024** (latest dated entry shown on the page)
- Link: <https://docs.aws.amazon.com/data-exchange/latest/userguide/doc-history.html>
- Provides dated evidence of platform evolution toward automated, multi-party sharing patterns: e.g., **data grants** (to share without becoming a Marketplace seller), provider

notifications tied to schema/data changes, and explicit discussion of logging changes (CloudTrail), mapping onto “repeatable secure sharing + auditability” maturity indicators. [8]

#### 5) **Sep 30, 2025: Declarative Sharing (Preview)**

- Authors/organisation: Snowflake[9] documentation
- Venue/type: Vendor technical doc (release notes)
- Publication date: **September 2025**
- Link: <https://docs.snowflake.com/en/release-notes/2025/other/2025-09-30-declarative-sharing>
- Shows continued productisation of marketplace-style sharing for “data products” (including a declarative/YAML development flow and version control), which is concrete evidence that major capitalised vendors are still investing in automation, packaging, and developer-facing interfaces for scalable sharing. [10]

### **Interoperability protocols and connector ecosystems**

#### 6) **IDSA Statement: Making the Dataspace Protocol an international standard**

- Authors/organisation: International Data Spaces Association[11]
- Venue/type: Standards/consortium report (authoritative statement/roadmap)
- Publication date: **July 2024**
- Link: [https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Statement\\_Making-the-Dataspace-Protocol-an-international-standard.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Statement_Making-the-Dataspace-Protocol-an-international-standard.pdf)
- Describes the Dataspace Protocol as an orchestrating specification for requesting catalogues, negotiating contracts, and managing transfer, and lays out a concrete standardisation path (via Eclipse process to ISO/IEC), which is direct evidence that the “interoperable exchange” layer is being formalised rather than remaining fragmented. [12]

#### 7) **Data Connector Report 84 | No. 16 (September 2024)**

- Authors/organisation: International Data Spaces Association
- Venue/type: Consortium technical report
- Publication date: **September 2024**
- Link: [https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Connector-Report-84-No-16-September-2024-4.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Connector-Report-84-No-16-September-2024-4.pdf)
- Summarises connector typologies and explicitly positions the **Dataspace Protocol “stable version” milestone (March 2024)** plus the emerging **Technology Compatibility Kit (TCK)** concept as the mechanism to validate interoperability—evidence of maturing interoperability governance beyond one-off integrations. [13]

#### 8) **IDSA Data Space Connector Report**

- Authors/organisation: International Data Spaces Association
- Venue/type: Consortium technical registry/report (web)
- Publication date: **2025–2026** (connector entries include “Last Update” timestamps; page states protocol release timing)
- Link: <https://internationaldataspaces.org/idsa-data-space-connector-report/>
- States that Dataspace Protocol **2025-1 was published as a final release (1.0.0) in July 2025** and that the **Dataspace Protocol TCK** is the official verification suite; it also lists

multiple connectors with dated compliance artefacts (test output/config), indicating a transition from “spec-only” to measurable interoperability expectations and implementer ecosystem. [14]

### **Governance, legal, and institutional scaffolding for “marketplaces at scale”**

#### **9) European Data Governance Act**

- Authors/organisation: European Commission[15] (policy page)
- Venue/type: Authoritative government/legislative overview
- Publication date: **October 2024** (page “Last update”; includes legal timeline)
- Link: <https://digital-strategy.ec.europa.eu/en/policies/data-governance-act>
- Establishes the legal basis for “trusted data sharing” infrastructure in the European Union[16] and explicitly frames the Act as supporting Common European Data Spaces; critically for maturity assessment, it provides concrete dates (entered into force June 2022; applicable since September 2023), signalling that governance is not hypothetical. [17]

#### **10) New practical guide to the Data Governance Act**

- Authors/organisation: European Commission
- Venue/type: Government guidance/report
- Publication date: **September 2024**
- Link: <https://digital-strategy.ec.europa.eu/en/library/new-practical-guide-data-governance-act>
- Reports that DGA implementation had become “tangible” one year into application and cites counts of notified organisations (data intermediation services) as real-world uptake signals; this supports plausibility that neutral intermediaries/marketplaces can exist under enforceable constraints rather than bespoke trust. [18]

#### **11) EU register of data intermediation services**

- Authors/organisation: European Commission
- Venue/type: Government registry (operational evidence)
- Publication date: **January 2026** (page date)
- Link: <https://digital-strategy.ec.europa.eu/en/policies/data-intermediary-services>
- Provides a live register of notified data intermediation service providers by Member State, which is unusually concrete “market formation” evidence (named entities, jurisdictions) for the ART’s governance-and-trust feasibility constraints. [19]

#### **12) Second staff working document on data spaces**

- Authors/organisation: European Commission
- Venue/type: Government roadmap/status report
- Publication date: **January 2024**
- Link: <https://digital-strategy.ec.europa.eu/en/library/second-staff-working-document-data-spaces>
- Summarises progress milestones (including the DGA entering into application and updated status of support actions such as DSSC and open-source middleware), serving as “programme-level” evidence that multi-sector data sharing marketplaces/spaces are being operationalised across domains rather than remaining isolated pilots. [20]

### 13) **Staff Working Document on Common European Data Spaces (SWD(2022) 45 final)**

- Authors/organisation: European Commission (staff working document; distributed here via Council document service)
- Venue/type: Authoritative government roadmap/report
- Publication date: **February 2022**
- Link: <https://data.consilium.europa.eu/doc/document/ST-6532-2022-INIT/en/pdf>
- Defines what “common European data spaces” include—tools/services for pooling/sharing by an open number of organisations, governance structures, and improved interoperability/quality—and explicitly notes voluntary reuse that may be compensated or free, matching the ART’s incentive/marketplace framing. [21]

### **Safeguards, compute-to-data, and misuse prevention**

### 14) **Engineering Personal Data Protection in EU Data Spaces**

- Authors/organisation: ENISA[22]
- Venue/type: Government/agency technical report
- Publication date: **January 2024**
- Link: <https://www.enisa.europa.eu/publications/engineering-personal-data-protection-in-eu-data-spaces>
- Targets privacy engineering and design principles for data spaces, explicitly grounded in the DGA context; it is directly relevant to the ART’s feasibility bottlenecks (re-identification risk, safeguards, and compliance-by-design) and provides institutional evidence that security/privacy requirements are being translated into engineering guidance. [23]

### 15) **Approach to data spaces from a data protection law perspective**

- Authors/organisation: Agencia Española de Protección de Datos[24] (AEPD)
- Venue/type: National regulator guidance/technical-legal report
- Publication date: **October 2022**
- Link: <https://www.aepd.es/documento/approach-to-data-spaces-from-gdpr-perspective.pdf>
- Treats “access” as potentially occurring without data transmission and discusses privacy-by-design patterns (including compute-to-data and secure processing environments) plus risk management topics like re-identification—directly addressing the ART’s safeguard feasibility requirements for scaling marketplaces beyond high-trust relationships. [25]

### 16) **NIST IR 8320D (Draft): Hardware-Enabled Security – Hardware-Based Confidential Computing**

- Authors/organisation: National Institute of Standards and Technology[26]
- Venue/type: National standards institute technical report (prototype/PoC guidance)
- Publication date: **February 2023** (document history)
- Link: <https://csrc.nist.gov/pubs/ir/8320/d/ipd>
- Describes a proof-of-concept prototype using hardware-based confidential computing/TEEs to protect sensitive material “in use”, providing concrete engineering evidence for the “analyse in place”/compute-to-data security premise when data must not leave an owner-controlled environment. [27]

### 17) **An Introduction to the Gaia-X Trust Framework (v1.6)**

- Authors/organisation: Gaia-X[28]

- Venue/type: Standards/consortium technical specification (framework)
- Publication date: **March 2024**
- Link: [https://gaia-x.eu/wp-content/uploads/2024/05/An-Introduction-to-the-Gaia-X-Trust-Framework\\_2024-V4.pdf](https://gaia-x.eu/wp-content/uploads/2024/05/An-Introduction-to-the-Gaia-X-Trust-Framework_2024-V4.pdf)
- Specifies machine-actionable approaches to trust and interoperability (e.g., linked-data models, cryptographic claims, provenance of claims, and automated compliance intent), directly relevant to making marketplace permissions, provenance, and policy enforcement “programmable” rather than manual. [29]

### Academic and research evidence for machine-readable policies and contracting

#### 18) Interoperable and Continuous Usage Control Enforcement in Dataspaces

- Authors/organisation: Ines Akaichi[30] et al.
- Venue/type: Peer-reviewed workshop paper (CEUR-WS; ESWC workshop “Semantics in Dataspaces”)
- Publication date: **May 2024**
- Link: <https://ceur-ws.org/Vol-3705/paper10.pdf>
- Proposes and validates a framework for **continuous, interoperable usage-control enforcement** (including extending ODRL for deterministic time-dependent constraints) and reports validation in a logistics use case—directly supporting feasibility of “programmable permissions” beyond static access control. [31]

#### 19) Data Sharing Negotiation and Contracting

- Authors/organisation: Semih Yumusak[32] et al.
- Venue/type: Demo paper (CEUR-WS; ISWC 2024 Posters/Demos/Industry)
- Publication date: **November 2024**
- Link: <https://ceur-ws.org/Vol-3828/paper39.pdf>
- Presents a negotiation/contracting system (“UPCAST”) designed as a **plugin for data marketplaces**, referencing IDSA negotiation protocol concepts and using ODRL + DPV to form machine- and human-readable contracts—direct evidence that automated “negotiate terms → settle agreement” workflows are being engineered for marketplace contexts. [33]

#### 20) The Technology Landscape of Data Spaces (Working Paper)

- Authors/organisation: Sitra[34] (with contributions from Futurice[35])
- Venue/type: Authoritative technical landscape report (working paper)
- Publication date: **October 2023**
- Link: <https://www.sitra.fi/wp-content/uploads/2023/10/sitra-technology-landscape-of-data-spaces.pdf>
- Surveys the evolving implementation landscape (existing enterprise tooling, data space initiatives, and commercial offerings) and explicitly highlights that interoperability across solutions remains a challenge—useful maturity evidence that the marketplace concept is real and progressing, but still constrained by cross-ecosystem convergence work. [36]

### 3. Maturity score (1–7) and reasoning

- **A) Final maturity score: 6**
- **B) Evidence-to-rubric mapping**
- **What rules out levels 1–4 (theory/lab to PoC only)**  
Multiple major vendors operate production-grade “exchange” capabilities with concrete,



implementable mechanics—listings, publish/subscribe models, role-based access control, and usage measurement—updated as recently as **February 2026** in public technical documentation. [37]

On the “open protocol” axis, a peer-reviewed database-systems venue reports not only protocol design but also **large-scale production workload analysis** and multi-thousand enterprise adoption for an open sharing protocol, which is materially beyond PoC. [3]

On the governance axis, the EU has moved past proposal into enforceable infrastructure: the Data Governance Act is in force and applicable, implementation guidance has been published, and a live EU register lists notified data intermediation services—showing institutionalisation of “trusted intermediaries” rather than one-off contracts only. [38]

- **Why level 6 fits better than level 5**

Level 5 is characterised by “production prototype post-PoC” competition; however, evidence here shows **operational delivery** of marketplace and sharing services (not just pilots) across multiple independent platforms, plus ongoing feature releases and documentation change histories indicating sustained product evolution. [39]

In addition, interoperability is shifting from informal alignment to measurable conformance: the Dataspace Protocol standardisation path is documented, and the connector ecosystem is being measured via a test suite (TCK) with published test outputs/configurations for multiple implementations. [40]

- **What is still missing to justify level 7**

Level 7 would be easier to justify with stronger, comparable evidence of **rapidly rising customer demand and competitive growth across multiple interoperable marketplaces**, with clear multi-provider substitutability and broad cross-ecosystem interoperability “out of the box.” The current evidence strongly supports shipped products and accelerating standardisation, but also explicitly flags that interoperability across solutions remains a key challenge—suggesting the market is still converging on common, truly exchange-like interoperation rather than fully realising it at internet-protocol scale. [41]

- **C) Sub-scores (bundle) and aggregation**

- **Cloud/platform-native data exchanges & marketplaces → 6–7**

Evidence: production “exchange” patterns (listings, publish/subscribe, zero-copy/in-place sharing, usage metrics, ongoing releases). [42]

- **Open cross-platform sharing protocols → ~6**

Evidence: peer-reviewed protocol + production workload study and high adoption signal; complemented by vendor documentation of operational authentication and governance workflows. [43]

- **Interoperable multi-party “data spaces” with conformance testing → ~5–6**

Evidence: documented standardisation pathway; stable protocol releases and an emerging compliance regime (TCK) with multiple connector implementations publishing compliance artefacts; still converging ecosystem rather than universally commoditised. [44]

- **Safeguards enabling compute-to-data and misuse prevention → ~4–6 (heterogeneous)**

Evidence: regulator and cybersecurity-agency engineering guidance for data spaces, plus standards-institute confidential computing PoC blueprints; however, safeguards’ “market maturity” varies by technique and deployment context. [45]

- **Aggregation to one score**

Because the ART’s core functionality (marketplace-style data exchange with governance +

repeatability) is already delivered in multiple production systems, while the “interoperable exchange across vendors/consortia” layer sits slightly behind but is rapidly standardising, the overall maturity is best represented as **6** (shipping and expanding), not merely 5 (production prototypes) and not yet clearly 7 (fully mature, demand-led growth across interoperable competing exchanges). [46]

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[https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Connector-Report-84-No-16-September-2024-4.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Connector-Report-84-No-16-September-2024-4.pdf)

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<https://ceur-ws.org/Vol-3828/paper39.pdf>

## ART 11.086 Secure & Resilient Social Platforms

### ART extraction

- **Primary capability (what the ART claims)**

- Secure, resilient social platforms that keep user content and group coordination available under outages, blocking, and adversarial conditions, while reducing default data exposure (content + metadata).
- Interoperable “network-of-networks” behaviour (not walled gardens): portable social graph / content archives / reputation signals across compatible services; organisations can self-host nodes or buy hosted nodes without interoperability loss.
- “Graceful degradation” under disruption: multi-source fetch / mirroring, local queueing for later delivery, and multi-relay routing (where permitted), so coordination continues even with degraded connectivity.
- **Key sub-components / sub-threads**
- **Interoperable decentralised identity:** decentralised identifiers (DIDs), verifiable credentials (VCs), and selective disclosure / attribute proofs so users can prove properties without revealing real-world identity by default.
- **Security-by-default messaging + group spaces:** end-to-end encryption (E2EE) with scalable group key management; usable key management, recovery, and safety prompts.
- **Federated / multi-node architectures:** replication across independently operated servers; optional replication to user devices; removal of single points of failure.
- **Censorship / outage resilience mechanisms:** alternate relays, store-and-forward patterns, local-first replication, and fallbacks that tolerate intermittent routing failures.
- **Transparent moderation + governance controls:** auditable policy change, interoperable moderation signals, and integration APIs.
- **Operational scaling and cost discipline:** demonstrable deployments with measurable user uptake, support, security incident response, and sustainable hosting models.
- **What maturity indicators would count as strong evidence**
- **Standards maturity:** core primitives standardised (e.g., group E2EE) and identity standards at Recommendation/Proposed Standard level; interoperable test suites and multiple independent implementations.
- **Security validation:** formal analyses, audit trails, vulnerability handling processes, and coordinated fixes across implementations (demonstrating real operational maturity rather than toy prototypes).
- **Deployment proof:** real-world multi-organisation federation, government/enterprise deployments, repeatable infrastructure packaging (e.g., Kubernetes/Helm), and documented procurement/mandates.
- **Ecosystem competition:** multiple independent providers implementing compatible protocols (federation), plus evidence users can switch services or services can interoperate without data lock-in.
- **Resilience trade-off metrics:** measured overheads (bandwidth/storage/replication) and engineering work to manage those costs while maintaining availability and privacy-by-default.

## 2. Evidence (10–20 recent, reliable sources)

## Security and identity-by-default building blocks

### 1) The Messaging Layer Security (MLS) Protocol (RFC 9420)

**Org:** Internet Engineering Task Force[1] (IETF)

**Type:** Standards-track RFC (Proposed Standard)

**Date:** Jul 2023

**Link:** <https://datatracker.ietf.org/doc/rfc9420/>

**Why it matters:** Defines efficient asynchronous group key establishment with forward secrecy and post-compromise security for groups “ranging from two to thousands,” directly underpinning secure-by-default private groups at scale (a core ART requirement). [2]

### 2) Decentralized Identifiers (DIDs) v1.0

**Org:** World Wide Web Consortium[3] (W3C)

**Type:** Web standard (W3C Recommendation)

**Date:** Jul 2022

**Link:** <https://www.w3.org/TR/did-core/>

**Why it matters:** Standardises decentralised identifiers that can be decoupled from central identity providers/registries, enabling verifiable identity primitives without mandatory real-world disclosure (ART identity pillar). [4]

### 3) Verifiable Credentials Data Model v2.0

**Org:** W3C

**Type:** Web standard (W3C Recommendation)

**Date:** May 2025

**Link:** <https://www.w3.org/TR/vc-data-model-2.0/>

**Why it matters:** Provides a standard, extensible model for cryptographically verifiable credentials, supporting portable proofs/claims across services—one route to portable “reputation/attributes” across interoperable social systems. [5]

### 4) Verifiable Credential Data Integrity 1.0

**Org:** W3C

**Type:** Web standard (W3C Recommendation)

**Date:** May 2025

**Link:** <https://www.w3.org/TR/vc-data-integrity/>

**Why it matters:** Specifies mechanisms (digital signatures/proofs) to ensure authenticity/integrity of VC-like documents, enabling cross-service verification while minimising trust in any single platform operator. [6]

### 5) Bitstring Status List v1.0

**Org:** W3C

**Type:** Web standard (W3C Recommendation)

**Date:** May 2025

**Link:** <https://www.w3.org/TR/vc-bitstring-status-list/>

**Why it matters:** Specifies a privacy-preserving and space-efficient way to publish credential status (revocation/suspension) using bitstrings—important for “selective proof” systems that must avoid turning credential checks into trackable metadata leaks. [7]

### 6) BBS Cryptosuite v2023

**Org:** W3C

**Type:** Standards-track Working Draft

**Date:** May 2023

**Link:** <https://www.w3.org/TR/2023/WD-vc-di-bbs-20230524/>

**Why it matters:** Defines selective-disclosure proofs using BBS signatures, explicitly enabling zero-knowledge proof disclosures; it also states it is “not fit for production deployment,” which is crucial maturity evidence: the capability is plausible but still stabilising for wide rollout. [8]

#### **Deployment and operational maturity evidence**

##### **7) Practically-exploitable Cryptographic Vulnerabilities in Matrix (IACR ePrint 2023/485)**

**Authors:** Martin R. Albrecht[9] et al.

**Type:** Cryptology ePrint (preprint; “published elsewhere” per record)

**Date:** Apr 2023 (received 4 Apr; approved 5 Apr 2023)

**Link:** <https://eprint.iacr.org/2023/485>

**Why it matters:** Reports vulnerabilities across Matrix/Element that can invalidate confidentiality/authentication guarantees against a malicious server, demonstrating both (a) realistic threat models for federated systems and (b) the need for continuous auditing and protocol hardening as these platforms mature. [10]

##### **8) A Mechanized Formal Analysis of the Matrix Cryptographic Protocol Suite (arXiv:2408.12743)**

**Authors:** Jacob Ginesin[11] et al.

**Type:** Technical preprint (formal methods / mechanised analysis)

**Date:** Aug 2024

**Link:** <https://arxiv.org/abs/2408.12743>

**Why it matters:** Provides mechanised symbolic models for Matrix E2EE (Olm/Megolm) and derives proofs/limitations/previous attacks using automated tools—evidence of maturing “security engineering discipline” needed for security-by-default platforms. [12]

##### **9) Project Hydra: Improving state resolution in Matrix**

**Org:** Matrix.org Foundation[13]

**Type:** Technical incident-response / protocol hardening blog (with CVE references)

**Date:** Aug 2025

**Link:** <https://matrix.org/blog/2025/08/project-hydra-improving-state-res/>

**Why it matters:** Documents fixes for state-resolution vulnerabilities (including CVE-2025-49090) that could enable “state resets” via crafted event/API sequences—concrete evidence that resilient federated systems face complex distributed-consensus edge cases, and that the ecosystem is actively shipping protocol-level mitigations. [14]

##### **10) French government circular mandating broad deployment of Tchap**

**Org:** France[15] (Prime Minister’s circular published on Légifrance)

**Type:** Government circular / administrative instruction (opposable circular)

**Date:** Signed Jul 2025 (online Aug 2025; effective Sep 2025)

**Link:** <https://www.legifrance.gouv.fr/circulaire/id/45618>

**Why it matters:** Requires wide deployment of the Tchap instant-messaging system to secure conversations and information—strong “market pull” and operational maturity evidence for secure, sovereign, deployable messaging based on open protocols rather than consumer apps. [16]



#### 11) DINUM press release: support for Matrix.org Foundation to strengthen digital autonomy

**Org:** Direction interministérielle du numérique (DINUM)[17]

**Type:** Government press release with technical contribution details

**Date:** Oct 2025

**Link:** <https://www.numerique.gouv.fr/sinformer/espace-presse/dinum-soutien-fondation-matrixorg/>

**Why it matters:** Describes a state actor funding and contributing to Matrix as a long-lived “digital commons,” citing concrete work such as improving “Sliding Sync” performance and developing a community “border gateway” to secure inter-organisation communications—evidence of scaling, hardening, and institutional investment. [18]

#### 12) Federation between BwMessenger and BundesMessenger started

**Org:** BWI GmbH[19]

**Type:** Deployment report / technical-operational announcement

**Date:** Sep 2024

**Link:** <https://www.bwi.de/magazin/artikel/foederation-schafft-sicheres-messaging-zwischen-bundeswehr-und-bwi>

**Why it matters:** Describes an operational federation go-live enabling cross-organisation chat rooms between distinct platforms, explicitly framing Matrix as an open standard enabling interoperable decentralised operation “over server and organisation boundaries”—direct evidence for the ART’s “organisation-run nodes + interoperability” claim. [20]

#### 13) T-Systems becomes operating and sales partner for BundesMessenger (SaaS model)

**Orgs:** T-Systems International GmbH[21]; includes first SaaS customer Bundesdruckerei[22]

**Type:** Deployment / commercialisation milestone (incl. procurement mention)

**Date:** Oct 2024

**Link:** <https://www.bwi.de/magazin/artikel/t-systems-wird-betriebs-und-vertriebspartner-der-bwi-fuer-bundesmessenger>

**Why it matters:** Reports a procurement-awarded concession enabling SaaS hosting in German data centres, citing “over 100 enquiries” and naming an initial user; this is strong maturity evidence of scaling pathways (hosted + self-run) for secure federated communications. [23]

#### 14) BundesMessenger backend Helm chart (openCode GitLab project)

**Org:** OpenCode / public-sector repository (BWI group)

**Type:** Public infrastructure-as-code artefact (deployment packaging)

**Date:** Created Oct 2022 (with many commits/releases visible)

**Link:** <https://gitlab.opencode.de/bwi/bundesmessenger/backend/helm-chart>

**Why it matters:** Shows repeatable, production-style deployment tooling (“Helm Charts” for Kubernetes) with extensive commit/release history—evidence that some resilient platform components are operationalised for reproducible deployment, not only prototypes. [24]

#### Decentralised social network protocol and ecosystem evidence

#### 15) Flocking to Mastodon: Tracking the Great Twitter Migration

**Authors:** Jiahui He[25] et al.

**Type:** Peer-reviewed conference proceeding (ACM IMC ’23 listing)

**Date:** Oct 2023

**Link:** <https://openresearch.surrey.ac.uk/esploro/outputs/conferenceProceeding/Flocking-to-Mastodon-Tracking-the-Great/99928696602346>

**Why it matters:** Empirically analyses migration of 136,009 users from Twitter to Mastodon and studies ecosystem pressure towards centralisation, giving concrete evidence that federated social platforms operate at meaningful scale and face real-world resilience/governance stresses. [26]

#### 16) **Building a Mastodon Compatible Java Server for ActivityPub (arXiv:2412.09011)**

**Authors:** Sean Nian[27] et al.

**Type:** Technical preprint / engineering proof

**Date:** Dec 2024

**Link:** <https://arxiv.org/abs/2412.09011>

**Why it matters:** Deconstructs ActivityPub interoperability and implements a Mastodon-compatible server using Java Spring Boot, demonstrating that “interoperable servers by independent implementers” is feasible in practice (plausibility) while highlighting implementation complexity (maturity constraint). [28]

#### 17) **Bluesky and the AT Protocol: Usable Decentralized Social Media (arXiv:2402.03239)**

**Authors/Org:** Martin Kleppmann[29] et al.; Bluesky Social[30]

**Type:** Technical paper + workshop publication reference (DIN '24 via arXiv record)

**Date:** Feb 2024 (revised Oct 2024)

**Link:** <https://arxiv.org/abs/2402.03239>

**Why it matters:** Presents an architecture explicitly targeting multiple interoperable providers, user-friendly account/provider switching, and user agency over feeds/moderation; also reports growth to over 10 million registered users by Oct 2024—strong evidence of market traction for “interoperable social” designs. [31]

#### 18) **Authenticated Transfer: Architecture Overview (draft-newbold-at-architecture-00)**

**Org:** IETF Internet-Draft (authors affiliated with Bluesky Social per draft)

**Type:** Standards-track precursor (Internet-Draft; informational)

**Date:** Sep 2025

**Link:** <https://datatracker.ietf.org/doc/draft-newbold-at-architecture/>

**Why it matters:** Provides a cohesive overview of AT as implemented “in late 2025,” describing interoperable social web applications built from self-certifying data records—evidence the protocol stack is being documented for broader standardisation and multi-implementer interoperability (maturity still pre-RFC). [32]

#### 19) **An Empirical Analysis of the Nostr Social Network: Decentralization, Availability, and Replication Overhead (arXiv:2402.05709)**

**Authors:** Yiluo Wei[33] et al.

**Type:** Measurement study (preprint; accepted to CoNEXT '25 per record)

**Date:** Feb 2024 (revised Sep 2025)

**Link:** <https://arxiv.org/abs/2402.05709>

**Why it matters:** Measures decentralisation and replication behaviour; finds improved decentralisation vs Fediverse applications and highlights the resilience–overhead trade-off (replication increases censorship-resistance/availability but introduces significant overhead), directly matching the ART’s stated constraints. [34]

## 20) Approaches to Conflict-free Replicated Data Types (ACM Computing Surveys)

**Author:** Paulo Sérgio Almeida[35]

**Type:** Peer-reviewed survey / foundational engineering reference

**Date:** Nov 2024 (publication date)

**Link:** <https://repositorio.inesctec.pt/server/api/core/bitstreams/d83841fa-9642-4162-aca9-50a7ae7b18e3/content>

**Why it matters:** CRDTs enable replicas to proceed independently (availability under partitions) while converging deterministically—core technical grounding for “local queueing + later merge” and multi-device replication patterns that underpin graceful degradation in contested connectivity. [36]

### 3. Maturity score (1–7) and reasoning

**Final maturity score: 5**

**Evidence-to-rubric mapping and aggregation**

#### What evidence rules out lower levels (1–4)

The ART is well beyond “principle only” or “lab demo” because multiple components are standardised and deployed in real operational settings. Group E2EE has a standards-track protocol designed for thousands of participants (MLS) rather than being only a research prototype. [2] Government and defence/public-sector deployments show functioning federated secure messaging in production (mandated rollouts and cross-organisation federation), which exceeds PoC: the French Prime Minister’s circular orders broad deployment of Tchap, and German public-sector programmes report live federation and SaaS operating models. [37] Large-scale adoption dynamics exist for federated social platforms and newer interoperable architectures: Mastodon migration was measured at 136,009 migrating users in an IMC’23 study, and Bluesky reports >10M registered users by Oct 2024 in its architectural paper. [38] These collectively rule out maturity levels 1–4 for the overall theme (the ecosystem contains multiple production deployments and scaling pathways).

#### Why the score is not higher (why not 6–7 for the ART as a whole)

Despite production deployments, the *full* ART bundle—secure, resilient, interoperable social platforms combining portable identity/attribute proofs, strong privacy-by-default (including metadata minimisation), and graceful-degradation distribution across devices and independent servers—is not yet uniformly delivered at “expanding product families with economies of scale” maturity across the whole stack.

Key gaps and constraints are evidenced by the sources: - **Selective disclosure credentials are not yet uniformly production-grade in the web-standards track:** the BBS Cryptosuite explicitly says it is “not fit for production deployment,” meaning one of the most direct mechanisms for privacy-preserving attribute proofs is still maturing. [8] - **Federated secure systems still face deep distributed-security edge cases and require major protocol hardening:** state-resolution vulnerabilities (CVE-2025-49090) and the need for a “Project Hydra” remediation programme show that resilience and correctness in adversarial federation is hard and still evolving. [14] - **Security assurance remains an active research and engineering frontier:** practically exploitable cryptographic vulnerabilities were documented for Matrix/Element in 2023, while mechanised formal analysis work is still emerging (2024), indicating the assurance story is improving but not “settled.” [39] - **Resilience features carry measurable overhead and sustainability constraints:** Nostr’s

replication-first approach increases censorship resistance but introduces significant overhead and relay sustainability challenges, mirroring the ART's stated cost/overhead bottleneck. [34] - **Interoperable social architectures are still standardising**: AT is documented in an IETF Internet-Draft (pre-RFC), which is a sign of momentum but not yet a stable, widely standardised foundation across competing mass-market providers. [32]

For these reasons, the technology bundle is best described as **post-PoC with multiple well-capitalised and institutional actors pushing toward production-ready interoperability and resilience**, but **not yet at the stage where the integrated vision is broadly delivered with clear economies of scale across the entire stack** (rubric 6) or where **competing mass-market products have clearly accelerating demand and internally financed growth across multiple vendors** (rubric 7).

#### Sub-component maturity breakdown and how it aggregates to one score

- Federated secure messaging (Matrix-like deployments + operational federation) → 6**  
 Evidence: mandated public-sector deployment driver and operational federation / SaaS pathways (Tchap circular; DINUM investment and technical contributions; BWI federation; BWI SaaS concession). [40]  
*Caveat:* continuing security hardening programmes (Project Hydra) indicate active maturation. [14]
- Group E2EE standardisation for scaling secure group spaces (MLS) → 5–6**  
 Evidence: MLS is a standards-track RFC explicitly designed for asynchronous groups “ranging from two to thousands.” [2]  
*Reason it is not clearly 7:* the dossier does not include shipment/market share evidence across multiple competing consumer products adopting MLS at massive scale (outside scope of these sources).
- Federated public social networking (Fediverse / ActivityPub ecosystems) → 5–6**  
 Evidence: measured large migration into Mastodon and continued ecosystem dynamics; independent implementer can build interoperable servers (Java ActivityPub interoperability). [41]  
*Reason it is not clearly 7:* the dossier shows traction and feasibility but does not show dominant, sustained commercial scaling by multiple large firms with rising demand signals comparable to top-tier mainstream platforms.
- Interoperable “portable account + modular providers” social architecture (AT / Bluesky) → 5**  
 Evidence: explicit engineering design for provider switching and modular components; protocol is being documented in an IETF draft reflecting a late-2025 implementation. [42]  
*Reason it is not 6–7:* standardisation remains draft-level and the architecture’s multi-provider ecosystem is still consolidating.
- Decentralised identity with selective disclosure and privacy-preserving status → 4–5**  
 Evidence: DID and VC/VC Data Integrity/Bitstring Status List are W3C Recommendations (strong plausibility + interoperability intent), but production-grade selective disclosure via BBS cryptosuite remains working-draft and explicitly not production-ready. [43]
- Local-first / offline-tolerant replication foundations (CRDTs) → 3–4**  
 Evidence: peer-reviewed survey consolidates CRDT approaches enabling availability under partitions with deterministic convergence—necessary technical basis for “queue locally,

merge later” behaviours, but not evidence of ubiquitous integration into major social platforms yet. [36]

**Aggregation to one score:** these sub-components span roughly **3–6**, with the “core user-visible systems” (federated messaging and federated social) closer to **5–6**, while privacy-preserving portable identity and local-first replication are **earlier-stage for broad deployment**. Using an average-weighted view (because the ART’s benefits are divided across distinct application layers—identity, messaging, social feed, replication), the combined maturity lands most defensibly at **5**: multiple serious actors and deployments exist, but the fully integrated, interoperable, privacy-and-resilience-by-default social platform vision is not yet broadly delivered at scale. [44]

[1] [13] [24] [27] <https://gitlab.opencode.de/bwi/bundesmessenger/backend/helm-chart>

<https://gitlab.opencode.de/bwi/bundesmessenger/backend/helm-chart>

[2] [30] <https://datatracker.ietf.org/doc/rfc9420/>

<https://datatracker.ietf.org/doc/rfc9420/>

[3] [36] <https://repositorio.inesctec.pt/server/api/core/bitstreams/d83841fa-9642-4162-aca9-50a7ae7b18e3/content>

<https://repositorio.inesctec.pt/server/api/core/bitstreams/d83841fa-9642-4162-aca9-50a7ae7b18e3/content>

[4] [43] <https://www.w3.org/TR/did-core/>

<https://www.w3.org/TR/did-core/>

[5] <https://www.w3.org/TR/vc-data-model-2.0/>

<https://www.w3.org/TR/vc-data-model-2.0/>

[6] <https://www.w3.org/TR/vc-data-integrity/>

<https://www.w3.org/TR/vc-data-integrity/>

[7] <https://www.w3.org/standards/history/vc-bitstring-status-list/>

<https://www.w3.org/standards/history/vc-bitstring-status-list/>

[8] [9] [21] [44] <https://www.w3.org/TR/2023/WD-vc-di-bbs-20230524/>

<https://www.w3.org/TR/2023/WD-vc-di-bbs-20230524/>

[10] [11] [39] <https://eprint.iacr.org/2023/485>

<https://eprint.iacr.org/2023/485>

[12] [35] <https://arxiv.org/abs/2408.12743>

<https://arxiv.org/abs/2408.12743>

[14] [33] <https://matrix.org/blog/2025/08/project-hydra-improving-state-res/>

<https://matrix.org/blog/2025/08/project-hydra-improving-state-res/>

[15] [19] [26] [38] [41]

<https://openresearch.surrey.ac.uk/esploro/outputs/conferenceProceeding/Flocking-to-Mastodon-Tracking-the-Great/99928696602346>

<https://openresearch.surrey.ac.uk/esploro/outputs/conferenceProceeding/Flocking-to-Mastodon-Tracking-the-Great/99928696602346>

[16] [17] [37] [40] <https://www.legifrance.gouv.fr/circulaire/id/45618?origin=list>

<https://www.legifrance.gouv.fr/circulaire/id/45618?origin=list>

[18] <https://numerique.gouv.fr/sinformer/espace-presse/dinum-soutien-fondation-matrixorg/>

<https://numerique.gouv.fr/sinformer/espace-presse/dinum-soutien-fondation-matrixorg/>

[20] <https://www.bwi.de/magazin/artikel/foederation-schafft-sicheres-messaging-zwischen-bundeswehr-und-bwi>

<https://www.bwi.de/magazin/artikel/foederation-schafft-sicheres-messaging-zwischen-bundeswehr-und-bwi>

[22] [34] <https://arxiv.org/abs/2402.05709>

<https://arxiv.org/abs/2402.05709>

[23] <https://www.bwi.de/magazin/artikel/t-systems-wird-betriebs-und-vertriebspartner-der-bwi-fuer-bundesmessenger>

<https://www.bwi.de/magazin/artikel/t-systems-wird-betriebs-und-vertriebspartner-der-bwi-fuer-bundesmessenger>

[25] [29] [32] <https://datatracker.ietf.org/doc/draft-newbold-at-architecture/>

<https://datatracker.ietf.org/doc/draft-newbold-at-architecture/>

[28] <https://arxiv.org/abs/2412.09011>

<https://arxiv.org/abs/2412.09011>

[31] [42] <https://arxiv.org/abs/2402.03239>

<https://arxiv.org/abs/2402.03239>

## ART 11.087 Collective Open Innovation Networks

### ART extraction

- **Primary capability claimed**



- Internet-native networks (not single-company tools) that coordinate invention/R&D across organisational boundaries by lowering collaboration friction (problem discovery → secure workspaces → testing/validation → adjudication). [1]
- Machine-readable, provenance-tracking collaboration (versioned “innovation branches”) that preserves intermediate artefacts and supports trust via audit trails and repeatable validation. [2]
- Scalable matching of problems to contributors via reputational signals grounded in past demonstrated performance, supported by identity, access control, and dispute-resolution/governance procedures. [3]
- **Key sub-components or variants**
  - **Challenge/prize & crowdsourcing layer** (problem definition, incentive design, submission pipelines, evaluation and judging process, reporting). [4]
  - **Federated identity & credentialing** (strong identity, verifiable credentials, cross-network authentication/authorisation). [5]
  - **Secure collaboration workspaces** (confidential compute, policy controls, access control, high-assurance environments for sensitive inputs). [6]
  - **Provenance and supply-chain style audit trails** (attestations, SBOM-like artefacts, signed provenance, immutable logs/ledgers). [7]
  - **Interoperable “ecosystem plumbing”** (connectors, catalogues, test suites/compatibility kits, compliance services) enabling cross-organisation and cross-vendor federation. [8]
  - **Governance & dispute-resolution mechanisms** (rules-of-participation, contractual/relational governance, platform governance). [9]
- **Maturity indicators that would constitute evidence**
  - **Operational deployments** supporting multi-party participation with measurable usage (accounts, participants, challenges, prizes, connectors certified/tested, etc.). [10]
  - **Interoperability/test infrastructure** (formal specs + conformance tests + certified/compatible implementations). [11]
  - **Security and trust foundations** demonstrably implementable at scale (federated AAI, confidential computing, auditability). [12]
  - **Evidence of governance working in practice** (published governance frameworks/standards; empirical studies of governance tensions and mechanisms). [13]
  - **Evidence of growing investment and expansion** (explicit funding/programme budgets; ecosystem growth metrics). [14]

**Evidence (10–20 recent, reliable sources)**

**Evidence dossier**

### 1) Governing innovation platforms in multi-business organisations

**Authors/Org:** Maximilian Schreieck[15]; Manuel Wiesche[16]; Helmut Krcmar[17]

**Venue/type:** Peer-reviewed journal article (European Journal of Information Systems)

**Date:** March 2022 (published online 07 Mar 2022)

**Link (URL):**

[https://www.researchgate.net/publication/359066712\\_Governing\\_innovation\\_platforms\\_in\\_multi-business\\_organisations](https://www.researchgate.net/publication/359066712_Governing_innovation_platforms_in_multi-business_organisations)

**Why it matters:** Empirically documents governance “tensions” (rigidity, mistrust, competition, etc.) when an innovation platform spans semi-autonomous business units, directly supporting the ART’s claim that scaling cross-boundary innovation depends on well-designed governance and incentive structures. [18]

**2) Digital governance: A conceptual framework and research agenda**

**Authors/Org:** Johannes Hanisch[19] et al.

**Venue/type:** Peer-reviewed journal article (Research Policy)

**Date:** 2023

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0148296323001352>

**Why it matters:** Defines “digital governance” mechanisms (control, coordination, incentives, trust) and argues governance choices change with network “transactivity,” aligning closely with the ART’s emphasis on friction reduction, incentive design, and trust at scale. [20]

**3) Governance mechanisms and practices in project-based interorganisational collaboration for innovation**

**Authors/Org:** Katri Valkokari[21] et al.

**Venue/type:** Peer-reviewed journal article (International Journal of Project Management; open access)

**Date:** November 2024

**Link (URL):**

<https://www.sciencedirect.com/science/article/pii/S0263786324000942>

**Why it matters:** Based on 10 Finnish interorganisational innovation collaborations, shows real-world interplay between formal contracts, relational agreements, and governance practices—evidence that “dispute resolution/governance complexity” is a dominant maturity constraint for cross-organisation innovation networks. [22]

**4) ISO 56001:2024 — Innovation management system — Requirements**

**Authors/Org:** International Organization for Standardization[23]

**Venue/type:** Standards body publication (management system standard)

**Date:** 2024 (standard edition ISO 56001:2024)

**Link (URL):** <https://www.iso.org/standard/79278.html>

**Why it matters:** Provides a formalised, auditable management-system framing for innovation activity—relevant to the ART’s governance claims (repeatability, decision rights, evidence trails), even if it does not prescribe a specific platform architecture. [24]

**5) Implementation of Federal Prize and Citizen Science Authority — Fiscal Years 2021–2022 (Appendices)**

**Authors/Org:** White House Office of Science and Technology Policy[25]

**Venue/type:** Authoritative government report (programme reporting to Congress; appendices volume)

**Date:** April 2024

**Link (URL):** [https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/04/Appendices\\_Implementation-of-Federal-Prize-and-Citizen-Science-Authority-Fiscal-Years-2021-2022.pdf](https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/04/Appendices_Implementation-of-Federal-Prize-and-Citizen-Science-Authority-Fiscal-Years-2021-2022.pdf)

**Why it matters:** Demonstrates sustained, government-scale use of prize competitions/challenges/citizen science across multiple agencies—evidence that “challenge definition → participation → adjudication → reporting” workflows are mature and institutionalised at national scale. [26]

#### 6) Implementation of Federal Prize and Citizen Science Authority

**Authors/Org:** Executive Office of the President of the United States[27] (report published via White House archive)

**Venue/type:** Authoritative government report

**Date:** May 2022

**Link (URL):** <https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/05/05-2022-Implementation-of-Federal-Prize-and-Citizen-Science-Authority.pdf>

**Why it matters:** Provides formal evidence that the federal prize/challenge ecosystem is not ad hoc: it describes role of Challenge.gov[28] and toolkit resources as enabling infrastructure for recurring open innovation campaigns—supporting the plausibility of “network-native” innovation coordination. [29]

#### 7) 2023 Challenge.Gov Federal Agency Toolkit

**Authors/Org:** U.S. General Services Administration[30] (Challenge.Gov programme)

**Venue/type:** Government technical/practitioner toolkit

**Date:** 2023 (month not specified)

**Link (URL):** <https://www.challenge.gov/assets/document-library/Challenge-Gov-Federal-Agency-Toolkit.pdf>

**Why it matters:** Provides an end-to-end operational process map (preparation → development → conduct → award → transition), including evaluation/judging design and required reporting—directly evidencing mature “full-stack” contest operations and repeatable workflows for distributed problem-solving. [31]

#### 8) Open Innovation at NASA

**Authors/Org:** NASA[32]

**Venue/type:** Government programme publication/webpage with metrics

**Date:** June 2025 (page last updated 17 Jun 2025)

**Link (URL):** <https://www.nasa.gov/open-innovation-2023/>

**Why it matters:** Reports “by the numbers” metrics for prizes/challenges and citizen science (e.g., counts of competitions/projects and prize totals for Oct 2020–Sep 2022), demonstrating an operational, scaled solver network and repeatable adjudication pathways—key maturity evidence for the ART’s challenge-network layer. [33]

#### 9) Open Innovation: Boosting NASA Higher, Faster, and Farther

**Authors/Org:** National Aeronautics and Space Administration[34]

**Venue/type:** Government report (programme publication PDF; “open innovation” case studies + metrics)

**Date:** 2022 (labelled by NASA as the “2022 Open Innovation Publication”; month not specified)

**Link (URL):**

<https://www3.nasa.gov/sites/default/files/atoms/files/fy1920openinnovationreport-final.pdf>

**Why it matters:** Includes concrete scale metrics for global participation (e.g., multi-country

participation in hackathon formats; explicit participant and team counts in the cited programme example), supporting plausibility that large, distributed contributor networks can generate usable outputs under structured rules. [35]

#### 10) **Commission Staff Working Document on Common European Data Spaces (SWD(2022) 45 final)**

**Authors/Org:** European Commission[36] (transmitted via Council of the European Union[37] document register)

**Venue/type:** Authoritative EU roadmap/report

**Date:** February 2022 (23 Feb 2022)

**Link (URL):** <https://data.consilium.europa.eu/doc/document/ST-6532-2022-INIT/en/pdf>

**Why it matters:** Sets out a concrete governance-and-infrastructure vision for sectoral “data spaces,” including interoperability, trust mechanisms, and EU funding lines—high-quality evidence that multi-party, cross-border data-sharing ecosystems (a major dependency of collective innovation networks) are being built as policy-backed infrastructure. [38]

#### 11) **Simpl: Cloud-to-edge federations empowering EU data spaces**

**Authors/Org:** European Commission Directorate-General for Communications Networks, Content and Technology[39]

**Venue/type:** Authoritative programme/technical overview (policy + technical positioning for open-source middleware)

**Date:** October 2024 (11 Oct 2024)

**Link (URL):** <https://digital-strategy.ec.europa.eu/en/policies/simpl>

**Why it matters:** Explicitly positions an “open source, smart and secure middleware” as the shared interoperability layer across European data spaces—direct evidence of real-world efforts to create interoperable, multi-party networks rather than siloed tools. [40]

#### 12) **IDSA Data Space Connector Report 1 (October 2025 edition)**

**Authors/Org:** International Data Spaces Association[41]

**Venue/type:** Consortium technical report (interoperability, conformance, connector landscape)

**Date:** October 2025 (01 Oct 2025)

**Link (URL):** [https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Space-Connector-Report-1\\_October\\_2025-1.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Space-Connector-Report-1_October_2025-1.pdf)

**Why it matters:** Provides concrete conformance primitives (protocol versioning, TCK versions) and reports “productively used” connector deployments (e.g., Eclipse Tractus-X connector used in Catena-X), which is strong maturity evidence for interoperable multi-party collaboration infrastructure. [42]

#### 13) **Gaia-X Architecture Document — 22.04 Release**

**Authors/Org:** Gaia-X Association AISBL[43]

**Venue/type:** Consortium architecture specification (PDF)

**Date:** June 2022 (document hosted under 2022/06; “22.04 release”)

**Link (URL):** <https://gaia-x.eu/wp-content/uploads/2022/06/Gaia-x-Architecture-Document-22.04-Release.pdf>

**Why it matters:** Specifies federation services including identity & access management,

federated catalogues, and compliance/notarisation services—directly aligned with the ART’s feasibility dependencies (identity, access control, dispute/trust mechanisms). [\[44\]](#)

#### 14) EOSC Multi-Annual Roadmap 2023–2024

**Authors/Org:** European Open Science Cloud[\[45\]](#) (SRIA roadmap document)

**Venue/type:** Consortium roadmap/report (PDF)

**Date:** November 2022 (document dated 07 Nov 2022 in filename)

**Link (URL):** [https://www.eosc.eu/sites/default/files/2022-11/20221107\\_MAR%202023-2024.pdf](https://www.eosc.eu/sites/default/files/2022-11/20221107_MAR%202023-2024.pdf)

**Why it matters:** Describes a “minimum viable” federated research environment with an interoperability framework and trust/reproducibility focus—evidence that large multi-institution collaboration is being engineered as a federated system rather than a single platform. [\[46\]](#)

#### 15) EOSC Federated Authorisation and Authentication Activities (D7.3, EOSC Future)

**Authors/Org:** GÉANT[\[47\]](#) (deliverable produced in EOSC Future context)

**Venue/type:** Consortium technical deliverable/report (PDF)

**Date:** February 2023 (file dated 2023-02-03)

**Link (URL):** <https://eoscfuture.eu/wp-content/uploads/2023/10/EOSC-Future-WP7-GEANT-D7.3-EOSC-Federated-Authorisation-and-Authentication-Activities-2023-02-03.pdf>

**Why it matters:** Documents concrete federation engineering for identity and access (SAML2 federation, OpenID Connect bridging, registry/metadata operations, monitoring) and explicitly notes operationalisation work—direct feasibility evidence for the ART’s “robust identity + access control” requirement. [\[48\]](#)

#### 16) Verifiable Credentials Data Model v2.0

**Authors/Org:** World Wide Web Consortium[\[49\]](#)

**Venue/type:** Standards specification (W3C Recommendation family; VC 2.0 data model)

**Date:** 2025 (VC 2.0 Recommendation announcement and TR publication cycle)

**Link (URL):** <https://www.w3.org/TR/vc-data-model-2.0/>

**Why it matters:** Provides a standard, interoperable method for expressing tamper-evident claims about identity/attributes—critical building block for contributor discovery, reputation credentials, and auditable participation in cross-organisation innovation networks. [\[50\]](#)

#### 17) Decentralized Identifiers (DIDs) v1.0

**Authors/Org:** W3C[\[51\]](#)

**Venue/type:** Standards specification (W3C Recommendation)

**Date:** July 2022 (W3C Recommendation 19 Jul 2022)

**Link (URL):** <https://www.w3.org/TR/did-core/>

**Why it matters:** Standardises decentralised identifier formats and resolution—supporting identity portability across networks and ecosystems, which is central to the ART’s “internet-native network” and cross-jurisdiction participation. [\[52\]](#)

#### 18) OpenSSF Announces SLSA Version 1.0 Release

**Authors/Org:** Open Source Security Foundation[\[53\]](#)

**Venue/type:** Standards-like framework release (supply-chain provenance; press release with technical framing)

**Date:** April 2023 (19 Apr 2023)

**Link (URL):** <https://openssf.org/press-release/2023/04/19/openssf-announces-slsa-version-1-0-release/>

**Why it matters:** Establishes a widely-used vocabulary and checklists for provenance and tamper-resistance across build/source/dependency tracks—directly relevant to the ART’s requirement for provenance-tracked “innovation branches” and trustable audit trails. [54]

#### 19) **NIST SP 800-204D: Strategies for the Integration of Software Supply Chain Security in DevSecOps CI/CD Pipelines**

**Authors/Org:** National Institute of Standards and Technology[55]

**Venue/type:** Government technical guideline (NIST Special Publication)

**Date:** February 2024

**Link (URL):**

<https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-204D.pdf>

**Why it matters:** Provides concrete operational guidance for securing collaborative production pipelines (assurance, CI/CD controls), strengthening the plausibility of scaling evidence-bearing workflows and auditability in production-grade innovation networks. [56]

#### 20) **Confidential Computing Deep Dive / Technical Analysis (v1.3)**

**Authors/Org:** Confidential Computing Consortium[57]

**Venue/type:** Consortium technical report/whitepaper (confidential computing/TEE properties)

**Date:** 2023 (PDF hosted under 2023/03; versioned release)

**Link (URL):** [https://confidentialcomputing.io/wp-content/uploads/sites/10/2023/03/CCC-A-Technical-Analysis-of-Confidential-Computing-v1.3\\_unlocked.pdf](https://confidentialcomputing.io/wp-content/uploads/sites/10/2023/03/CCC-A-Technical-Analysis-of-Confidential-Computing-v1.3_unlocked.pdf)

**Why it matters:** Defines the security properties of TEEs (confidentiality/integrity for data and code “in use”), supporting the ART’s feasibility claim of protecting sensitive inputs while still enabling meaningful computation and review in shared environments. [58]

#### 21) **Confidential Consortium Framework: Secure Multiparty Applications with Confidentiality, Integrity, and High Availability**

**Authors/Org:** Heidi Howard[59] et al. (Microsoft[60] research)

**Venue/type:** Peer-reviewed systems paper (Proc. VLDB Endowment; PDF)

**Date:** October 2023 (PVLDB Vol. 17, No. 2; paper dated with issue timing)

**Link (URL):** <https://www.vldb.org/pvldb/vol17/p225-howard.pdf>

**Why it matters:** Presents a concrete architecture for mutually untrusted parties to govern and audit shared state using TEEs and an immutable ledger—highly relevant to the ART’s need for reliable discourse, dispute resolution, and provenance/auditability in cross-organisation collaboration. [61]

#### 22) **Octoverse: A new developer joins GitHub every second...**

**Authors/Org:** GitHub[62]

**Venue/type:** Industry data report/blog (platform-scale usage metrics)

**Date:** October 2025 (28 Oct 2025)

**Link (URL):** <https://github.blog/news-insights/octoverse/octoverse-a-new-developer-joins-github-every-second-as-ai-leads-typescript-to-1/>

**Why it matters:** Although software-centric, it is strong “market maturity” evidence that versioned collaboration with audit trails (pull requests, contributions, provenance in practice)



scales to extremely large populations, indicating the collaboration substrate the ART relies on is already mature at internet scale. [63]

### 23) 2024 Open Source Software Funding Report

**Authors/Org:** Collaboration between Harvard University[64] researchers and The Linux Foundation[65], with GitHub participation

**Venue/type:** Research/industry survey report (method + quantified investment)

**Date:** November 2024 (19 Nov 2024)

**Link (URL):** <https://opensourcefundingsurvey2024.com/>

**Why it matters:** Quantifies organisational investment in open collaboration (e.g., billions of USD annually in OSS contributions), demonstrating that cross-org “network R&D” is already materially funded and operational—supporting ART maturity beyond lab concepts. [66]

### 24) 2024 Global Spotlight Insights Report: The Role of Open Source in Uniting Innovation, Collaboration, and Resilience Across Regions and Industries

**Authors/Org:** Linux Foundation Research[67]

**Venue/type:** Industry/consortium survey report (PDF; cross-region metrics)

**Date:** December 2024

**Link (URL):**

[https://www.linuxfoundation.org/hubfs/LF%20Research/2024GlobalSpotlight\\_121224.pdf?hsLang=en](https://www.linuxfoundation.org/hubfs/LF%20Research/2024GlobalSpotlight_121224.pdf?hsLang=en)

**Why it matters:** Provides cross-region data on perceived value, security, and organisational practices around open collaboration—evidence that “internet-native collaboration networks” are expanding in scope and are being operationalised with governance practices like OSPOs and structured policies. [68]

**Maturity score (1–7) and reasoning**

**Final maturity score: 6**

#### Why this ART is at least level 6 (rules out levels 1–5)

- The dossier contains multiple *operational, scaled* examples of cross-boundary innovation mechanisms, not merely lab demonstrations or isolated pilots. For example, OSTP[69] reporting and companion toolkits show that prize/challenge infrastructures are institutionalised across many agencies and run continuously with formal processes (design → evaluation → reporting). [70]
- EU “data spaces” work shows a parallel, policy-backed, multi-country push to build trusted, interoperable ecosystems for sharing data (a key bottleneck for collaborative R&D). This includes explicit governance/infrastructure framing and budgetary earmarks in official documents. [38]
- Interoperability mechanisms are moving beyond PowerPoint into *conformance and “known-good implementation” environments*: the IDSA[71] connector report specifies protocol versions and test-compatibility information and reports connectors “productively used” in a real industrial data space. [72]
- Key feasibility dependencies—identity/credentialing, access control and secured computation, and provenance—are supported by mature standards and operational deployments: W3C Recommendations for VC and DIDs, EOSC federated AAI deliverables, and shipping-grade confidential computing foundations and multiparty governance designs (e.g., CCF). [73]

Together, these are consistent with rubric level **6**: “Products are being delivered to customers in increasing amounts; application areas are expanding; ... expansion of production has been clearly financed; progress is recent.” The strongest “delivered at scale” evidence is in the collaboration substrate and network operations (GitHub’s scale metrics; ongoing government and EU-funded infrastructures; deployed connector ecosystems). [74]

### **What is still missing to justify level 7 (why not 7 yet)**

- The ART description anticipates *full-stack*, interoperable innovation environments that unify challenge definition, discovery, secure workspaces, testing resources, and adjudication into a single interoperable system. The evidence shows many components are mature individually (and some are integrated within specific ecosystems), but there is limited direct evidence (in the provided time window) that multiple *competing* vendors/consortia are delivering broadly adopted, end-to-end “innovation network operating systems” across domains (e.g., spanning software + lab experimentation + cross-jurisdiction IP/dispute resolution) with clearly rising commercial demand akin to a competitive packaged product category. [75]
- Governance and dispute-resolution remain a visible constraint in empirical research, suggesting continued fragility when scaling cross-party innovation beyond narrow contexts—this weighs against assigning the highest maturity level. [76]

### **Sub-component maturity breakdown (bundle scoring → aggregated to one score)**

- **Challenge/prize/crowdsourcing platforms (problem definition → submission → adjudication): maturity ~6.** Strong evidence of recurring, institutionalised operations at national programme scale (toolkits, reporting, metrics). Key sources: OSTP FY21–22 reporting; Challenge.gov toolkit; NASA open innovation metrics. [77]
- **Federated research collaboration infrastructures (shared services, identity federation, onboarding processes): maturity ~5–6.** EOSC roadmaps and deliverables show operationalised AAI federation and interoperability work, but still explicitly framed as evolving federation building. Key sources: EOSC MAR 2023–2024; EOSC Future AAI deliverable. [78]
- **Industrial cross-org interoperability layer (data spaces, connectors, conformance): maturity ~5–6.** Architecture/specification is mature, with evidence of conformance tooling and production usage in at least one industrial data space context. Key sources: EU SWD on data spaces; Simpl programme; IDSA connector report; Gaia-X architecture doc. [79]
- **Trust foundations (identity credentials + provenance + secure compute): maturity ~5–6.** W3C identity standards are formal Recommendations; provenance frameworks are stabilised (e.g., SLSA v1.0) and NIST provides operational guidance; TEEs/confidential computing are well-specified and underpin multiparty governance systems like CCF. Key sources: W3C VC + DID; OpenSSF SLSA; NIST SP 800-204D; CCC technical analysis; CCF PVLDB paper. [80]

**Aggregation logic:** The ART is a bundle whose variants share a common functional aim (cross-boundary innovation coordination). The evidence suggests several sub-components are already in products and operational consortia, but “full-stack unification” across domains remains incomplete; therefore an **average-based score** is appropriate, yielding ~6 rather than the maximum possible from the most mature sub-component alone. [81]

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## ART 11.088 Scalable Decentralized Governance

### ART extraction

#### Primary capability

- Encode core governance functions (membership, proposals, voting, budgeting, rule enforcement) in software so decisions are auditable and not dependent on a single administrator. [1]
- Provide a “governance stack” that couples (i) rules/thresholds, (ii) identity/permissions, and (iii) transparent execution that can trigger agreed actions (e.g., releasing funds, changing access rights). [2]
- Scale to large and distributed groups using delegation and other participation-reduction techniques, while supporting privacy-preserving verification/auditing to reduce vote buying/coercion. [3]

#### Key sub-components and variants

- **Policy/rule expression (“policy-as-code” / rule engines):** formalising constraints (thresholds, quorums, tracks, enactment rules) in executable logic. [4]
- **Identity and permissions layer:** decentralised identifiers, verifiable credentials, wallet-based identity, role/permissioning contracts, and credential-based gating/sybil resistance. [5]
- **Proposal/vote/execution primitives:** on-chain governance modules, timelocks/executors, plugin frameworks, treasury execution patterns. [6]
- **Scaling participation:** delegation (liquid democracy), multi-track delegation, parallel referendums, and delegation hubs/UX interventions to reduce voter fatigue. [7]
- **Manipulation resistance:** mechanisms and monitoring to address bribery, vote buying, “whale” dominance, governance token borrowing, and social-engineering/HCI attack surfaces. [8]
- **Privacy-preserving voting/audits:** ZK-based schemes for coercion resistance (anti-collusion, private ballots with public verifiability). [9]
- **Security/compliance operations:** audits, certification/certification-like processes, incident response expectations, and legal/regulatory compatibility. [10]

#### Maturity indicators that would constitute evidence

- **Production-grade deployments** governing real treasuries/protocol parameters with documented governance rules (e.g., multiple concurrent proposals, delegation features, threshold logic). [11]
- **Independent security auditing / repeat audits** of governance-critical contracts and/or voting privacy systems, with clear scope and remediation. [12]
- **Empirical evidence at scale** (large numbers of voters/proposals/DAOs) showing delegation patterns, participation changes from UX interventions, or measurable governance centralisation risks. [13]
- **Demonstrated attack taxonomies and incident analyses** showing known failure modes (bribery, token control, HCI attacks, protocol/contract vulnerabilities) and mitigations. [14]

- **Standards and government-grade identity guidance** enabling more realistic sybil resistance and compliance integration (credentials, DIDs, authentication/assurance guidance, wallet architectural frameworks). [5]
- **Regulatory/legal pathway clarity** (or at least credible scoping and frameworks) addressing liability, legal classification, and governance changes under law. [15]

**Evidence (10–20 recent, reliable sources)**

**Evidence dossier**

#### 1) **Decentralized Identifiers (DIDs) v1.0 — Core architecture, data model, and representations**

- Authors/Org: World Wide Web Consortium[16] (W3C)
- Venue/type: Standards specification (W3C Recommendation)
- Publication date: July 2022
- Link: <https://www.w3.org/TR/did-core/>
- Why it matters: Defines decentralised identifiers designed to be decoupled from central registries/identity providers, supporting verifiable control of identifiers—an enabling building block for governance identity/permissions without a single administrator. [17]

#### 2) **Verifiable Credentials Data Model v2.0**

- Authors/Org: W3C
- Venue/type: Standards specification (W3C Recommendation)
- Publication date: May 2025
- Link: <https://www.w3.org/TR/vc-data-model-2.0/>
- Why it matters: Standardises machine-verifiable, privacy-respecting digital credentials; credentials can supply membership/role assertions for governance stacks (e.g., “eligible voter”, “delegate”, “auditor-approved”). [18]

#### 3) **Verifiable Credential Data Integrity 1.0 — Securing the Integrity of Verifiable Credential Data**

- Authors/Org: W3C
- Venue/type: Standards specification (W3C Recommendation)
- Publication date: May 2025
- Link: <https://www.w3.org/TR/vc-data-integrity/>
- Why it matters: Specifies cryptographic proof mechanisms for verifiable credential integrity—relevant to “privacy-preserving audits” where systems need strong verification without exposing all underlying attributes. [19]

#### 4) **Digital Identity Guidelines (NIST SP 800-63-4)**

- Authors/Org: National Institute of Standards and Technology[20] (NIST)
- Venue/type: Government technical standard/guideline
- Publication date: July 2025
- Link: <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-63-4.pdf>
- Why it matters: Provides detailed requirements for identity proofing, authentication, and federation—directly relevant to governance systems that must resist fake identities and meet compliance expectations in high-stakes contexts. [21]

#### 5) **The European Digital Identity Wallet Architecture and Reference Framework (ARF) — “ARF v1.0.0 for publication”**



- Authors/Org: European Commission[22]
- Venue/type: Government/consortium architecture and reference framework
- Publication date: February 2023
- Link: <https://digital-strategy.ec.europa.eu/en/library/european-digital-identity-wallet-architecture-and-reference-framework>
- Why it matters: Establishes a common architecture for interoperable digital identity wallets in the EU ecosystem, supplying a realistic path to verified credentials usable as governance eligibility/permission inputs (especially for regulated or consortium settings). [23]

#### 6) **Version 1.4 of the Architecture and Reference Framework (ARF) released**

- Authors/Org: European Commission (EU Digital Identity Wallet programme)
- Venue/type: Government programme update / technical framework release note
- Publication date: November 2024 (page last updated 27 Nov 2024)
- Link: <https://ec.europa.eu/digital-building-blocks/sites/spaces/EUDIGITALIDENTITYWALLET/pages/797082397/Version+1.4+of+the+Architecture+and+Reference+Framework+ARF+released>
- Why it matters: Explicitly ties ARF evolution to a reference implementation and notes Large Scale Pilots “test driving” use cases in the real world—evidence of maturing identity infrastructure needed for sybil-resistant, compliant governance stacks. [24]

#### 7) **Decentralised autonomous organisations (DAOs): A scoping paper**

- Authors/Org: Law Commission[25]
- Venue/type: Government law reform scoping paper (PDF)
- Publication date: July 2024
- Link: <https://cdn.websitebuilder.service.justice.gov.uk/uploads/sites/54/2026/01/Decentralised-autonomous-organisations-scoping-paper.pdf>
- Why it matters: Provides an authoritative mapping of how DAOs can be characterised in law and highlights liability/regulatory issues, directly informing the “real-world accountability” and compliance constraints the ART flags. [26]

#### 8) **Report of the Working group on Smart Contract Certification (ACPR-AMF Fintech Forum)**

- Authors/Org: Autorité de contrôle prudentiel et de résolution[27] and Autorité des marchés financiers[28] (joint working group)
- Venue/type: Regulator-led technical report (PDF)
- Publication date: February 2025 (file dated 2025-02 in URL; report summarises WG work begun Jan 2024)
- Link: [https://acpr.banque-france.fr/system/files/2025-02/20250203\\_Discussion\\_papers\\_GT\\_Certification-smart-contracts\\_synthese\\_consultation\\_0.pdf](https://acpr.banque-france.fr/system/files/2025-02/20250203_Discussion_papers_GT_Certification-smart-contracts_synthese_consultation_0.pdf)
- Why it matters: Proposes certification principles spanning **security, governance, and service compliance**, and discusses audit methods and renewal triggers—evidence that “governance stacks” are moving toward auditability/certification norms needed for scaling into regulated environments. [29]

#### 9) **On-Chain Governance Overview (OpenGov)**

- Authors/Org: Polkadot[30] (developer documentation)
- Venue/type: Technical documentation (system design + operational features)

- Publication date: October 2024 (page created 16 Oct 2024; later updates continue through Jan 2026)
- Link: <https://docs.polkadot.com/reference/governance/>
- Why it matters: Documents an operating governance system that explicitly targets scale: **origins/tracks** (different thresholds/timelines), **simultaneous referendums**, and **multi-role delegation**—direct evidence of production governance mechanisms beyond lab prototypes. [31]

#### 10) Aragon OSx Protocol — architecture, plugins/permissions, and audit history

- Authors/Org: Aragon[32] (open-source protocol documentation)
- Venue/type: Vendor/open-source technical documentation (with audit metadata)
- Publication date: February 2025 (v1.4.0 audit marked “Finished: 2025-02-13” in repo documentation)
- Link: <https://github.com/aragon/osx/tree/v1.4.0>
- Why it matters: Describes a modular governance framework where a DAO contract “holds a DAO’s assets and possible actions” and a permission system mediates plugin/actor capabilities; includes explicit third-party audit timelines, supporting maturity of “execution + permission layer” components. [33]

#### 11) MACI Security Audit

- Authors/Org: [2]entity[2]“organization”, “Privacy & Scaling Explorations”, “ethereum ecosystem r&d”[2] (audit by Kyle Charbonnet[34] and Yufei Li[35])
- Venue/type: Technical security audit report (ZK voting protocol)
- Publication date: July 2024
- Link: [https://maci.pse.dev/assets/files/20240731\\_PSE\\_Audit\\_audit\\_report-a0a0f08a5c621ccd0389d5e345c119be.pdf](https://maci.pse.dev/assets/files/20240731_PSE_Audit_audit_report-a0a0f08a5c621ccd0389d5e345c119be.pdf)
- Why it matters: Audits a ZK-based “collusion resistant voting platform” and documents that the coordinator cannot tamper with results; this is concrete progress toward privacy-preserving audits and reducing vote buying/coercion—while also showing remaining decentralisation trade-offs (e.g., coordinator liveness). [36]

#### 12) SoK: Attacks on DAOs

- Authors/Org: Rainer Feichtinger[37] et al.
- Venue/type: Peer-reviewed conference paper (LIPIcs, AFT 2024)
- Publication date: September 2024 (16 Sep 2024)
- Link: <https://drops.dagstuhl.de/entities/document/10.4230/LIPIcs.AFT.2024.28>
- Why it matters: Systematises DAO attack vectors and examines **28 real-world incidents** across multiple blockchains, highlighting that many incidents exploit human/economic governance layers and are often under-analysed by purely code-focused audits—directly mapping to the ART’s “manipulation + vulnerability” constraints. [38]

#### 13) Perils of current DAO governance

- Authors/Org: Aida Manzano Kharman[39], Ben Smyth[40]
- Venue/type: Preprint (arXiv)
- Publication date: June 2024 (posted 12 Jun 2024)
- Link: <https://arxiv.org/abs/2406.08605>
- Why it matters: Surveys DAO governance protocols and argues that vote buying/coercion and privacy weaknesses remain practical; includes a protocol case study, underscoring that

“tamper-evident” governance can still fail on privacy/manipulation without additional mechanisms. [41]

#### 14) DAO Decentralization: Voting-Bloc Entropy, Bribery, and Dark DAOs

- Authors/Org: James Austgen[42] et al.
- Venue/type: Preprint (arXiv; cryptography/security-focused)
- Publication date: November 2023 (arXiv v1 dated 6 Nov 2023)
- Link: <https://www.cs.cornell.edu/~babel/papers/dao-vbe-dd.pdf>
- Why it matters: Introduces a formal decentralisation metric (Voting-Bloc Entropy) and presents a **Dark DAO prototype** using TEEs to enable vote-buying attacks—high-salience evidence for the ART’s “coordinated manipulation” risk and for why privacy systems must be designed with adversarial economics in mind. [43]

#### 15) The Governance of Decentralized Autonomous Organizations: A Study of Contributors’ Influence, Networks, and Shifts in Voting Power

- Authors/Org: Stefan Kitzler[44] et al.
- Venue/type: Preprint (arXiv; large-scale empirical study)
- Publication date: September 2023 (submitted 25 Sep 2023; revised 28 Sep 2023)
- Link: <https://arxiv.org/abs/2309.14232>
- Why it matters: Quantifies power concentration signals at scale (e.g., contributors holding governance-controlling majorities in a non-trivial fraction of DAOs and detecting ownership shifts shortly before polls), providing concrete maturity-relevant evidence of today’s governance limitations and attacker incentives. [45]

#### 16) What Happens When Anyone Can Be Your Representative? Studying the Use of Liquid Democracy for High-Stakes Decisions in Online Platforms

- Authors/Org: Andrew B. Hall[46], Sho Miyazaki[47]
- Venue/type: Working paper / empirical study (non-peer-reviewed in this version)
- Publication date: October 2024 (30 Oct 2024)
- Link: [https://andrewbenjaminhall.com/Hall\\_Miyazaki\\_Delegation.pdf](https://andrewbenjaminhall.com/Hall_Miyazaki_Delegation.pdf)
- Why it matters: Uses on-chain data from **250,000+ voters** and **1,700 proposals** across **18** Ethereum-based DAOs; finds ~**17%** of voting tokens delegated and estimates that delegation programmes (UI/info hubs) increase delegation and voting—direct evidence that delegation can scale participation but may centralise power via “super-delegates.” [48]

#### 17) Delegated voting in decentralized autonomous organizations: a scoping review

- Authors/Org: Lukas Weidener[49] et al.
- Venue/type: Peer-reviewed review article (Frontiers in Blockchain)
- Publication date: June 2025 (published 2 Jun 2025)
- Link: <https://www.frontiersin.org/journals/blockchain/articles/10.3389/fbloc.2025.1598283/pdf>
- Why it matters: Synthesises the literature on delegated voting and highlights governance trade-offs and implementation patterns; useful “state of practice” evidence for whether delegation is stabilising participation or creating new centralisation/manipulation risks. [50]

#### 18) Liquid Democracy in DPOS Blockchains

- Authors/Org: Chao Li[51] et al.
- Venue/type: Peer-reviewed conference paper (ACM BSCI ’23) + arXiv version
- Publication date: July 2023 (BSCI ’23 held 10 Jul 2023; arXiv posted Sep 2023)

- Link: <https://arxiv.org/pdf/2309.01090>
- Why it matters: Analyses real delegation data from EOS and Steem and reports that liquid democracy is deployed on platforms with **millions of users**, while also examining delegation networks and identifying suspicious Sybil accounts—direct evidence for both scalability potential and sybil/manipulation constraints. [52]

#### 19) Voting governance and value creation in decentralized autonomous organizations (DAOs)

- Authors/Org: Cristiano Bellavitis[53], Paul P. Momtaz[54]
- Venue/type: Peer-reviewed journal article (Journal of Business Venturing Insights)
- Publication date: June 2025
- Link: <https://www.sciencedirect.com/science/article/pii/S2352673425000241>
- Why it matters: Provides empirical evidence that governance design choices (on-chain vs off-chain voting, coalition size) correlate with measurable outcomes (e.g., fundraising/value effects), supporting the plausibility that governance stacks can create (or destroy) value at scale and that transparency/execution choices matter commercially. [55]

#### 20) Verifiable Off-Chain Governance

- Authors/Org: Jake Hartnell[56], Eugenio Battaglia[57]
- Venue/type: Preprint / technical framework proposal (web-published manuscript)
- Publication date: December 2025 (web-hosted version; manuscript itself labelled “December 2024”)
- Link: <https://arxiv.org/html/2512.23618v1>
- Why it matters: Proposes governance architectures that use verifiable off-chain computation (ZK proofs/TEEs) and explicitly frames “Policy-as-Code” and multidimensional legitimacy/attestations—directly aligned with the ART’s “governance stacks” concept, while still being early-stage evidence (framework-level rather than broadly deployed). [58]

#### Maturity score (1–7) and reasoning

##### Final maturity score 5

[59]

##### Evidence-to-rubric mapping

##### Why level 5 is justified (rules out levels 1–4):

- The ART is not merely theoretical or lab-only: there are **operational, production governance systems** with explicit scaling mechanisms (parallel referendums, delegation, threshold tracks) documented in deployed networks (e.g., OpenGov-style on-chain governance). [31]
- There are **mature, standardised identity primitives** (DIDs, verifiable credentials, credential integrity proofs) and **government-grade identity guidance** (NIST) that support building real identity/permission layers rather than bespoke, one-off implementations. [60]
- Security and operationalisation signals exist: governance frameworks and privacy-preserving voting components show **structured auditing** and explicit security analysis, including ZK voting infrastructure audits and systematised DAO attack taxonomies/incident analyses. [61]

Together, these exceed “PoC” in the narrow sense (level 4) because multiple components are fielded, iterated, and audited in production-like environments—yet they do not fully reach a “product at scale across many sectors with rising demand” posture as an integrated governance stack.

#### **Why level 6 is not yet justified (what is missing):**

- The strongest empirical and security literature still documents **systemic weaknesses** in real-world DAO governance—bribery, coercion, power concentration, and human/economic attack surfaces that audits often under-cover—implying the integrated system is not yet “production-scaled with expanding applications” under the rubric’s meaning. [62]
- While identity standards and EU wallet architectures are advancing (including pilots), **credential-based sybil resistance + compliance-grade governance** is not yet consistently delivered as a widely adopted, end-to-end governance stack across enterprises/consortia; regulators and law reform bodies are still scoping legal treatment and certification approaches. [63]
- Privacy-preserving voting/audit mechanisms (e.g., ZK anti-collusion voting) show meaningful progress and auditing, but remain **specialised** and may involve liveness/trust trade-offs (e.g., coordinator role), suggesting they are not yet ubiquitous infrastructure for mass governance. [36]

#### **Sub-component maturity breakdown and aggregation**

##### **Core proposal/voting/execution stacks (smart-contract governance frameworks and deployed governance systems) → maturity ~6**

- Evidence: production governance designs supporting parallelism, tracks/thresholds, and delegation in an operational network. [31]
- Evidence: modular governance frameworks with explicit permission systems and documented audit history for governance-critical contracts. [33]

##### **Participation scaling via delegation (liquid democracy, multi-role delegation, UX interventions) → maturity ~5–6**

- Evidence: large-scale empirical measurement (250k+ voters, 1,700 proposals, 18 DAOs) showing delegation is actively used (~17% tokens delegated) and that design interventions can raise participation. [48]
- Evidence: delegated voting literature synthesis and DPoS blockchain deployments analysing delegation networks and sybil signals. [64]

##### **Manipulation resistance and security resilience (bribery/coercion, governance attacks, HCI threats) → maturity ~3–4**

- Evidence: peer-reviewed incident taxonomy with 28 real-world cases and explicit observation that many incidents exploit non-code attack surfaces; multiple studies documenting concentration and strategic behaviour around votes. [65]
- Interpretation: The threats are well-characterised and partially mitigated, but “robust at scale” remains unproven for many governance contexts (especially where large values and adversarial incentives exist). [66]

##### **Privacy-preserving audits / coercion-resistant voting → maturity ~4–5**

- Evidence: audited ZK voting protocol designs explicitly aimed at deterring vote bribery/coercion while preserving verifiability; nonetheless with non-trivial operational roles/trade-offs (coordinator liveness). [36]

### Identity/credentials and compliance integration → maturity ~4

- Evidence: standards maturity (W3C Recommendations) plus government guidance (NIST) and EU wallet architecture frameworks with pilots and reference implementations. [5]
- Evidence: legal/regulatory scoping and certification frameworks still actively developing. [15]

### Aggregation to one score:

- Taking a pragmatic average across these subcomponents (core stack ~6; delegation ~5.5; security/manipulation resistance ~3.5; privacy voting ~4.5; identity/compliance ~4) yields ~4.7–4.9, rounded to **5** to reflect that: (i) base governance stacks and delegation are already operational, but (ii) the ART's *full* stack vision (credible sybil resistance + privacy-preserving audits + compliance-grade governance) is not yet broadly delivered as a unified, scalable market-standard system. [67]

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## ART 11.089 Digital Learning Networks and Skill Credentialing

### ART extraction

#### A) Primary capability (what the ART claims)

- A globally scalable digital learning network that couples online instruction (short modules + practice + community) with **portable, independently verifiable skill credentials** (not locked to a single platform).
- **AI tutors** that personalise explanation, generate practice, run interactive “task-like” simulations, and adapt difficulty/feedback across text/voice/visual modalities.
- **Automated (but auditable) credentialing**: evidence-based assessment mapped to explicit rubrics, producing cryptographically signed credentials that can be stored in a personal wallet and selectively disclosed.

#### B) Key sub-components / sub-threads

- AI tutoring systems with pedagogical guardrails (reducing answer leakage; handling hallucinations; safe feedback).
- AI-assisted or AI-mediated assessment at scale (rubric adherence; prompt-hacking resistance; human review fallback).
- Credential data standards for portability (verifiable credential data models, badge records, learner record bundles).
- Digital identity + wallets (issuer/holder/verifier flows; consent and selective disclosure; interoperability).
- Credential “market plumbing” (registries, schemas, metadata, search/discovery, competency alignment).
- Anti-fraud and trust systems (identity proofing, audit trails, behavioural signals, dispute resolution).
- Governance/quality assurance (standards bodies, policy frameworks for micro-credentials, cross-border recognition).

#### C) Maturity indicators that would count as strong evidence for this ART

- Peer-reviewed or well-documented **RCTs / field trials** showing AI tutoring improves learning outcomes and/or reduces time-to-competency in authentic settings.
- Demonstrations of **AI-based assessment** in real courses or certification workflows, including documentation of failure modes (bias, rubric drift, prompt hacking) and mitigations.
- Stable, widely adoptable **open standards** for credential formats and verification (W3C/standards body “final” publications; conformance/certification programs).
- **Cross-platform credential portability** proven via interoperable wallets, issuance protocols, and verifier tooling (multi-actor interoperability events; specs reaching final release).
- Evidence of **multi-party deployment** (multi-country pilots; multiple well-capitalised actors; integration with existing platforms and workflows).
- Clear progress on **identity / privacy / selective disclosure** mechanisms suitable for credentials (privacy-preserving presentations; selective disclosure standards; operational pilots).

- Early signs of **scaling economics** (increasing production deployment beyond pilots; repeatable implementation toolkits; ecosystem directories/certification).

#### **Evidence (10–20 recent, reliable sources)**

##### **1) AI tutoring outperforms in-class active learning: an RCT introducing a novel research-based design in an authentic educational setting**

- Authors/organisation: Greg Kestin[1] et al. (Harvard affiliations listed)
- Venue/type: Peer-reviewed paper (Scientific Reports)
- Publication date: 03 June 2025
- Link: <https://www.nature.com/articles/s41598-025-97652-6>
- Why it matters: Reports a randomised controlled trial in an authentic educational setting where “AI tutoring” is evaluated against in-class active learning, directly supporting plausibility for learning gains from scalable AI-mediated tutoring. [2]

##### **2) GPT-4 as a Homework Tutor Can Improve Student Engagement and Learning Outcomes**

- Authors/organisation: Alessandro Vanzo[3] et al.
- Venue/type: Peer-reviewed conference paper (ACL 2025, long papers)
- Publication date: July–August 2025 (conference proceedings dated July 27–Aug 1, 2025)
- Link: <https://aclanthology.org/2025.acl-long.1502.pdf>
- Why it matters: Describes a prompting strategy for interactive homework sessions with GPT-4 and reports an RCT in four high-school classes, observing significant learning and engagement improvements—evidence that AI “tutor sessions” can substitute a slice of instruction with measurable outcomes. [4]

##### **3) Large Language Model as an Assignment Evaluator: Insights, Feedback, and Challenges in a 1000+ Student Course**

- Authors/organisation: Cheng-Han Chiang[5] et al.
- Venue/type: Peer-reviewed conference paper (EMNLP 2024)
- Publication date: November 2024
- Link: <https://aclanthology.org/2024.emnlp-main.146/>
- Why it matters: Documents use of GPT-4 as an automatic assignment evaluator in a course with over 1,000 students, and concretely reports both acceptance and failure modes (instruction non-adherence; prompt manipulation to secure high scores), which directly informs maturity constraints for AI-automated credentialing and anti-fraud design. [6]

##### **4) AutoTutor meets Large Language Models: A Language Model Tutor with Rich Pedagogy and Guardrails**

- Authors/organisation: Sankalan Pal Chowdhury[7] et al.
- Venue/type: Technical preprint (arXiv)
- Publication date: Submitted 14 Feb 2024 (revised through Apr 2024)
- Link: <https://arxiv.org/abs/2402.09216>
- Why it matters: Targets a key feasibility bottleneck for AI tutors—maintaining pedagogical strategy and preventing “answer leakage”—by proposing a structured tutoring-system design with guardrails, supporting the plausibility of safer, more instructionally consistent AI tutors. [8]

##### **5) ChatGPT in lesson preparation – A Teacher Choices Trial**

- Authors/organisation: Palak Roy[9] et al., National Foundation for Educational Research[10]

- Venue/type: Field trial report (school-randomised controlled trial)
- Publication date: 12 December 2024
- Link: <https://www.nfer.ac.uk/publications/chatgpt-in-lesson-preparation-a-teacher-choices-trial/>
- Why it matters: In a 2024 school-randomised trial (259 teachers, 68 schools), teachers using ChatGPT spent ~69% of the lesson-prep time of the control group (with no detected quality difference in sampled outputs), showing a near-term path for scaling “structured practice + feedback” production capacity beyond human constraints. [11]

#### 6) **Council recommends European approach to micro-credentials**

- Authors/organisation: Council of the European Union[12]
- Venue/type: Authoritative policy / press release (PDF)
- Publication date: 16 June 2022
- Link: <https://www.consilium.europa.eu/en/press/press-releases/2022/06/16/council-recommends-european-approach-to-micro-credentials/pdf/>
- Why it matters: Establishes an EU-level push for a common definition, standards, and principles for micro-credentials—direct maturity evidence that governments are formalising an ecosystem where modular learning outcomes can become portable and recognisable across institutions. [13]

#### 7) **Micro-credentials for Lifelong Learning and Employability: Uses and Possibilities (Education Policy Perspectives No. 66)**

- Authors/organisation: OECD[14]
- Venue/type: Authoritative intergovernmental report
- Publication date: 2023 (report hosted under 2023/03)
- Link: [https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/03/micro-credentials-for-lifelong-learning-and-employability\\_13dd81a9/9c4b7b68-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/03/micro-credentials-for-lifelong-learning-and-employability_13dd81a9/9c4b7b68-en.pdf)
- Why it matters: Synthesises policy and ecosystem development, and provides concrete market signal that micro-credential offerings on major platforms expanded rapidly (e.g., aggregated counts rising from ~600 in 2018 to ~1900 in 2022 across several large platforms), supporting the “scales globally with low marginal cost” claim and showing demand-side pull. [15]

#### 8) **Credential Engine Schemas Handbook (CTDL)**

- Authors/organisation: Credential Engine[16]
- Venue/type: Technical schema documentation (public handbook)
- Publication date: Last updated 20 Feb 2024
- Link: <https://credreg.net/ctdl/handbook>
- Why it matters: Provides a concrete, implementable metadata framework (CTDL) for describing credentials, assessments, learning opportunities, value transfer, and evidence—an enabling substrate for an open “skill exchange” where third parties can search, compare, and verify credential claims independent of any single platform. [17]

#### 9) **Decentralized Identifiers (DIDs) v1.0**

- Authors/organisation: W3C[18]
- Venue/type: Standards body document (W3C Recommendation)

- Publication date: 19 July 2022
- Link: <https://www.w3.org/TR/did-core/>
- Why it matters: DIDs provide a widely standardised building block for decentralised identity references, supporting the ART's feasibility requirement for identity controls and verifiable credential ecosystems (issuer/holder/verifier) without relying on a single platform's account system. [19]

#### 10) Verifiable Credentials Data Model v2.0

- Authors/organisation: World Wide Web Consortium[20] (published as W3C Recommendation)
- Venue/type: Standards body document (W3C Recommendation)
- Publication date: 15 May 2025
- Link: <https://www.w3.org/TR/vc-data-model-2.0/>
- Why it matters: Defines the core issuer–holder–verifier model and extensible data model for tamper-resistant credentials (explicitly including “education certificate” as an example), underpinning the plausibility of portable credentials that can be verified outside the issuing platform. [21]

#### 11) Open Badges Specification v3.0 (Final Release)

- Authors/organisation: 1EdTech Consortium[22]
- Venue/type: Standards body specification (Final Release)
- Publication date: Date issued 06 Nov 2025
- Link: <https://www.imsglobal.org/spec/ob/v3p0>
- Why it matters: Updates Open Badges to align with W3C Verifiable Credentials conventions, explicitly aiming at portability and cryptographic proofs so that skills/achievements can be packaged into verifiable credentials and shared across systems—core to “open, portable skill credentialing.” [23]

#### 12) Comprehensive Learner Record (CLR) 2.0 Certification Guide

- Authors/organisation: 1EdTech Consortium
- Venue/type: Conformance/certification guide for a standards-based record format
- Publication date: Date issued 15 Dec 2025
- Link: <https://www.imsglobal.org/spec/clr/v2p0/cert>
- Why it matters: Defines how systems can certify conformance to a machine-readable, multi-provider achievement record, supporting the “continuously updated skill exchange” concept where achievements from different issuers can be curated into verifiable portable records. [24]

#### 13) Question & Test Interoperability (QTI) 3.0 Best Practices and Implementation Guide

- Authors/organisation: 1EdTech Consortium
- Venue/type: Standard implementation guide for test/item interchange and reporting
- Publication date: Date issued 01 Oct 2024
- Link: <https://www.imsglobal.org/spec/qti/v3p0/impl>
- Why it matters: Provides technical interoperability for exchanging assessment items, tests, results and usage data between tools—an essential supporting layer for evidence-based assessment at scale (including multi-vendor assessment delivery and analytics). [25]

#### 14) Updates to the European Digital Credential Infrastructure – EDC Release 1.8

- Authors/organisation: Europass / European Commission[26] (EDC infrastructure release

note)

- Venue/type: Technical release note (PDF)
- Publication date: June 2023
- Link: <https://europass.europa.eu/system/files/2023-07/EDC%20Newsletter%201.8.pdf>
- Why it matters: Describes concrete infrastructure evolution for issuing verifiable learning credentials across Europe (e.g., migration toward JSON-LD compatibility and updated signing approaches), showing real engineering work on portable credential formats and tooling—not just conceptual standards. [27]

#### 15) The European Digital Identity Wallet Architecture and Reference Framework (ARF)

- Authors/organisation: European Commission (Shaping Europe’s digital future library item)
- Venue/type: Authoritative specification/report (policy & legislation library)
- Publication date: 10 Feb 2023 (last update 25 Aug 2023)
- Link: <https://digital-strategy.ec.europa.eu/en/library/european-digital-identity-wallet-architecture-and-reference-framework>
- Why it matters: Provides a published reference framework for interoperable EU digital identity wallets, directly supporting feasibility of “personal wallets” for storing and selectively sharing verifiable credentials at population scale. [28]

#### 16) EU Digital Identity Wallet Pilot implementation

- Authors/organisation: European Commission (Shaping Europe’s digital future)
- Venue/type: Government programme status page (pilot deployment evidence)
- Publication date: Last update 18 Feb 2025
- Link: <https://digital-strategy.ec.europa.eu/en/policies/eudi-wallet-implementation>
- Why it matters: Documents real large-scale pilots launched in April 2023 with **over 350 entities** across **26 Member States plus Norway, Iceland, and Ukraine**, and explicitly includes “education certification” as a tested use case—strong maturity evidence for cross-border credential wallets moving beyond PoC. [29]

#### 17) Meeco Report: EUDI Large Scale Pilots, Insights & Recommendations

- Authors/organisation: Meeco[30]
- Venue/type: Industry report synthesising pilot learnings (cross-consortium)
- Publication date: January 2026
- Link: [https://media.meeco.me/public-assets/reports/Meeco\\_Report\\_EUDI\\_Large\\_Scale\\_Pilots.pdf](https://media.meeco.me/public-assets/reports/Meeco_Report_EUDI_Large_Scale_Pilots.pdf)
- Why it matters: Summarises results across the four major EU wallet pilots, reporting testing at substantial scale (e.g., “over 1,300”) and highlighting remaining large-scale integration and governance gaps—useful maturity evidence for what’s working versus what still blocks full market rollout. [31]

#### 18) OpenID for Verifiable Credential Issuance (OpenID4VCI) – Final Specification

- Authors/organisation: OpenID Foundation[32]
- Venue/type: Standards body specification (final)
- Publication date: 16 Sept 2025
- Link: [https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0-final.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0-final.html)
- Why it matters: Specifies interoperable issuance flows for verifiable credentials (issuer ↔



wallet), making it materially easier to integrate credential issuance into web/mobile apps and software APIs—directly aligned with the ART’s “integrated via web apps and APIs” claim. [33]

### 19) SD-JWT-based Verifiable Credentials (SD-JWT VC)

- Authors/organisation: Internet Engineering Task Force[34] (OAuth WG Internet-Draft)
- Venue/type: Standards-track Internet-Draft (selective disclosure VC format)
- Publication date: 05 Feb 2026
- Link: <https://datatracker.ietf.org/doc/draft-ietf-oauth-sd-jwt-vc/>
- Why it matters: Defines a concrete format and processing rules for selectively disclosable verifiable credentials using SD-JWT, directly supporting the ART’s privacy claim: users can reveal only necessary attributes (e.g., a claim without sharing full credential payload). [35]

### 20) Verification of Education Credentials on European Blockchain Services

#### Infrastructure (EBSI): Action Research in a Cross-Border Use Case between Belgium and Italy

- Authors/organisation: Evrim Tan[36] et al.
- Venue/type: Peer-reviewed paper (Big Data and Cognitive Computing, MDPI)
- Publication date: April 2023
- Link: <https://www.mdpi.com/2504-2289/7/2/79>
- Why it matters: Reports an empirical cross-border pilot verifying education credentials using EBSI and identifies practical blockers (ecosystem onboarding, wallet issuance/data schemes, interoperability with identity systems), providing grounded evidence of both feasibility and the remaining maturity gaps for real-world verification networks. [37]

#### Maturity score (1–7) and reasoning

##### A) Final maturity score: 5

##### B) Why this is a 5 (and not lower or higher)

A score of **5** is justified because multiple core components have moved beyond “lab prototype” into operational proof-of-concept and early ecosystem implementation, with several strong signals of multi-actor, standards-driven convergence:

- **Evidence that rules out levels 1–3:**
- AI tutoring is already demonstrated in authentic educational settings and controlled studies (peer-reviewed RCT evidence, not just theory). [38]
- Large-scale classroom assessment usage has been demonstrated (GPT-4 used as an assignment evaluator in a 1000+ student course), with concrete operational insights about manipulation risks—this is well beyond basic lab demos. [6]
- Credential portability has mature standard foundations: W3C issued Recommendations for DIDs (2022) and VC Data Model v2.0 (2025), indicating the identity + credential data primitives are standardised enough for broad implementation. [39]
- **Evidence that supports level 5 specifically (multi-actor post-PoC development and fast progress toward deployable systems):**
- Multiple standards bodies have published or finalised key interoperability pieces across the credential lifecycle: Open Badges 3.0 (final, VC-aligned), CLR conformance guidance, and OpenID4VCI for issuance; while the IETF SD-JWT VC draft shows ongoing rapid standardisation for selective disclosure formats. [40]

- EU-level infrastructure and governance efforts are not hypothetical: the EUDI Wallet ARF is published, and large-scale pilots involve hundreds of entities across many countries, explicitly including education credentials. [\[41\]](#)
- Education-specific credential infrastructure (Europass EDC release updates) shows real “platform plumbing” work—format transitions, interoperability focus, and tooling development—consistent with late-stage PoC to production-prototype iteration. [\[27\]](#)
- **What is still missing to justify level 6:**
- Level 6 requires clear evidence that **products are being delivered in increasing amounts** with scaling production deployments, expanding applications, and financing for expansion. The evidence here is strong for *pilots, standards maturity, and operational PoCs*, but weaker on globally scaled, repeatable commercial deployment metrics for an end-to-end “skill exchange” where portable credentials are routinely used in hiring/HR workflows across sectors.
- Real-world reports still highlight material integration and governance gaps (e.g., interoperability/version churn during pilots, semantic interoperability fragility, and the need for stable rulebooks), which are typical of “finishing the production prototype” rather than fully scaled production rollouts. [\[42\]](#)
- AI-automated assessment has demonstrated vulnerabilities (e.g., prompt manipulation to obtain high scores), implying additional anti-fraud controls, validation, and human-in-the-loop escalation are still needed before high-stakes credentialing can be broadly trusted at scale. [\[6\]](#)

### C) Sub-component maturity breakdown and aggregation

- **AI tutoring and guided practice → ~4 (PoC demonstrated in authentic contexts)**
- Anchoring evidence: peer-reviewed RCT evidence for AI tutoring in authentic settings and RCT evidence for GPT-4 homework tutoring improving learning/engagement. [\[43\]](#)
- Rationale: Operational effectiveness has been shown, but broad, standardised, high-stakes deployment with consistently robust pedagogy and safety controls remains uneven. [\[44\]](#)
- **AI-mediated assessment and rubric adherence → ~4 (real deployment with known failure modes)**
- Anchoring evidence: GPT-4 used as an assignment evaluator at 1000+ scale, with documented instruction-following failures and prompt hacking risk. [\[6\]](#)
- Rationale: Demonstrated use at scale, but still not “production-grade for high-stakes credentialing” without stronger anti-fraud and audit designs.
- **Portable credential data formats and bundling (VCs, badges, learner records) → ~5**
- Anchoring evidence: W3C VC Data Model v2.0 Recommendation; Open Badges 3.0 Final Release aligned to VC conventions; CLR conformance guidance for multi-provider records. [\[45\]](#)
- Rationale: Standards are mature enough for multi-actor adoption and integration, and are actively being used as foundations for ecosystem build-out.
- **Wallet issuance / verification interoperability + selective disclosure → ~5**

- Anchoring evidence: OpenID4VCI (final) for issuance flows; SD-JWT VC Internet-Draft for selective disclosure VC representations; EUDI Wallet ARF and multi-country pilots. [46]
- **Ecosystem/policy scaffolding for micro-credentials** → ~5
- Anchoring evidence: EU Council micro-credentials recommendation push (2022) and OECD synthesis plus market growth signal (2023). [47]

**Aggregation to one score:** The ART is a *bundle* where major parts must work together (AI tutoring + assessment + wallet-based portable credentials + governance/trust). Subscores cluster around **4–5**, and the wallet/credential standards ecosystem is clearly at **5**, but reliable, widely adopted, end-to-end market scaling is not yet evidenced at level 6. Therefore, an average-based single score of **5** best fits the whole system’s maturity given the current evidence.

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## ART 11.090 Prediction-Market Forecasting Platforms

### ART extraction

- **Primary capability**
- Turn dispersed, partially held beliefs from many participants into a **single, continuously updated probability** for real-world events using **prediction-market price signals**. [1]
- Provide a **decision-support layer** (dashboards + APIs) so forecasts can be embedded into organisational planning workflows (not just “betting”). [2]
- Maintain credible **verification/settlement** so probabilities can be scored and incentives remain tied to accuracy. [3]
- **Key sub-components / variants**
- **Market mechanisms:** order books vs automated market makers (e.g., LMSR-style), including thin-liquidity robustness and bounded-loss design variants. [4]
- **Question engineering / decomposition:** generating well-posed, resolvable questions and (eventually) linking sub-questions so updates propagate. [5]
- **Identity, reputation, and calibration tracking:** measuring performance over time, weighting participants, and improving forecast quality by talent selection. [6]
- **Integrity controls:** manipulation resistance, anomaly detection (e.g., wash trading), and arbitrage/consistency checking across related markets. [7]
- **Outcome verification and dispute processes:** rulebooks, data sources, and—in harder cases—mechanisms that reduce reliance on an external “ground truth”. [8]
- **Regulation and compliance:** whether event contracts are permitted, how they are supervised, and requirements for reporting/transparency. [9]
- **Integration and developer surfaces:** real-time market data feeds, execution APIs, versioning, and operational tooling for downstream systems. [10]
- **Maturity indicators that would constitute strong evidence**
- **Peer-reviewed/field evidence** that prediction markets produce calibrated, decision-relevant probabilities (especially under low participation / thin markets). [11]
- **Operational scaling evidence:** large numbers of markets/contracts, transaction data, and real-time data infrastructure. [12]
- **Demonstrated governance and settlement:** explicit rulebooks (including scalar/numeric contracts), audit trails, and dispute/verification procedures. [13]
- **Integrity tooling** shown by measurement and mitigation of manipulation/wash trading/arbitrage. [7]
- **Regulatory path** (permissions + constraints) and evidence of institutional buy-in or major infrastructure partnerships. [14]

**Evidence (10–20 recent, reliable sources)**

**Peer-reviewed forecasting deployments and benchmarks**

**[1] Crowd prediction systems: Markets, polls, and elite forecasters.** Authors: Pavel Atanasov[15] et al.; Venue/type: *International Journal of Forecasting* (peer-reviewed journal article); Publication date: Apr–Jun 2025; Link:

<https://www.sciencedirect.com/science/article/abs/pii/S0169207023001413>.

Finds (i) prediction markets and prediction polls are statistically tied on aggregate accuracy,

(ii) **LMSR markets outperform continuous double auctions especially on low-activity questions**, and (iii) “small, elite” crowds outperform larger sub-elite crowds—directly informing platform design choices around liquidity and reputation/talent selection. [16]

**[2] When do prediction markets return average beliefs? Experimental evidence.** Authors: Marco Mantovani[17] & Antonio Filippin; Venue/type: *Games and Economic Behavior* (peer-reviewed journal article, open access); Publication date: Feb 2026; Link: <https://www.sciencedirect.com/science/article/pii/S0899825625001861>.

Lab evidence on how market institution affects the relationship between **prices and average beliefs**, finding prices are closer to average belief in a **double auction** than in a call auction, and highlighting that traders update beliefs toward observed prices—important for interpreting “probability dashboards” and for UI/UX cues around confidence and feedback. [18]

**[3] Using prediction markets and forecasting surveys to predict 28 replication outcomes in psychology.** Authors: Dara Viganola[19] et al.; Venue/type: *Royal Society Open Science* (peer-reviewed journal article); Publication date: Jan 2026; Link: <https://royalsocietypublishing.org/doi/full/10.1098/rsos.242056>.

Demonstrates a real deployment where prediction markets (and parallel surveys) are used to generate probabilistic forecasts for **28 verifiable future outcomes**, directly supporting plausibility that market-based probabilities can be operationalised and evaluated as a repeatable signal stream. [20]

**[4] Examining the replicability of online experiments selected by a decision market.**

Authors: Felix Holzmeister[21] et al.; Venue/type: *Nature Human Behaviour* (peer-reviewed journal article, open access); Publication date: Nov 2024; Link: <https://www.nature.com/articles/s41562-024-02062-9>.

A proof-of-concept “decision market” with **n = 162** social scientists trading on **41** experiments; replication rates were **83% for top-12 vs 33% for bottom-12**, showing markets can both forecast and drive structured prioritisation decisions (a concrete analogue of forecast-graph task decomposition and portfolioing). [22]

**[5] Can expert prediction markets forecast climate-related risks?** Authors: Mark Roulston[23] & Kim Kaivanto; Venue/type: *Bulletin of the American Meteorological Society* (peer-reviewed journal article; accessed via institutional record); Publication date: Oct 2024 (early online Aug 2024); Link: <https://research.lancaster-university.uk/en/publications/can-expert-prediction-markets-forecast-climate-related-risks/>.

Reports results from **24** expert-focused prediction markets on climate variables (2–12 month horizons) using an **automated market maker** to address low activity, with forecasts described as showing “good reliability”—evidence that domain-specific, expert-recruited platforms can work outside mass-liquid retail settings. [24]

**[6] Joint-outcome prediction markets for climate risks.** Authors: Roulston & Kaivanto; Venue/type: *PLOS ONE* (peer-reviewed journal article, open access); Publication date: Aug 2024; Link: <https://journals.plos.org/plosone/article?id=10.1371%2Fjournal.pone.0309164>. Demonstrates that “joint-outcome” markets with many outcomes can function using an automated market maker and argues that subsidised market making can overcome liquidity constraints—directly relevant to the ART’s forecast graphs/linked sub-questions and numeric/threshold forecasting variants. [25]



## Market mechanism design and market-making

**[7] Prediction-market innovations can improve climate-risk forecasts.** Authors: Todd Kaplan[26] et al.; Venue/type: *Nature Climate Change* (peer-reviewed commentary; accessed via institutional record); Publication date: Oct 2022 (early online Sep 2022); Link: <https://research.lancaster-university.uk/en/publications/prediction-market-innovations-can-improve-climate-risk-forecasts/>.

Motivates advanced market designs for climate-risk contexts (e.g., **conditional forecasts** / **“circularity”** where policies and forecasts interact), providing credible scientific grounding for why future platforms may need richer contract structures than simple binary events. [27]

**[8] A logarithmic market scoring rule agent-based model to evaluate prediction markets.**

Authors: Athos V. C. Carvalho[28] et al.; Venue/type: *Journal of Evolutionary Economics* (peer-reviewed journal article; bibliographic record); Publication date: Sep 2023; Link: [https://ideas.repec.org/a/spr/joevec/v33y2023i4d10.1007\\_s00191-023-00822-w.html](https://ideas.repec.org/a/spr/joevec/v33y2023i4d10.1007_s00191-023-00822-w.html).

Presents an agent-based simulation framework for **LMSR-style automated market makers** to study parameter-setting and behaviour under different processes, supporting engineering plausibility for “model-assisted market making” and controlled-liability liquidity provision.

[29]

## Incentives, settlement, and unverifiable outcomes

**[9] Self-Resolving Prediction Markets for Unverifiable Outcomes.** Authors: Siddarth Srinivasan[30] et al.; Venue/type: arXiv preprint (mechanism design; revised Feb 2025 noted in arXiv HTML record); Publication date: Jun 2023 (revised Feb 2025); Link: <https://arxiv.org/pdf/2306.04305>.

Proposes a mechanism that can elicit/aggregate beliefs **without observing ground truth** by paying participants against a reference agent’s forecast (negative cross-entropy), directly addressing the ART’s “hard-to-verify outcomes” constraint and providing a research-backed alternative to purely human adjudication. [31]

## Manipulation, arbitrage, and market integrity

**[10] Makers and Takers: The Economics of the Kalshi Prediction Market.** Authors: Constantin Bürgi et al.; Venue/type: University College Dublin[32] working paper (UCD Centre for Economic Research, WP25/19); Publication date: Jul 2025 (paper shows “September 2025” on inner title page); Link: [https://www.ucd.ie/economics/t4media/WP2025\\_19.pdf](https://www.ucd.ie/economics/t4media/WP2025_19.pdf).

Uses transaction-level data on **46,282 contracts** across **12,403 events** and analyses **313,972** yes/no contract prices, finding a pronounced favourite–longshot bias: contracts priced < **\$0.10 lose over 60%** on average; also reports average contract returns around **–20% pre-fee** / **–22% post-fee**—evidence of real-world scale plus design needs for exposure caps, education, and integrity monitoring. [33]

**[11] How manipulable are prediction markets?** Authors: Itzhak Rasooly[34] & Roberto Rozzi; Venue/type: arXiv preprint (large-scale field experiment); Publication date: Mar 2025; Link: <https://arxiv.org/html/2503.03312v1>.

Randomly shocks prices across **817** markets and tracks outcomes, finding manipulation effects remain visible even **60 days** later, while higher-trader/volume markets and those with external probability benchmarks revert more—directly motivating anomaly detection, benchmark comparison, and liquidity/diversity strategies in production platforms. [35]

**[12] Unravelling the Probabilistic Forest: Arbitrage in Prediction Markets.** Authors: Oriol Saguillo et al. (IMDEA Networks/Oxford); Venue/type: research paper (public PDF; empirical analysis); Publication date: 2025 (month not stated in the PDF front-matter visible via crawl); Link: <https://suarez-tangil.networks.imdea.org/papers/2025aft-arbitrage.pdf>. Empirically analyses on-chain data and finds mispricing across logically related outcomes on Polymarket, estimating **~\$40M** in realised arbitrage profits—concrete evidence that large platforms need consistency checks, linked-market reasoning, and guardrails when markets form a forecast “graph.” [\[36\]](#)

**[13] Network-Based Detection of Wash Trading.** Authors: Allen Sirolly et al.; Venue/type: Columbia Business School [\[37\]](#) research paper (SSRN working paper); Publication date: Nov 2025 (revised Jan 2026); Link: <https://ssrn.com/abstract=5714122>. Proposes a network method to detect wash-trading clusters and applies it to Polymarket [\[38\]](#), estimating suspicious activity peaking at **nearly 60% of volume (Dec 2024)**—directly relevant to maturity of “anomaly detection” and the operational necessity of identity/integrity layers. [\[39\]](#)

### Regulation, compliance, and industrial scaling evidence

**[14] Automating forecasting question generation.** Authors not fully enumerated in the arXiv crawl excerpt; Venue/type: arXiv preprint (LLM/agent workflow + evaluation); Publication date: Jan 2026; Link: <https://www.arxiv.org/pdf/2601.22444>. Describes an agentic workflow for generating forecasting questions and reports evaluation on **1,499 generated questions** (with filtering/verification for resolvability)—direct evidence that “question engineering” can be partially automated, improving throughput and standardisation. [\[40\]](#)

**[15] CFTC Disapproves KalshiEX LLC’s Congressional Control Contracts.** Organisation: Commodity Futures Trading Commission [\[41\]](#); Venue/type: government press release; Publication date: Sep 2023; Link: <https://www.cftc.gov/PressRoom/PressReleases/8790-23>. Shows that market maturity is not purely technical: regulators can prohibit whole market categories, anchoring the ART’s constraint that regulation and safety considerations shape feasibility, product scope, and go-to-market strategy. [\[42\]](#)

**[16] D.C. Circuit opinion in Kalshi stay litigation (order denying stay pending appeal).** Organisation: United States Court of Appeals for the District of Columbia Circuit [\[43\]](#); Venue/type: court opinion (PDF); Publication date: Oct 2024; Link: <https://media.cadc.uscourts.gov/opinions/docs/2024/10/24-5205-2077790.pdf>. Details contested issues around political event contracts and cites scale-related risk factors (e.g., concerns about manipulation and the court noting Kalshi’s plan could allow, in some cases, **up to \$100M per contract**), underscoring how governance, integrity, and legal definitions are hard constraints for scaled forecasting markets. [\[44\]](#)

**[17] CFTC Letter No. 24-15 (No-Action).** Organisation: CFTC; Venue/type: government no-action letter (PDF); Publication date: Oct 2024; Link: <https://www.cftc.gov/csl/24-15/download>. Grants a no-action position subject to conditions including that contracts are **fully collateralised**, that time-and-sales data are published promptly, and that transaction information is provided under CFTC rules—evidence of audit-trail and reporting expectations that a production platform must meet. [\[45\]](#)

**[18] KalshiEX LLC – Rulebook Amendment for Scalar Contracts.** Organisation: Kalshi[46] (submitted to CFTC); Venue/type: regulatory filing / rulebook update (PDF); Publication date: Feb 2025; Link: <https://www.cftc.gov/sites/default/files/filings/orgrules/25/02/rules02172515652.pdf>. Documents rule changes to support scalar outcomes (beyond simple binary), directly aligning with the ART’s expectation that platforms will support numeric thresholds/timelines and require formalised settlement and market-structure definitions. [47]

**[19] Kalshi API Changelog.** Organisation: Kalshi; Venue/type: vendor technical documentation (dated changelog); Publication date: Feb 2026 (recent entries); Link: <https://docs.kalshi.com/changelog>. Shows a production-grade integration surface (e.g., WebSocket channels for real-time tickers and order updates, precision timing fields, order-group controls, and deprecations/breaking changes), supporting maturity of “standard APIs” and operational readiness for embedding probabilities into other systems. [10]

**[20] ICE Announces Strategic Investment in Polymarket.** Organisation: Intercontinental Exchange[48]; Venue/type: corporate press release (primary source); Publication date: Oct 2025; Link: <https://ir.theice.com/press/news-details/2025/ICE-Announces-Strategic-Investment-in-Polymarket/default.aspx>. Reports ICE will invest **up to \$2B** and become a distributor of Polymarket’s event-driven data—strong evidence of late-stage commercialisation, institutional demand for market-implied probabilities, and scaling via established financial infrastructure providers. [49]

### **Maturity score (1–7) and reasoning**

**Final maturity score: 7**

#### **Why this score fits the rubric**

- **What rules out lower levels (≤5)**
- The technology is not merely theoretical or lab-prototype: there is large-scale, real-world operational evidence from a commercial event-contract platform analysed with transaction-level data (**46,282 contracts across 12,403 events, 313,972 prices**) and measurable behavioural/market effects (favourite–longshot bias; large losses in low-probability contracts). [50]
- Prediction/decision markets have repeatedly been deployed in rigorous, peer-reviewed contexts (science replication selection and forecasting; climate risk expert markets), showing the mechanism is workable outside purely academic toy settings. [51]
- The ecosystem has production-grade integration surfaces (dated API change management, real-time streaming interfaces), which is characteristic of shipping platforms rather than post-PoC prototypes. [10]
- **What supports level 7 specifically (competing products delivered + rising demand + major financing)**
- Evidence of **multiple operating platforms and active research scrutiny**: studies directly measure wash trading on Polymarket and arbitrage inconsistencies across related markets, which only become salient at meaningful scale. [52]

- **Major industrial financing and distribution commitment:** ICE's announcement of investing up to **\$2B** and distributing event-driven data is strong "institutional mainstreaming" evidence of demand and scale-up financing. [49]

**What is still missing or constraining, despite a 7**

Because **7 is the rubric maximum**, the remaining gaps are not about "is there a product?" but about **how fully the ART's 20-year vision is realised across domains:**

- **Regulatory stability and scope** remain binding constraints: US regulatory actions and litigation show that whole market categories (especially politics/elections) can be restricted or contested, affecting what an "enterprise forecasting platform" can legally offer in different jurisdictions. [53]
- **Integrity and participant-protection tooling** is still an active technical frontier: field and empirical studies document manipulability persistence in some settings and substantial wash-trading signatures, implying continuing needs for surveillance, exposure caps, benchmark comparison, and identity/reputation engineering. [54]
- **Automated question engineering** is emerging but not yet a settled industry standard; early evidence shows feasibility at scale (1,499 generated questions) but this remains preprint-stage and must be operationalised safely to avoid ill-posed or gameable markets. [40]

**Sub-component breakdown and aggregation**

- **Core market-based probability production + API delivery** → **7** → supported by large-scale transaction analysis and production API evolution. [55]
- **Regulatory/compliance + audit trail expectations** → **6–7** → strong evidence of formalised filings, no-action conditions, and court-reviewed constraints. [56]
- **Integrity (manipulation detection, arbitrage consistency, wash-trading surveillance)** → **6** → strong measurement evidence exists, but the research indicates persistent vulnerabilities that require ongoing mitigation and standardisation. [57]
- **Question engineering / forecast-graph automation** → **3–4** → clear technical progress and evaluation exists, but it remains early and not yet robustly standardised across production forecasting-market platforms. [58]

**Aggregation approach:** functionality is largely continuous across variants (all aim to produce market-implied probabilities usable in decision workflows). The existence of scaled products and institutional financing justifies scoring by the **maximum demonstrated maturity for the core functionality**, while explicitly noting that automation and some governance subcomponents lag behind. [59]

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[7] [35] [54] [57] How manipulable are prediction markets? For comments on our experimental design, we are grateful to Jesper Akesson, Adam Brzezinski, Robin Hanson, Junnan He and Koleman Strumpf. For additional comments and suggestions, we would like to thank Sam Altmann, Johannes Abeler, Miguel Ballester, Gabriele Camera, Jeanne Commault, Antoine Ferey, Laure Goursat, Robert Hahn, Emeric Henry, Marco Mantovani, Théo Marquis, Ryan Oprea, Franz Ostrizek, Lionel Page, Eduardo Perez-Richet, Stefan Pollinger, Daniela Puzzello, Catriona Scott, Alessandro Stringhi, Jasmine Theilgaard, Séverine Toussaert and Eugenio Verrina. We are also grateful to audiences at Sciences Po, the University of Oxford, the Lisbon School of Economics and Management, City St George's, and the Panthéon-Sorbonne Prediction Markets Workshop. This project received IRB approval from the Paris School of Economics (2023-042). [Main pre-registration; Follow-up] [Simulations] [Replication package]

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## Group 12 - Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 Universal IoT Interoperability Standards

#### 1. ART extraction

- **A) Primary capability (claimed)**
- A *globally adopted* bundle of open protocols + certification profiles enabling “plug-and-play” interoperability for IoT devices across vendors and ecosystems (identity, discovery, capability description, permissions, data exchange, updates).
- Standardised, machine-readable device descriptions and common APIs/schemas so software agents can interact with heterogeneous devices without bespoke adapters/gateways.



- Built-in security baseline (hardware-backed identity where possible, secure onboarding, encryption, signed updates, revocation/auditability) scalable to constrained devices and large fleets.
- **B) Key sub-components / variants (sub-threads)**
- **Application-layer interoperability + data models** (e.g., common clusters/capability models for device control/telemetry).
- **Machine-readable “Thing” description & metadata** (capabilities/interfaces; protocol bindings to HTTP/CoAP/MQTT, etc.).
- **Discovery & onboarding** (QR/NFC/other bootstraps; “join network + join ecosystem” workflows; late binding/ownership transfer).
- **Security baseline + certification/labels** (minimum technical requirements, audit evidence, test labs, verified marks; mapping across regions).
- **Device management + firmware update interoperability** (secure update manifests, update status reporting, cryptographic profiles; constrained device compatibility).
- **Network-layer foundations** (IPv6 mesh, credential sharing, border routers; time/connectivity assumptions; datagram security).
- **C) Maturity indicators that would constitute strong evidence**
- Widely adopted *standards formally published* by major standards bodies (Recommendation/RFC/approved specs) **plus** stable compatibility profiles and test suites.
- Demonstrated *cross-vendor interoperability in real deployments* (multi-ecosystem / multi-admin, bridging across platforms; measurable overhead).
- Evidence of *certification programmes operating at scale* (authorised test labs, published certification processes, increasing certified product counts).
- Evidence of *shipping products and expanding device categories* that rely on the standards (not just pilots), with repeatable onboarding and lifecycle management.
- Demonstrated *secure onboarding + secure update pipelines* suitable for constrained devices and fleet operations (algorithm profiles, manifest formats, encryption, revocation/credential rotation).
- Signs of convergence (multiple major ecosystems aligning on the same core interoperability layer; decreasing fragmentation at least within significant IoT segments).

## 2. Evidence (10–20 recent, reliable sources)

### 1) Web of Things (WoT) Architecture 1.1

**Organisation:** W3C<sup>[1]</sup> (Web of Things Working Group)

**Type:** Standards body document (W3C Recommendation)

**Date:** Dec 2023 (05 Dec 2023)

**Link:** <https://www.w3.org/TR/wot-architecture11/> <sup>[2]</sup>

**Why it matters:** Defines an architecture explicitly aimed at interoperability across IoT platforms and

domains, describing modular building blocks (Thing Description, Discovery, Binding Templates) and how they compose into interoperable deployments. [2]

## 2) Web of Things (WoT) Thing Description 1.1

**Organisation:** W3C[1] (Web of Things Working Group)

**Type:** Standards body document (W3C Recommendation)

**Date:** Dec 2023 (05 Dec 2023)

**Link:** <https://www.w3.org/TR/wot-thing-description11/> [3]

**Why it matters:** Standardises a machine-readable description format for a device/service’s metadata and network-facing interfaces (including JSON(-LD)), directly matching the ART requirement for devices to advertise capabilities in a reusable, ecosystem-agnostic way. [4]

## 3) Web of Things (WoT) Discovery

**Organisation:** W3C[1]

**Type:** Standards body document (W3C Recommendation)

**Date:** Dec 2023 (Recommendation dated 05 Dec 2023; referenced in WoT Architecture 1.1)

**Link:** <https://www.w3.org/TR/wot-discovery/> [5]

**Why it matters:** Specifies mechanisms to obtain Thing Descriptions (directories, self-description, secure access control before metadata disclosure), addressing a core interoperability bottleneck: secure, scalable discovery of capabilities. [5]

## 4) Web of Things (WoT) Binding Templates

**Organisation:** W3C[1]

**Type:** Standards body document (W3C Working Group Note)

**Date:** May 2024 (28 May 2024)

**Link:** <https://www.w3.org/TR/2024/NOTE-wot-binding-templates-20240528/> [6]

**Why it matters:** Provides guidance and examples for mapping the WoT interaction model onto multiple concrete protocols/ecosystems, which is essential to make “universal” descriptions practically interoperate across heterogeneous IoT stacks. [6]

## 5) Matter Application Cluster Specification 1.1

**Organisation:** Connectivity Standards Alliance[7]

**Type:** Standards body specification (technical spec PDF)

**Date:** May 2023 (17 May 2023)

**Link:** <https://csa-iot.org/wp-content/uploads/2023/05/matter-1-1-application-cluster-specification.pdf> [8]

**Why it matters:** Defines standardised “clusters” (generic interfaces for functions like on/off, sensing, HVAC, closures, etc.), directly representing the ART’s need for common, machine-consumable capability models and interoperable APIs. [8]

## 6) Matter 1.4 Enables More Capable Smart Homes

**Organisation:** Connectivity Standards Alliance[7]

**Type:** Standards body release announcement (press release with concrete feature claims)

**Date:** Nov 2024 (07 Nov 2024)

**Link:** <https://csa-iot.org/newsroom/matter-1-4-enables-more-capable-smart-homes/> [9]

**Why it matters:** Documents continued evolution of a cross-ecosystem interoperability standard (e.g., enhanced multi-admin; certifiable home routers/access points integrating Wi-Fi + Thread border router; credential handling), and explicitly claims Matter products are in “millions of homes” since 2022—an adoption signal relevant to maturity. [9]

## 7) Matter 1.5 Introduces Cameras, Closures, and Enhanced Energy Management Capabilities

**Organisation:** Connectivity Standards Alliance[7]

**Type:** Standards body release announcement (press release with concrete feature claims)

**Date:** Nov 2025 (20 Nov 2025)

**Link:** <https://csa-iot.org/newsroom/matter-1-5-introduces-cameras-closures-and-enhanced-energy-management-capabilities/> [10]

**Why it matters:** Shows expansion into high-impact device classes (notably cameras) with specified technical choices (e.g., WebRTC-based streaming; TCP transport support for larger messages), indicating the standard is extending toward broader capability coverage and more demanding data flows—key for “universal” interoperability trajectories. [10]

## 8) IoT Device Security Specification 1.0

**Organisation:** Connectivity Standards Alliance[7]

**Type:** Standards body specification (technical requirements PDF; certification-oriented)

**Date:** Mar 2024 (18 Mar 2024)

**Link:** <https://csa-iot.org/wp-content/uploads/2024/03/23-80986-013-PSWG-1.0-Specification-18-March-2024.pdf> [11]

**Why it matters:** Provides a concrete baseline security requirements set (identity, secure communications, secure boot, update verification, audit logging, etc.) designed for certification—direct evidence for the ART’s “baseline security + certification profiles” component. [11]

## 9) Matter PKI Certificate Policy (Matter PKI CP)

**Organisation:** Connectivity Standards Alliance[7]

**Type:** Standards body technical policy (PKI/certificate lifecycle; technical detail PDF)

**Date:** Aug 2024 (approved version metadata shows 2024-08-26)

**Link:** <https://csa-iot.org/wp-content/uploads/2024/02/pki-certificate-policy-2025.pdf> [12]

**Why it matters:** Provides concrete detail for hardware-/PKI-backed device identities and attestation certificate hierarchies (e.g., device attestation PKI concepts), supporting feasibility of scalable identity + trust chains (and revocation-related practices) within interoperability ecosystems. [13]

## 10) Lightweight M2M Core Specification v1.2.1

**Organisation:** Open Mobile Alliance[14]

**Type:** Standards body specification (approved technical spec PDF)

**Date:** Dec 2022 (09 Dec 2022)

**Link:** [https://www.openmobilealliance.org/release/LightweightM2M/V1\\_2\\_1-20221209-A/OMA-TS-LightweightM2M\\_Core-V1\\_2\\_1-20221209-A.pdf](https://www.openmobilealliance.org/release/LightweightM2M/V1_2_1-20221209-A/OMA-TS-LightweightM2M_Core-V1_2_1-20221209-A.pdf) [15]

**Why it matters:** Defines interoperable device lifecycle management (incl. bootstrap, telemetry objects, and firmware update object evolution), and explicitly extends core objects (e.g., firmware update; OSCORE object; MQTT server object), which are key building blocks for standardised fleet operations across constrained devices. [15]

## 11) FIDO Device Onboard Specification (Working Draft v2.0)

**Organisation:** FIDO Alliance[16]

**Type:** Standards body technical spec (working draft)

**Date:** Jun 2025 (17 Jun 2025)

**Link:** <https://fidoalliance.org/specs/FDO/FIDO-Device-Onboard-WD-v2.0-20250617/FIDO-Device-Onboard-WD-v2.0-20250617.html> [17]

**Why it matters:** Specifies automated onboarding with “late binding” and ownership transfer mechanisms (e.g., rendezvous server and ownership voucher concepts), aligning with the ART’s requirement for standardised, vendor-neutral provisioning/permission establishment at scale. [17]

## 12) Towards Automating IoT Security: Implementing Trusted Network-Layer Onboarding (NIST CSWP 42, draft)

**Organisation:** National Institute of Standards and Technology[18]

**Type:** Government/standards institute report (draft practice guide/overview)

**Date:** Apr 2025 (14 Apr 2025)

**Link:** <https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.42.ipd.pdf> [19]

**Why it matters:** Describes a NIST/NCCoE effort implementing and demonstrating trusted network-layer onboarding approaches (notably Wi-Fi Easy Connect and BRSKI), and frames how network-layer onboarding can support application-layer onboarding—directly relevant to scalable, secure “join network then join ecosystem” flows. [19]

## 13) RFC 9147: The Datagram Transport Layer Security (DTLS) Protocol Version 1.3

**Organisation:** IETF[20]

**Type:** Standards track specification (RFC; internet standard)

**Date:** Apr 2022

**Link:** <https://datatracker.ietf.org/doc/rfc9147/> [21]

**Why it matters:** DTLS 1.3 is a concrete, standardised basis for end-to-end encryption and integrity over datagram transports, supporting the ART’s security baseline requirement for constrained/IoT deployments that cannot rely on bespoke, proprietary security layers. [21]

## 14) Thread 1.4 Features White Paper

**Organisation:** Thread Group[22]

**Type:** Industry alliance technical white paper (feature-focused; tied to Thread 1.4 specification)

**Date:** Sep 2024

**Link:**

[https://www.threadgroup.org/Portals/0/Documents/Thread\\_1.4\\_Features\\_White\\_Paper\\_September\\_2024.pdf](https://www.threadgroup.org/Portals/0/Documents/Thread_1.4_Features_White_Paper_September_2024.pdf) [23]

**Why it matters:** Highlights specific enhancements informed by real-world deployments (credential management, commissioning/onboarding improvements, diagnostics, infrastructure considerations), supporting maturity of the low-power IPv6 mesh substrate that underpins interoperable IoT stacks (including Matter-over-Thread). [23]

## 15) A CBOR-based Serialization Format for the Software Updates for Internet of Things (SUIT) Manifest (draft-ietf-suit-manifest-34)

**Organisation:** IETF[20]

**Type:** Internet-Draft (standards track work-in-progress; detailed format spec)

**Date:** May 2025 (28 May 2025)

**Link:** <https://datatracker.ietf.org/doc/draft-ietf-suit-manifest/> [24]

**Why it matters:** Specifies a concrete interoperable manifest format for secure software/firmware updates on IoT devices (metadata, applicability, cryptographic protection, update sequences), addressing a core element of “universal” lifecycle interoperability beyond simple telemetry/control. [24]

## 16) Connectivity Standards Alliance Matter: State of the art and opportunities

**Organisation:** National Research Council of Italy[25] (authors affiliated with ISTI-CNR; paper on Matter)

**Type:** Peer-reviewed review article (journal: *Internet of Things*, Elsevier; open access)

**Date:** Apr 2024 (Volume 25, April 2024)

**Link:** <https://www.sciencedirect.com/science/article/pii/S2542660523003281> [26]

**Why it matters:** Reviews Matter’s specification (in its 1.0 state), discusses market adoption and

certification tooling/processes, and identifies challenges for large-scale adoption—directly useful for plausibility and “how close to scaling” assessment. [26]

**17) Towards interworking of matter and oneM2M: Design and implementation of a matter–oneM2M Interworking Proxy Entity**

**Organisation:** Academic research group integrating standards (Matter + oneM2M)

**Type:** Peer-reviewed research article (journal: *Internet of Things*, Elsevier)

**Date:** 2024 (month not stated on the landing page; DOI indicates 2024)

**Link:** <https://www.sciencedirect.com/science/article/abs/pii/S2542660524002543> [27]

**Why it matters:** Implements and tests an interworking proxy that exposes Matter devices via oneM2M standard interfaces, validated with commercial and experimental Matter devices and reporting negligible overhead—evidence that cross-platform interoperability layers are practically buildable today (not merely theoretical). [27]

**18) Web access as a service for CSA matter protocol: Bridging matter and the W3C Web of Things framework for smart home interoperability**

**Organisation:** Academic research group bridging two interoperability stacks (Matter + WoT)

**Type:** Peer-reviewed research article (journal: *Internet of Things*, Elsevier)

**Date:** Jul 2025 (Volume 32, July 2025)

**Link:** <https://www.sciencedirect.com/science/article/abs/pii/S2542660525001325> [28]

**Why it matters:** Proposes and evaluates a Matter controller that exposes Matter devices as WoT Thing Descriptions (bi-directional communication + discoverability), explicitly targeting reduction of cloud/platform lock-in—an enabling step toward universal interoperability beyond a single ecosystem. [28]

**19) Next-generation smart homes: CO<sub>2</sub> monitoring with Matter protocol to support indoor air quality**

**Organisation:** Academic research group building a Matter-integrated device

**Type:** Peer-reviewed research article (journal: *Internet of Things*, Elsevier; open access)

**Date:** Jul 2025 (Volume 32, July 2025)

**Link:** <https://www.sciencedirect.com/science/article/pii/S2542660525001635> [29]

**Why it matters:** Demonstrates an end-to-end Matter-enabled device integrated into a real ecosystem (Home Assistant) with rapid onboarding and dual commissioning (Wi-Fi + Thread), providing concrete evidence of practical interoperability workflows and real telemetry consumption via standardised integration. [29]

**20) Connected Smart Home over Matter Protocol**

**Organisation:** Morgan State University[30] (smart-home Matter testbed work)

**Type:** Peer-reviewed conference paper (IEEE ICCE 2023)

**Date:** 2023 (conference proceedings; DOI indicates 2023 IEEE ICCE)

**Link:** <https://par.nsf.gov/servlets/purl/10429924> [31]

**Why it matters:** Shows an implemented Matter testbed (development kits + Thread border router components) and practical control of Matter applications (e.g., door lock), illustrating feasibility of multi-protocol IP-based interoperability even in early-stage ecosystems (while noting scarcity of mature commercial devices at the time). [31]

3. Maturity score (1–7) and reasoning

**A) Final maturity score: 5**

**B) Why this score fits the rubric (evidence-to-rubric mapping)**

- **What evidence rules out levels 1–3 (theory / lab verification / early lab prototype)?**

Multiple major interoperability components already exist as *formal, maintained standards* (e.g., W3C WoT Recommendations, IETF RFCs, OMA specs, CSA specifications), which is well beyond theoretical or single-lab validation. [32]

- **What evidence rules out level 4 (single PoC) and supports level 5?**

The evidence base shows (i) **fast-paced, multi-actor standard evolution** (Matter 1.4 → 1.5 adds new device types, transport support, and more demanding capabilities like camera streaming), and (ii) **working implementations/bridges** connecting standards layers (Matter↔oneM2M; Matter↔WoT) validated with commercial/experimental devices and characterised as feasible for deployment settings. [33]

Additionally, the **security/certification layer is being formalised** via CSA's IoT Device Security Specification (a concrete baseline requirements set designed for certification), indicating institutional movement from “good ideas” to auditable compliance profiles. [11]

- **What is still missing to justify level 6 (products scaling broadly) or level 7 (competing products scaling with rising demand) for the ART as a whole?**

While Matter shows strong market penetration signals in the smart-home domain (claimed “millions of homes”), the ART describes **universal, cross-domain** interoperability (smart home + industrial + city + healthcare + energy, etc.) with globally adopted profiles and reduced need for bespoke integrations. The evidence here shows **partial convergence** (notably smart home plus bridging research), but not yet a single globally dominant, end-to-end “universal bundle” spanning the majority of IoT verticals with uniformly deployed certification and lifecycle tooling. [34]

In particular, decisive level-6/7 evidence that is missing includes:

- Public, verifiable metrics that the *same* interoperability stack is deployed at very large scale across heterogeneous vertical sectors (beyond smart home), with reduced integration labour demonstrated across many organisations. (Not established by this source set within the time window.)
- Clear evidence that security certification (and revocation/patching operations) is being executed broadly across vendors/regions at high volume (the CSA security specification exists, but wide deployment data is not demonstrated here). [11]
- A widely adopted, standardised approach to *cloud-layer interoperability* (multiple sources explicitly describe ongoing fragmentation/lock-in at cloud/platform layers and the need for bridging). [35]

### C) Sub-scores (bundle breakdown) and aggregation

- **Smart-home application-layer interoperability (Matter + standard device/capability model) → 6**

**Key evidence:** New releases expanding device categories and capabilities (including higher-bandwidth features like camera streaming; improved transports), and explicit adoption signal (“millions of homes”). [36]

- **Machine-readable capability descriptions + discovery across protocols (W3C WoT stack) → 4**

**Key evidence:** WoT Architecture/Thing Description/Discovery are W3C Recommendations with binding guidance—strong standard maturity—but the evidence in this set does not



demonstrate mass commercial adoption at the level of dominant market delivery across device domains. [37]

- **Device lifecycle management + firmware update interoperability (LwM2M + emerging SUIT manifest work) → 5**

**Key evidence:** An approved LwM2M core spec version that explicitly evolves firmware update and security-related objects, plus active IETF SUIT manifest specification work that targets interoperable secure updates for constrained devices. [38]

- **Secure onboarding / ownership transfer / credential provisioning → 4–5 (≈4.5)**

**Key evidence:** FDO working draft specifies late binding and ownership transfer; NIST report describes implemented/demonstrated trusted network-layer onboarding protocols and positions onboarding as repeatable lifecycle activity. [39]

- **Baseline security certification harmonisation → 4**

**Key evidence:** CSA IoT Device Security Specification 1.0 provides concrete technical requirements aimed at certification, but the evidence set does not yet show broad, high-volume, multi-region deployment of the certification mark across product categories. [11]

**Aggregation method:** Because the ART is a **bundle whose benefits are divided across multiple layers** (application interoperability, descriptions/discovery, onboarding, device management/updates, certification), I used an **average-based score** rather than the maximum. The sub-scores centre around ~4–6, yielding an overall **≈5** (competitive, well-capitalised development with strong momentum, but not yet universal at cross-domain scale). [40]

[1] [3] [4] Web of Things (WoT) Thing Description 1.1

<https://www.w3.org/TR/wot-thing-description11/>

[2] [32] [37] Web of Things (WoT) Architecture 1.1

<https://www.w3.org/TR/wot-architecture11/>

[5] Web of Things (WoT) Discovery

<https://www.w3.org/TR/wot-discovery/>

[6] Web of Things (WoT) Binding Templates

<https://www.w3.org/TR/2024/NOTE-wot-binding-templates-20240528/>

[7] [14] [17] [30] [39] FIDO Device Onboard Specification

<https://fidoalliance.org/specs/FDO/FIDO-Device-Onboard-WD-v2.0-20250617/FIDO-Device-Onboard-WD-v2.0-20250617.html>

[8] Matter Application Clusters

<https://csa-iot.org/wp-content/uploads/2023/05/matter-1-1-application-cluster-specification.pdf>

[9] [18] [25] [33] [34] [36] [40] Matter 1.4 Enables More Capable Smart Homes - CSA-IOT

<https://csa-iot.org/newsroom/matter-1-4-enables-more-capable-smart-homes/>

[10] Matter 1.5 Introduces Cameras, Closures, and Enhanced Energy Management Capabilities - CSA-IOT

<https://csa-iot.org/newsroom/matter-1-5-introduces-cameras-closures-and-enhanced-energy-management-capabilities/>

[11] csa-iot.org

<https://csa-iot.org/wp-content/uploads/2024/03/23-80986-013-PSWG-1.0-Specification-18-March-2024.pdf>

[12] [13] PKI Certificate Policy

<https://csa-iot.org/wp-content/uploads/2024/02/pki-certificate-policy-2025.pdf>

[15] [16] [38] OMA-TS-LightweightM2M\_Core-V1\_2\_1-20221209-A\_full

[https://www.openmobilealliance.org/release/LightweightM2M/V1\\_2\\_1-20221209-A/OMA-TS-LightweightM2M\\_Core-V1\\_2\\_1-20221209-A.pdf](https://www.openmobilealliance.org/release/LightweightM2M/V1_2_1-20221209-A/OMA-TS-LightweightM2M_Core-V1_2_1-20221209-A.pdf)

[19] Towards Automating IoT Security- Implementing Trusted Network-Layer Onboarding

<https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.42.ipd.pdf>

[20] [21] RFC 9147 - The Datagram Transport Layer Security (DTLS) Protocol Version 1.3

<https://datatracker.ietf.org/doc/rfc9147/>

[22] [23] Thread 1.4.0 White Paper

[https://www.threadgroup.org/Portals/0/Documents/Thread\\_1.4\\_Features\\_White\\_Paper\\_September\\_2024.pdf](https://www.threadgroup.org/Portals/0/Documents/Thread_1.4_Features_White_Paper_September_2024.pdf)

[24] draft-ietf-suit-manifest-34 - A Concise Binary Object Representation (CBOR)-based Serialization Format for the Software Updates for Internet of Things (SUIT) Manifest

<https://datatracker.ietf.org/doc/draft-ietf-suit-manifest/>

[26] Connectivity Standards Alliance Matter: State of the art and opportunities - ScienceDirect

<https://www.sciencedirect.com/science/article/pii/S2542660523003281>

[27] Towards interworking of matter and oneM2M: Design and implementation of a matter-oneM2M Interworking Proxy Entity - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S2542660524002543>

[28] [35] Web access as a service for CSA matter protocol: Bridging matter and the W3C Web of Things framework for smart home interoperability - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S2542660525001325>

[29] Next-generation smart homes: CO2 monitoring with Matter protocol to support indoor air quality - ScienceDirect

<https://www.sciencedirect.com/science/article/abs/pii/S2542660525001635>

[31] Connected Smart Home over Matter Protocol

<https://par.nsf.gov/servlets/purl/10429924>

## ART 12.092 Interoperable Digital Twin Ecosystems

### 1. ART extraction

#### A) Primary capability (what the ART claims)

- Portable, *multi-party* digital twins that can move between tools and organisations (and across long asset lifecycles) **without being rebuilt**, via shared protocols and reference models.
- Continuous synchronisation between physical assets and their virtual representations using both real-time updates (streams/events) and periodic reconciliation (snapshots), with vendor-neutral access patterns.
- Policy-aware and auditable sharing (identity, access control, provenance, and governance) so that multiple actors can collaborate on the “same” twin while managing liability, trust, and model disagreement.

#### B) Key sub-components / sub-threads (technology bundle)

- Standardised **twin data structures and semantics** (reference models, identifiers, submodels/aspects, common terminology).
- **Packaging and interchange formats** for transporting twins (or twin components) between parties (e.g., packaged serialisations + attachments).
- **Runtime APIs** for querying/updating twin state, discovering twin endpoints/registries, and exchanging submodels.
- **Eventing and “right-time” context updates** for synchronisation (subscriptions, notifications, context brokers).
- **Cross-organisation governance layer**: identity, credentialing, usage control/policy enforcement, compliance, and trusted self-descriptions.
- **Interoperability via mappings/bridges** between major twin modelling approaches (e.g., DTDL ↔ AAS; NGSI-LD representations; geospatial OGC APIs).
- **Operational ecosystems / registries** demonstrating multi-party deployment (e.g., digital twin registries in industrial data spaces).

#### C) What would count as maturity evidence for this ART

- International standards and widely adopted consortium specifications defining **portable twin structures, APIs, and conformance expectations** (not just conceptual papers).
- Demonstrated **multi-vendor interoperability** (cross-platform twin exchange, not merely internal integration) in pilots or operational ecosystems.
- Evidence of **production-grade infrastructure**: registries/discovery, stable versioned APIs, packaging formats, conformance tests (TCKs), certification schemes, and backward compatibility strategies.
- **Scaling signals**: repeated deployments across organisations, published reference implementations, and ecosystem releases indicating ongoing upgrades rather than one-off PoCs.
- Governance mechanisms that are concrete enough to implement (machine-readable policies, verifiable credentials, enforceable usage control), not only “principles”.

### 2. Evidence (10–20 recent, reliable sources)

### 1) IEC 63278-1:2023 — Asset Administration Shell for industrial applications — Part 1: Asset Administration Shell structure

**Org:** IEC[1]

**Type:** International standard (industrial digital representation structure)

**Date:** 2023-12 (standard designation “:2023”)

**Link:** <https://webstore.iec.ch/en/publication/65628>

**Why it matters:** Defines a standardised digital representation of an asset (“AAS”) with the explicit purpose of enabling two or more software applications to exchange and reuse information in a trusted/secure way—core plausibility for “twin portability” across tools. [2]

### 2) Specification of the Asset Administration Shell — Part 1: Metamodel (v3.0RC03 / Part 1: Metamodel Schema)

**Org:** Industrial Digital Twin Association[3]

**Type:** Consortium technical specification (metamodel + exchange/serialization considerations)

**Date:** April 2023

**Link:** [https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0\\_SpecificationAssetAdministrationShell\\_Part1\\_Metamodel.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0_SpecificationAssetAdministrationShell_Part1_Metamodel.pdf)

**Why it matters:** Specifies the AAS metamodel and explicitly frames interoperability mechanics: exchange format for transporting information along the value chain, identifiers, access control, and mappings to common serialisations/technologies (XML/JSON/RDF/AutomationML/OPC UA). This is a concrete “portable twin schema” substrate rather than a platform-specific model. [4]

### 3) Specification of the Asset Administration Shell — Part 2: Application Programming Interfaces (API) (IDTA 01002-3-02)

**Org:** Industrial Digital Twin Association

**Type:** Consortium technical specification (runtime API surface; profiles)

**Date:** June 2023

**Link:** [https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0\\_SpecificationAssetAdministrationShell\\_Part2\\_API\\_.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0_SpecificationAssetAdministrationShell_Part2_API_.pdf)

**Why it matters:** Defines versioned, technology-neutral and HTTP/REST API specifications for accessing AASs and submodels, a required ingredient for tool-to-tool interoperability (query/update/discovery patterns) beyond file-based exchange. [5]

### 4) Specification of the Asset Administration Shell — Part 5: Package File Format (AASX) (IDTA 01005-3-0-12)

**Org:** Industrial Digital Twin Association

**Type:** Consortium technical specification (portable packaging)

**Date:** June 2024

**Link:** [https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-](https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1_SpecificationAssetAdministrationShell_Part5_AASXPackageFileFormat.pdf)

[1\\_SpecificationAssetAdministrationShell\\_Part5\\_AASXPackageFileFormat.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1_SpecificationAssetAdministrationShell_Part5_AASXPackageFileFormat.pdf)

**Why it matters:** Defines how one or more AAS(s) can be packed into a compound file format (AASX), providing a concrete “structured package” mechanism aligned with the ART’s portability requirement (moving twin artefacts with attachments without full rebuild). [6]

### 5) ISO/IEC 30173:2023 — Digital twin — Concepts and terminology (Edition 1)

**Org:** ISO[7] / IEC (ISO/IEC work)[8]

**Type:** International standard (terminology foundation for cross-stakeholder interoperability)

**Date:** 2023-11

**Link:** <https://www.iso.org/standard/81442.html>

**Why it matters:** Establishes shared terminology/concepts (stakeholders, lifecycle, functional views), which is a practical prerequisite for interoperability efforts to converge on compatible “twin packages” and interfaces across vendors and sectors. [9]

#### 6) Interoperability of Digital Twins: Challenges, Success Factors, and Future Research Directions

**Authors:** Istvan David[10] et al. (panel report with standardisation perspective via NIST)

**Org/Venue:** NIST[11] publication (conference proceedings listing)

**Type:** Peer-reviewed conference paper (systems-of-digital-twins interoperability analysis)

**Date:** October 30, 2024

**Link:** <https://www.nist.gov/publications/interoperability-digital-twins-challenges-success-factors-and-future-research>

**Why it matters:** Provides credible “state of practice” evidence that many aggregated/system-of-systems digital twins still rely on ad-hoc API alignment and are far from high interoperability levels, while identifying emerging solution paths (including standardisation and co-simulation). This is critical for maturity assessment (what’s working vs. what remains blocking). [12]

#### 7) Manufacturing Digital Twin Standards

**Author:** Guodong Shao[13]

**Org/Venue:** NIST publication (EDTconf 2024 listing)

**Type:** Peer-reviewed conference paper / standards roadmap discussion

**Date:** September 24, 2024

**Link:** <https://www.nist.gov/publications/manufacturing-digital-twin-standards>

**Why it matters:** Summarises manufacturing digital twin standards activity and explicitly focuses on standards organisations/consortia and roadmapping around ISO 23247 and related efforts—evidence that interoperability is being formalised into standard tracks rather than remaining purely bespoke integration. [14]

#### 8) Architecture for manufacturing-X: Bringing asset administration shell, eclipse dataspace connector and OPC UA together

**Authors:** Michael Neubauer[15] et al.

**Venue/Type:** Peer-reviewed journal article (Manufacturing Letters)

**Date:** September 2023 (Volume 37)

**Link:** <https://www.sciencedirect.com/science/article/pii/S221384632300024X>

**Why it matters:** Proposes an architecture that explicitly composes (1) a standardised data model (AAS), (2) sovereign inter-organisational data exchange (Eclipse Dataspace Connector), and (3) internal communication (OPC UA)—a concrete blueprint matching the ART’s “network layer” direction for multi-party twin portability. [16]

#### 9) CX-0002 Digital Twins in Catena-X v2.3.0

**Org:** Catena-X Automotive Network e.V.[17]

**Type:** Implementable ecosystem standard/specification (registry + APIs + conformance framing)

**Date:** November 2025 (released within CX Saturn release cycle; standard page indicates

copyright year 2025)

**Link:** <https://catenax-ev.github.io/docs/standards/CX-0002-DigitalTwinsInCatenaX>

**Why it matters:** Defines how digital twins and their “aspects” are administered in a multi-party industrial data ecosystem, including digital twin registry and submodel API expectations—direct evidence of an operational interoperability target, not merely an academic proposal. [18]

#### 10) Catena-X Release Notes — CX-Saturn

**Org:** Catena-X Automotive Network e.V.

**Type:** Technical release notes (ecosystem upgrade cadence; compatibility constraints)

**Date:** November 25, 2025

**Link:** <https://catenax-ev.github.io/blog-releasenotes>

**Why it matters:** Shows an active, versioned standards-and-implementation release cycle that explicitly strengthens interoperability and extends support for digital twins (including updates aligned with AAS interface releases), signalling post-PoC ecosystem hardening rather than one-off trials. [19]

#### 11) Supporting Changes in Digital Ownership and Data Sovereignty Across the Automotive Value Chain with Catena-X (preprint)

**Org/Context:** Catena-X ecosystem (automotive), AAS-based DTs, Tractus-X references

**Type:** Technical preprint (arXiv) with specific lifecycle/governance considerations

**Date:** June 11, 2024 (arXiv:2406.07194v1)

**Link:** <https://arxiv.org/pdf/2406.07194>

**Why it matters:** Provides a concrete multi-stakeholder lifecycle scenario (OEMs, suppliers, repair shops, dismantlers) and explicitly ties Catena-X digital twins to AAS submodels plus “industry core” governance for interoperability and lifecycle status—directly aligned with the ART’s “ownership change/tool change continuity” claim. [20]

#### 12) ETSI GR CIM 017 V1.1.1 — Feasibility of NGSI-LD for Digital Twins

**Org:** ETSI [21]

**Type:** Standards body group report (technical analysis)

**Date:** 2022-12

**Link:**

<https://cdn.standards.iteh.ai/samples/59463/1f99a12b505b412d85a19ebfa4d4d451/ETSI-GR-CIM-017-V1-1-1-2022-12-.pdf>

**Why it matters:** Analyses how NGSI-LD information models/APIs can represent and handle digital twins across domains, covering lifecycle stages/capabilities and discussing needs such as “what-if” handling and simulator integration—evidence for feasible real-time and scenario-oriented interoperability at the API/model layer. [22]

#### 13) ETSI GS CIM 009 V1.9.1 (2025-07) — NGSI-LD API

**Org:** ETSI

**Type:** Standards body specification (API for interoperable context/twin access, including subscriptions)

**Date:** 2025-07

**Link:**

[https://www.etsi.org/deliver/etsi\\_gs/CIM/001\\_099/009/01.09.01\\_60/gs\\_CIM009v010901p.pdf](https://www.etsi.org/deliver/etsi_gs/CIM/001_099/009/01.09.01_60/gs_CIM009v010901p.pdf)



**Why it matters:** Defines a standardised API for providing/consuming/subscribing to context information, explicitly modelling context entities (“digital twins”) and supporting change notifications—directly relevant to the ART’s event-stream synchronisation and multi-actor access needs. [23]

#### 14) Increasing Interoperability between Digital Twin Standards and Specifications: Transformation of DTDL to AAS

**Authors/Org:** Carlos Schmidt[24] et al., Fraunhofer IOSB[25]

**Type:** Peer-reviewed journal paper (Sensors, open access)

**Date:** 7 September 2023

**Link:** <https://www.mdpi.com/1424-8220/23/18/7742>

**Why it matters:** Implements and analyses a concrete transformation path from Microsoft’s DTDL models into AAS constructs, demonstrating that cross-standard portability is technically achievable (with identified gaps/edge cases), a key plausibility lever for “twins moving between tools without rebuild.” [26]

#### 15) Urban Digital Twins: Integrating Infrastructure, natural environment and people (OGC Discussion Paper 24-025)

**Org:** Open Geospatial Consortium[27]

**Type:** Standards body discussion paper (interoperability framing + standards mapping)

**Date:** Publication Date 2024-07-02

**Link:** <https://docs.ogc.org/dp/24-025.pdf>

**Why it matters:** Provides an explicit “data interoperability” treatment for urban digital twins and maps concrete standards (e.g., CityGML, SensorThings, OGC API family, plus references to IFC) to support interoperable exchange of geometry/semantics/sensor updates—evidence for the built-environment branch of interoperable twin ecosystems. [28]

#### 16) An OGC API-Based Framework for Scalable and Interoperable Urban Digital Twin Ecosystems: Insights from the OGC Urban Digital Twins Interoperability Pilot

**Authors:** Thunyathep Santhanavanich[29] et al.

**Venue/Type:** Peer-reviewed conference proceedings (ISPRS Archives)

**Date:** 18 September 2025

**Link:** <https://isprs-archives.copernicus.org/articles/XLVIII-4-W15-2025/135/2025/isprs-archives-XLVIII-4-W15-2025-135-2025.html>

**Why it matters:** Reports practical use of modern OGC APIs (Features, Tiles, SensorThings, etc.) in pilot use cases (e.g., urban noise simulation, Geo-AI) integrating 3D city models and sensor/imagery data—evidence of multi-source, standards-based data exchange that resembles the ART’s “network layer” for twins in cities. [30]

#### 17) Gaia-X Trust Framework — 22.04 Release

**Org:** Gaia-X[31]

**Type:** Authoritative framework/specification (governance + self-descriptions + portability emphasis)

**Date:** 22.04 release (April 2022)

**Link:** <https://gaia-x.eu/wp-content/uploads/2022/05/Gaia-X-Trust-Framework-22.04.pdf>

**Why it matters:** Defines machine-readable self-descriptions and trust/compliance rules that explicitly target interoperability, portability, and policy expression in federated ecosystems—

directly relevant to the ART's access-control and governance layer for cross-organisation digital twins. [32]

#### 18) Making the Dataspace Protocol an international standard (Version 1.0)

**Org:** International Data Spaces Association[33]

**Type:** Standards/roadmap report (standardisation pathway + conformance testing emphasis)

**Date:** July 2024

**Link:** <https://eurogeographics.org/app/uploads/2024/07/Making-the-Dataspace-Protocol-an-international-standard-1.pdf>

**Why it matters:** Documents how a shared protocol for data spaces is being stabilised and paired with a Technology Compatibility Kit (TCK) and compatible implementations to ensure interoperability—an enabling layer for sharing twin data across organisations with enforceable usage control. [34]

#### 19) Dataspace Protocol 2025-1 (specification)

**Org:** Eclipse Foundation[35] (specification hosting)

**Type:** Protocol specification for interoperable, policy-governed data sharing

**Date:** 12 August 2025

**Link:** <https://eclipse-dataspace-protocol-base.github.io/DataspaceProtocol/2025-1/>

**Why it matters:** Defines schemas/protocol steps for publishing data, negotiating agreements, and accessing data within a federated dataspace—an essential plumbing layer if digital-twin “packages” and streams must move across organisational boundaries under usage constraints. [36]

#### 20) Data Space Connector Report — Report No 1

**Org:** International Data Spaces Association

**Type:** Technical report (connector interoperability + conformance details + ecosystem adoption signals)

**Date:** October 2025

**Link:** [https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Space-Connector-Report-1\\_October\\_2025-1.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Space-Connector-Report-1_October_2025-1.pdf)

**Why it matters:** Describes connectors as interoperability APIs plus policy-enforcement components and lists concrete implementations with protocol/TCK versions; notably, it states the Eclipse Tractus-X EDC connector is “productively used” in the Catena-X dataspace and adopted by multiple service providers—strong maturity evidence of operational, standard-aligned cross-company exchange infrastructure. [37]

### 3. Maturity score (1–7) and reasoning

#### A) Final maturity score: 5

#### B) Why level 5 fits (and what rules out lower levels)

- **Rules out levels 1–3 (theory/lab-only):** This ART is not a single lab breakthrough; it is being formalised as **international standards** and multi-organisation specifications with concrete, implementable artefacts: a standardised industrial twin structure (IEC 63278-1:2023) plus detailed metamodel/API/package specs from IDTA (AAS metamodel, runtime APIs, and the AASX package format). [38]

- **Rules out level 4 (PoC only):** Evidence indicates **ecosystem-scale implementation and**

**competition** rather than a single PoC: Catena-X publishes implementable standards for digital twin registries/APIs and ships recurring releases with interoperability upgrades; IDSA documents multiple connector implementations and aligns them to a shared protocol/TCK approach, including productive use in a real dataspace. [39]

- **Why not level 6 yet (what's missing):** The strongest recent evidence still highlights that digital twin interoperability is often **limited to lower interoperability levels** and frequently relies on ad-hoc alignment, with substantial remaining complexity for distributed systems-of-digital-twins. Broad, repeatable “twin portability” across *multiple competing commercial toolchains* with minimal integration effort (and with published scaling metrics across many asset classes) is not consistently demonstrated in the evidence set. [40]

### **C) Sub-component maturity snapshot (bundle → subscores → aggregation)**

- **Standardised twin representation + packaging (AAS + AASX): ~5.** International standardisation and implementable specs exist for structure, APIs, and portable packaging. [38]

- **Cross-organisation ecosystem deployment (registries + governed exchange, exemplified by Catena-X): ~5–6.** Catena-X releases show ongoing operational hardening and explicit digital twin support; companion evidence documents lifecycle governance patterns and multi-party update challenges. [41]

- **Policy/usage-control “network layer” for data (Dataspace Protocol + connectors, Gaia-X trust framing): ~5.** Protocol and connector ecosystems plus trust frameworks exist, paired to conformance ideas (TCKs/certification), and explicitly target interoperable, sovereign sharing—an enabler for interoperable twin ecosystems. [42]

- **Cross-standard mappings and multi-domain interoperability (e.g., DTDL→AAS; NGS-ILD twin APIs; OGC API pilots): ~3–5 depending on domain.** There are implementable mappings and pilots (strong plausibility), but integration remains uneven across domains and standards, and gaps are documented. [43]

**Aggregation rationale:** Because the ART’s “interoperable ecosystem” value depends on the **slowest-moving components** (shared semantics + conformance + multi-party governance + operational adoption), and because credible sources still describe interoperability as often low/ad-hoc in practice, the overall maturity is best represented as **level 5**: multiple well-capitalised actors and consortia are clearly building and iterating toward production-grade interoperability, with concrete deployments emerging, but not yet at broad, cross-industry “increasing amounts” maturity implied by level 6. [44]

[1] [2] [38] <https://webstore.iec.ch/en/publication/65628>

<https://webstore.iec.ch/en/publication/65628>

[3] [25] [26] [43] <https://www.mdpi.com/1424-8220/23/18/7742>

<https://www.mdpi.com/1424-8220/23/18/7742>

[4] [21] [https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0\\_SpecificationAssetAdministrationShell\\_Part1\\_Metamodel.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0_SpecificationAssetAdministrationShell_Part1_Metamodel.pdf)

[https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0\\_SpecificationAssetAdministrationShell\\_Part1\\_Metamodel.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0_SpecificationAssetAdministrationShell_Part1_Metamodel.pdf)

[5] [8] [https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0\\_SpecificationAssetAdministrationShell\\_Part2\\_API\\_.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0_SpecificationAssetAdministrationShell_Part2_API_.pdf)

[https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0\\_SpecificationAssetAdministrationShell\\_Part2\\_API\\_.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0_SpecificationAssetAdministrationShell_Part2_API_.pdf)

[6] [https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1\\_SpecificationAssetAdministrationShell\\_Part5\\_AASXPackageFileFormat.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1_SpecificationAssetAdministrationShell_Part5_AASXPackageFileFormat.pdf)

[https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1\\_SpecificationAssetAdministrationShell\\_Part5\\_AASXPackageFileFormat.pdf](https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-01005-3-0-1_SpecificationAssetAdministrationShell_Part5_AASXPackageFileFormat.pdf)

[7] [40] [https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=956427](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=956427)

[https://tsapps.nist.gov/publication/get\\_pdf.cfm?pub\\_id=956427](https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=956427)

[9] <https://www.iso.org/standard/81442.html>

<https://www.iso.org/standard/81442.html>

[10] [19] [31] [41] <https://catenax-ev.github.io/blog-releasenotes>

<https://catenax-ev.github.io/blog-releasenotes>

[11] [28] <https://docs.ogc.org/dp/24-025.pdf>

<https://docs.ogc.org/dp/24-025.pdf>

[12] [17] [35] [44] <https://www.nist.gov/publications/interoperability-digital-twins-challenges-success-factors-and-future-research>

<https://www.nist.gov/publications/interoperability-digital-twins-challenges-success-factors-and-future-research>

[13] [36] [42] <https://eclipse-dataspace-protocol-base.github.io/DataspaceProtocol/2025-1/>

<https://eclipse-dataspace-protocol-base.github.io/DataspaceProtocol/2025-1/>

[14] <https://www.nist.gov/publications/manufacturing-digital-twin-standards>

<https://www.nist.gov/publications/manufacturing-digital-twin-standards>

[15] [22]

<https://cdn.standards.iteh.ai/samples/59463/1f99a12b505b412d85a19ebfa4d4d451/ETSI-GR-CIM-017-V1-1-1-2022-12-.pdf>

<https://cdn.standards.iteh.ai/samples/59463/1f99a12b505b412d85a19ebfa4d4d451/ETSI-GR-CIM-017-V1-1-1-2022-12-.pdf>

[16] <https://www.sciencedirect.com/science/article/pii/S221384632300024X>

<https://www.sciencedirect.com/science/article/pii/S221384632300024X>

[18] [24] [29] [33] [39] <https://catenax-ev.github.io/docs/standards/CX-0002-DigitalTwinsInCatenaX>

<https://catenax-ev.github.io/docs/standards/CX-0002-DigitalTwinsInCatenaX>

[20] [arxiv.org](https://arxiv.org)

<https://arxiv.org/pdf/2406.07194>

[23] GS CIM 009 - V1.9.1 - Context Information Management (CIM); NGSI-LD API

[https://www.etsi.org/deliver/etsi\\_gs/CIM/001\\_099/009/01.09.01\\_60/gs\\_CIM009v010901p.pdf](https://www.etsi.org/deliver/etsi_gs/CIM/001_099/009/01.09.01_60/gs_CIM009v010901p.pdf)

[27] [30] <https://isprs-archives.copernicus.org/articles/XLVIII-4-W15-2025/135/2025/isprs-archives-XLVIII-4-W15-2025-135-2025.html>

<https://isprs-archives.copernicus.org/articles/XLVIII-4-W15-2025/135/2025/isprs-archives-XLVIII-4-W15-2025-135-2025.html>

[32] <https://gaia-x.eu/wp-content/uploads/2022/05/Gaia-X-Trust-Framework-22.04.pdf>

<https://gaia-x.eu/wp-content/uploads/2022/05/Gaia-X-Trust-Framework-22.04.pdf>

[34] <https://eurogeographics.org/app/uploads/2024/07/Making-the-Dataspace-Protocol-an-international-standard-1.pdf>

<https://eurogeographics.org/app/uploads/2024/07/Making-the-Dataspace-Protocol-an-international-standard-1.pdf>

[37] [https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Space-Connector-Report-1\\_October\\_2025-1.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Space-Connector-Report-1_October_2025-1.pdf)

[https://internationaldataspaces.org/wp-content/uploads/dlm\\_uploads/IDSA-Data-Space-Connector-Report-1\\_October\\_2025-1.pdf](https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Data-Space-Connector-Report-1_October_2025-1.pdf)

## ART 12.093 Global Supply Chain Traceability Networks

### ART extraction

#### Primary capability the ART claims

- Shared, multi-party “data rails” that let independent supply-chain actors record and query a product/material’s provenance and lifecycle events (custody, transformation, testing, compliance) using interoperable data models and governance rules.
- A portable, queryable “history file” tied to physical identifiers (e.g., barcodes/2D codes, RFID, embedded chips), exposing “what/where/when/why/how” event context via standard APIs and user interfaces.
- Tamper-evident (or tamper-resistant) records using cryptographic signatures, audit trails, and selective disclosure so participants can prove required attributes without revealing all commercially sensitive details.

#### Key sub-components or variants

- **Common event data models + vocabularies** for interoperable capture/query of “visibility events” across organisations (e.g., standard event types, semantics, and query interfaces).

- **Identifier-to-digital linking layer** (e.g., globally unique IDs, 2D codes/QR, RFID; “web-enabled” identifier encodings that support consumer/regulator lookup as well as B2B data exchange).
- **Cross-organisation data exchange interfaces/APIs** (industry-standard interface definitions and information models enabling multi-actor interoperability).
- **Identity, authentication, and data integrity primitives** (organisational identity, credentialing, signatures; privacy-preserving proofs / selective disclosure).
- **Governance + conformance** (rules for participation, permissions, certification/conformity assessment, dispute handling; validation rules for data quality and anomaly detection).
- **Regulatory/market “pull”** (mandates for digital product passports or electronic traceability in specific sectors such as batteries, pharmaceuticals, food).
- **Operational integration & automation** (integration with ERP/WMS/MES and scanners/connected equipment; practical handling of data quality, latency, and connectivity gaps).

#### What maturity indicators would constitute evidence

- Ratified, widely-supported **standards** for event data models, vocabularies, identifiers, and APIs; plus conformance test suites and governance frameworks.
- **Field pilots and live deployments** with multiple independent organisations exchanging interoperable traceability data (not single-vendor silos).
- **Regulatory adoption** (binding rules or final guidance) that specify traceability records, data elements, and electronic interoperability requirements.
- **Multiple competing implementations** (commercial and/or open-source) that demonstrate interoperability with shared schemas and measurable operational performance (throughput, scalability, reliability, conformance).
- Evidence of **scaling readiness**: large ecosystem onboarding, automated data capture at high volume, certification programs, and operational practices for data quality and dispute resolution.

#### Evidence (10–20 recent, reliable sources)

##### Standards, data models, and interoperability “rails”

###### 1) EPCIS Standard (Release 2.0, Ratified)

**Organisation:** GS1[\[1\]](#)

**Type:** standards body technical standard

**Publication date:** Jun 2022

**Link:** <https://ref.gs1.org/standards/epcis/2.0.0/>

**Why it matters:** Defines an interoperable event data model and interfaces so “disparate applications” can create and share supply-chain visibility event data across enterprises—core plausibility evidence for multi-actor traceability networks. [\[2\]](#)

###### 2) Core Business Vocabulary (CBV) Standard (Release 2.0, Ratified)

**Organisation:** GS1

**Type:** standards body technical standard

**Publication date:** Jun 2022

**Link:** <https://ref.gs1.org/standards/cbv/>



**Why it matters:** Specifies standard vocabulary structures and values to ensure consistent semantics for EPCIS events—evidence that interoperability is being engineered at the meaning/ontology layer, not just data transport. [3]

### 3) EPCIS and CBV Implementation Guideline (Release 2.0, Ratified)

**Organisation:** GS1

**Type:** standards body implementation guideline

**Publication date:** Mar 2023

**Link:** <https://ref.gs1.org/guidelines/epcis-cbv/>

**Why it matters:** Documents practical implementation patterns for using EPCIS/CBV to increase supply-chain visibility—evidence of movement from abstract standards into deployable integration guidance. [4]

### 4) GS1 Digital Link Standard: URI Syntax (Release 1.6.0, Ratified)

**Organisation:** GS1

**Type:** standards body technical standard

**Publication date:** Mar 2025

**Link:** <https://ref.gs1.org/standards/digital-link/uri-syntax/>

**Why it matters:** Standardises how identifiers can be encoded into web-address-compatible URIs, supporting the “portable history file” look-up pattern (scan code → resolve identifier → fetch data) via standardised syntax. [5]

### 5) GS1 Standards enabling the EU digital product passport (Release 2.2)

**Organisation:** GS1 in Europe

**Type:** standards-body technical report / implementation positioning

**Publication date:** Jan 2025

**Link:** <https://gs1.eu/wp-content/uploads/2024/12/GS1-Standards-Enabling-DPP.pdf>

**Why it matters:** Provides a concrete mapping from EU Digital Product Passport needs to identifiers, AIDC carriers (QR, RAIN RFID, NFC, DataMatrix), and layered data-sharing approaches—direct evidence that major standards ecosystems are engineering DPP-grade traceability mechanisms and migration plans. [6]

### 6) Track & Trace Standard Interface Document (Version 3.0 Beta 1)

**Organisation:** Digital Container Shipping Association [7]

**Type:** industry consortium standard (interface specification)

**Publication date:** Mar 2023

**Link:** <https://dcsa.org/standards/track-and-trace/>

**Why it matters:** Defines a standardised interface for track-and-trace data exchange in container shipping—evidence of sector-scale, multi-actor API interoperability work aligned with the ART’s “shared rails” requirement. [8]

### 7) Track & Trace Information Model (2023.Q1)

**Organisation:** Digital Container Shipping Association

**Type:** industry consortium standard (information model)

**Publication date:** Mar 2023

**Link:** <https://dcsa.org/standards/track-and-trace/>

**Why it matters:** Provides a harmonised domain information model that underpins consistent

data interchange—evidence of “common data models” being formalised for complex, multi-party logistics networks. [9]

#### 8) **ONE Record – Release 2025-07 (endorsed standard version details; “production-ready” milestone)**

**Organisation:** International Air Transport Association[10]

**Type:** industry standard release (specification + governance endorsement)

**Publication date:** Aug 2025

**Link:** <https://github.com/IATA-Cargo/ONE-Record/releases>

**Why it matters:** States an endorsed version (Ontology/API/Data Orchestration) and explicitly positions the release as “production-ready,” reflecting maturation from pilots toward live, interoperable data sharing in air cargo supply chains. [11]

#### **Identity, integrity, and selective disclosure primitives**

#### 9) **Decentralized Identifiers (DIDs) v1.0**

**Organisation:** World Wide Web Consortium[12]

**Type:** standards body specification (W3C Recommendation)

**Publication date:** Jul 2022

**Link:** <https://www.w3.org/TR/did-core/>

**Why it matters:** Provides a standard mechanism for decentralised identifiers, supporting cross-organisation identity and verification relationships—building blocks for signed, auditable, multi-party traceability assertions. [13]

#### 10) **Verifiable Credentials Data Model v2.0**

**Organisation:** World Wide Web Consortium

**Type:** standards body specification (W3C Recommendation)

**Publication date:** May 2025

**Link:** <https://www.w3.org/TR/vc-data-model-2.0/>

**Why it matters:** Defines a cryptographically verifiable claims/credential model, including security and privacy considerations (e.g., proofs, evidence, and zero-knowledge-proof-related concepts), aligning with the ART’s “selective disclosure while proving attributes” requirement. [14]

#### **Regulation and policy as “market forcing functions”**

#### 11) **Regulation (EU) 2024/1781 (Ecodesign for Sustainable Products Regulation – ESPR)**

**Organisation:** European Union[15]

**Type:** regulation / binding legal framework

**Publication date:** Jun 2024

**Link:** <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1781>

**Why it matters:** Establishes the EU’s legal framework that introduces a Digital Product Passport concept for product categories under ecodesign rules—strong maturity evidence that interoperable traceability/passport infrastructures are becoming regulatory requirements, not optional features. [16]

#### 12) **Circular economy: New law on more sustainable, circular and safe batteries enters into force**

**Organisation:** European Commission[17]

**Type:** authoritative government programme update (official EU communication)

**Publication date:** Aug 2023

**Link:** [https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17\\_en](https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en)

**Why it matters:** Explicitly ties battery labelling/QR codes to access a digital passport with detailed information, demonstrating a near-term, regulated rollout path for product-passport-style traceability in a major industrial domain. [18]

### 13) DSCSA Standards for the Interoperable Exchange of Information for Tracing of Certain Human, Finished, Prescription Drugs (Guidance for Industry)

**Organisation:** U.S. Food and Drug Administration[19]

**Type:** authoritative government guidance (final)

**Publication date:** Sep 2023

**Link:** <https://www.fda.gov/media/171796/download>

**Why it matters:** Defines standards to facilitate secure, interoperable, electronic data exchange across pharmaceutical distribution—clear maturity evidence of regulated, multi-party e-traceability requirements (and explicit attention to confidential commercial information). [20]

### 14) DSCSA compliance policies establish 1-year stabilization period for implementing electronic systems

**Organisation:** U.S. Food and Drug Administration

**Type:** authoritative government compliance policy update

**Publication date:** Aug 2023

**Link:** <https://www.fda.gov/drugs/drug-safety-and-availability/dscsa-compliance-policies-establish-1-year-stabilization-period-implementing-electronic-systems>

**Why it matters:** Shows that even with mandates, ecosystem-wide interoperability at scale faces readiness and integration challenges (stabilization to “implement, troubleshoot and mature” electronic interoperable systems), which is directly relevant to maturity scoring. [21]

### 15) Requirements for Additional Traceability Records for Certain Foods: Small Entity Compliance Guide

**Organisation:** U.S. Food and Drug Administration

**Type:** authoritative government guidance (implementation/compliance guide)

**Publication date:** May 2023

**Link:** <https://www.fda.gov/media/168142/download>

**Why it matters:** Operationalises the US Food Traceability Rule through defined recordkeeping concepts and references the final rule publication—evidence of regulated, multi-actor traceability data requirements beyond pharmaceuticals. [22]

## Government reference architectures and traceability meta-frameworks

### 16) Supply Chain Traceability: Manufacturing Meta-Framework (NIST IR 8536 2pd, Second Public Draft)

**Organisation:** National Institute of Standards and Technology[23]

**Type:** authoritative government technical report / draft meta-framework

**Publication date:** Jul 2025

**Link:** <https://nvlpubs.nist.gov/nistpubs/ir/2025/NIST.IR.8536.2pd.pdf>

**Why it matters:** Proposes a structured meta-framework to “organize, link, and query

traceability data” across manufacturing supply chains—directly aligned with the ART’s interoperable registry and cross-ecosystem query ambitions, while indicating ongoing standardisation refinement (draft status). [24]

#### 17) **Blockchain and Related Technologies to Support Manufacturing Supply Chain Traceability: Needs and Industry Perspectives (NISTIR 8419)**

**Organisation:** National Institute of Standards and Technology

**Type:** authoritative government technical report

**Publication date:** Apr 2022

**Link:** <https://nvlpubs.nist.gov/nistpubs/ir/2022/NIST.IR.8419.pdf>

**Why it matters:** Surveys traceability challenges, metrics, and enabling technologies (including “cyber-physical anchors”), and analyses industry case studies—useful plausibility evidence for tamper-evident records and ecosystem-scale adoption barriers. [25]

#### **Implementations, prototypes, and empirical research**

#### 18) **Oliot EPCIS: An open-source EPCIS 2.0 system for supply chain transparency**

**Organisation:** research group (Auto-ID Labs / academic EPCIS implementers)

**Type:** peer-reviewed paper (SoftwareX)

**Publication date:** Jul 2023

**Link:** <https://www.sciencedirect.com/science/article/pii/S2352711023001735>

**Why it matters:** Presents a full EPCIS 2.0-compliant open-source system and discusses scalability challenges and evaluation against existing open sources—evidence that standards can be implemented into functioning, testable software systems. [26]

#### 19) **Oliot EPCIS (open-source repository) – release v2.1.0**

**Organisation:** open-source project maintainers (KAIST-linked EPCIS implementation line)

**Type:** open-source software release (implementation evidence)

**Publication date:** Jan 2024

**Link:** <https://github.com/JaewookByun/epcis/releases>

**Why it matters:** A dated, packaged release supports maturity beyond “paper design” by showing ongoing maintenance and distributable build artefacts—useful when assessing real-world implementability and ecosystem tooling. [27]

#### 20) **A Blockchain-Based Product Traceability System with Off-Chain EPCIS and IoT Device Authentication**

**Organisation:** research team at Fudan University (China)

**Type:** peer-reviewed paper (Sensors)

**Publication date:** Nov 2022

**Link:** <https://www.mdpi.com/1424-8220/22/22/8680>

**Why it matters:** Implements and tests an architecture combining permissioned blockchain with off-chain EPCIS storage to reduce “data explosion,” while addressing device authentication/authorisation and confidentiality—direct plausibility evidence for tamper-evident records plus selective access in multi-party settings. [28]

#### **Maturity score (1–7) and reasoning**

**Final maturity score:** 5

**Why this score fits the rubric (evidence-to-rubric mapping)**

### **What evidence rules out scores 1–3 (theory → lab prototype stage):**

Core interoperability building blocks already exist as ratified, implementation-oriented standards and are being actively versioned and maintained by major standards/industry bodies: GS1 EPCIS/CBV (Jun 2022; plus implementation guidance in Mar 2023) and GS1 Digital Link (Mar 2025) show mature, specification-level definitions for event semantics, vocabularies, and identifier-to-information linking. [29]

In parallel, identity/credential primitives are not speculative: W3C DIDs (Jul 2022) and Verifiable Credentials DM v2.0 (May 2025) are W3C Recommendations, indicating standards-track completion and broad implementability for signed claims and privacy/security mechanisms relevant to selective disclosure. [30]

### **What evidence rules out score 4 (single PoC) and supports score 5 (multi-actor “production prototype” race / ecosystem buildout):**

Multiple sectors show formalised, multi-party interoperability efforts through industry consortium specifications (e.g., shipping track-and-trace interface + information model) and ongoing standard releases targeting production use (e.g., air cargo ONE Record endorsed release positioned as production-ready). [31]

Regulators are also codifying traceability/passport requirements in ways that force ecosystem alignment (EU ESPR for DPPs; EU battery rules communicating QR-enabled battery passports; US DSCSA and food traceability rule guidance). This moves the technology from “nice-to-have” prototypes into coordinated, funded implementation programmes across many firms. [32]

On the implementation side, peer-reviewed and open-source artefacts demonstrate that EPCIS-based interoperability is implementable and actively engineered (e.g., an EPCIS 2.0 open-source system with evaluation discussion; and a blockchain + off-chain EPCIS tested architecture addressing data volume and confidentiality). [33]

### **What evidence is still missing to justify score 6 (delivered at increasing scale) or 7 (broad competitive growth with rising demand):**

The ART’s emphasis is not just “traceability software exists,” but **global, interoperable, cross-organisation networks** with dependable data quality, automated capture at high volume, and credible governance/dispute handling. The evidence above shows strong standardisation and regulatory pull, but also highlights real scaling friction: FDA’s DSCSA stabilization period explicitly grants additional time to “implement, troubleshoot and mature” interoperable electronic systems, signalling that ecosystem-wide rollout remains operationally challenging even in a high-value, regulated sector. [21]

Similarly, EU DPP requirements under ESPR are a framework that still depends on delegated acts and product-category rollouts; the battery passport is described as accessible via QR code with staged introduction, implying ongoing implementation work rather than a fully scaled, cross-industry reality today. [34]

To justify **score 6–7**, the dossier would ideally include (within the time window) strong quantitative deployment indicators (e.g., transaction volumes across interoperable networks, numbers of firms exchanging standard-conformant event data, audited adoption metrics across multiple industries) and evidence that interoperability and data-quality governance have stabilised across borders and tiers. Such scaling metrics are not established by the sources above, which skew toward standards, guidance, and early-to-mid deployment evidence.

### **Sub-component maturity breakdown and aggregation**

- **Interoperable event data models + vocabularies (GS1 EPCIS/CBV + guidance) → 6 (component level)**  
Ratified standards and implementation guidance indicate mature specification and implementability. [35]
- **Identifier-to-web linking for “history file” discovery (GS1 Digital Link; DPP mapping) → 5–6**  
Digital Link is ratified and DPP mapping is concrete, but large-scale migration and regulatory alignment are still in progress. [36]
- **Sector-wide interface standards (shipping, air cargo) → 5–6**  
DCSA interface/info model specs exist for multi-party shipping interoperability; IATA ONE Record releases are endorsed and positioned as production-ready, with an explicit timeline push. [31]
- **Cryptographic identity, signatures, selective disclosure primitives (DIDs + Verifiable Credentials) → 6**  
W3C Recommendations provide mature, standardised building blocks; supply-chain-specific integration remains an engineering/governance task. [30]
- **Regulatory pull and compliance frameworks (EU ESPR/DPP; batteries; US DSCSA; US food traceability) → 5**  
Strong mandate signals but still staged rollout and stabilisation periods, indicating incomplete ecosystem maturity. [37]
- **Reference architectures and meta-frameworks (NIST) → 4–5**  
Clear technical structuring and data-model thinking are present, but key artefacts remain in draft iterations and are not themselves proof of globally scaled adoption. [38]

#### Aggregation to one score:

Because the ART’s value depends on *ecosystem-scale interoperability and governance* (not just mature component technologies), and multiple major programmes are still in rollout/stabilisation phases, the overall maturity is best represented as **5** (ecosystem buildout with multiple actors and strong regulatory pull, but not yet consistently scaled as global interoperable registries). [39]

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[1] [2] [17] [29] [35] <https://ref.gs1.org/standards/epcis/2.0.0/>

<https://ref.gs1.org/standards/epcis/2.0.0/>

[3] <https://ref.gs1.org/standards/cbv/>

<https://ref.gs1.org/standards/cbv/>

[4] <https://ref.gs1.org/guidelines/epcis-cbv/>

<https://ref.gs1.org/guidelines/epcis-cbv/>

[5] [12] [36] URI Syntax

<https://ref.gs1.org/standards/digital-link/uri-syntax/>

[6] [gs1.eu](https://gs1.eu)



<https://gs1.eu/wp-content/uploads/2024/12/GS1-Standards-Enabling-DPP.pdf>

[7] [16] [32] [34] [37] <https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng>

<https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng>

[8] [15] [31] [https://dcsa-website.cdn.prismic.io/dcsa-website/65ca14d29be9a5b998b5ad65\\_20230301-DCSA-Track%26Trace3.0Beta1-InterfaceStandard.pdf](https://dcsa-website.cdn.prismic.io/dcsa-website/65ca14d29be9a5b998b5ad65_20230301-DCSA-Track%26Trace3.0Beta1-InterfaceStandard.pdf)

[https://dcsa-website.cdn.prismic.io/dcsa-website/65ca14d29be9a5b998b5ad65\\_20230301-DCSA-Track%26Trace3.0Beta1-InterfaceStandard.pdf](https://dcsa-website.cdn.prismic.io/dcsa-website/65ca14d29be9a5b998b5ad65_20230301-DCSA-Track%26Trace3.0Beta1-InterfaceStandard.pdf)

[9] [https://dcsa-website.cdn.prismic.io/dcsa-website/65ca12999be9a5b998b5ad40\\_20230301-DCSA-InformationModelQ1.pdf](https://dcsa-website.cdn.prismic.io/dcsa-website/65ca12999be9a5b998b5ad40_20230301-DCSA-InformationModelQ1.pdf)

[https://dcsa-website.cdn.prismic.io/dcsa-website/65ca12999be9a5b998b5ad40\\_20230301-DCSA-InformationModelQ1.pdf](https://dcsa-website.cdn.prismic.io/dcsa-website/65ca12999be9a5b998b5ad40_20230301-DCSA-InformationModelQ1.pdf)

[10] [21] [39] DSCSA compliance policies establish 1-year stabilization period for implementing electronic systems | FDA

<https://www.fda.gov/drugs/drug-safety-and-availability/dcsa-compliance-policies-establish-1-year-stabilization-period-implementing-electronic-systems>

[11] <https://github.com/IATA-Cargo/ONE-Record/releases>

<https://github.com/IATA-Cargo/ONE-Record/releases>

[13] [30] <https://www.w3.org/TR/did-core/>

<https://www.w3.org/TR/did-core/>

[14] <https://www.w3.org/TR/vc-data-model-2.0/>

<https://www.w3.org/TR/vc-data-model-2.0/>

[18] [https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17\\_en](https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en)

[https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17\\_en](https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en)

[19] [27] <https://github.com/JaewookByun/epcis/releases>

<https://github.com/JaewookByun/epcis/releases>

[20] DSCSA Standards for the Interoperable Exchange of Information for Tracing of Certain Human, Finished, Prescription Drugs

<https://www.fda.gov/media/171796/download>

[22] Requirements for Additional Traceability Records for Certain Foods: What You Need to Know About the FDA Regulation: Small Entity Compliance Guide

<https://www.fda.gov/media/168142/download>

[23] [28] <https://www.mdpi.com/1424-8220/22/22/8680>

<https://www.mdpi.com/1424-8220/22/22/8680>

[24] [38] <https://nvlpubs.nist.gov/nistpubs/ir/2025/NIST.IR.8536.2pd.pdf>

<https://nvlpubs.nist.gov/nistpubs/ir/2025/NIST.IR.8536.2pd.pdf>

[25] <https://nvlpubs.nist.gov/nistpubs/ir/2022/NIST.IR.8419.pdf>

<https://nvlpubs.nist.gov/nistpubs/ir/2022/NIST.IR.8419.pdf>

[26] [33] <https://www.sciencedirect.com/science/article/pii/S2352711023001735>

<https://www.sciencedirect.com/science/article/pii/S2352711023001735>

## ART 12.094 Personal Data Portability & Trust Frameworks

### ART extraction

#### A) Primary capability the ART claims

- A *user-directed* personal data portability layer: individuals can permission, move, and revoke access to personal data across services with low friction (closer to “switching providers” than bespoke integrations).
- A standardised “personal data wallet” experience (or equivalent mediating layer) enabling *fine-grained*, time-bound, purpose-bound data sharing, with consistent consent prompts and machine-readable proof of consent.
- A trust and accountability layer: verifiers can validate what was shared and why, using verification methods, revocation/status mechanisms, and tamper-evident logging/auditability.

#### B) Key sub-components / sub-threads

- Interoperable data portability obligations and technical interoperability requirements (e.g., access rights, switching, cross-provider interoperability).
- Digital identity and attribute attestations (wallets, verifiable credentials, attestations of attributes).
- Standard consent/permission representations (consent records/receipts) and permission APIs (scopes, fields, expiry).
- Selective disclosure / privacy-preserving claims (e.g., SD-JWT style disclosure, ZK/anonymous credential approaches).
- Revocation / status signalling (status lists, expiry, verifiable credential “status” patterns).
- Tamper-evident auditability (transparency logs; audit logs for issuance and/or disclosures).
- Governance and certification frameworks (rules for relying parties, certification of wallets/providers; dispute and breach handling).
- Phishing-resistant authentication and usable recovery (wallet activation, keys, account takeover defences, recovery flows).

### C) Maturity indicators that would count as evidence

- Multiple *final* standards/specifications in the stack (identity, credentials, presentation/issuance, selective disclosure), plus visible conformance testing.
- Enacted regulation plus implementing rules/certification requirements that make the framework enforceable, not merely aspirational.
- Large-scale, multi-party pilots (ideally cross-border), showing interoperability across implementations and relying parties.
- Evidence of production-grade security guidance (phishing-resistant options, wallet threat models) and operational governance (registration of relying parties, breach response processes).
- Independent research showing scalability/overhead for transparency/audit logging and privacy-preserving disclosure, beyond toy examples.

#### Evidence

##### Source selection notes and time window

All sources below are dated **February 2022–February 2026** (the last 4 years from **19 February 2026**) and prioritise standards bodies, government/public-sector programmes, and peer-reviewed or technically detailed research, in line with your eligibility rubric. [\[1\]](#)

##### Evidence links and annotations

#### 1) Regulation (EU) 2022/868 (Data Governance Act) (Text with EEA relevance)

**Organisation:** Publications Office of the European Union[\[2\]](#) (corporate authors: European Parliament[\[3\]](#) and Council of the European Union[\[4\]](#))

**Type:** authoritative legal instrument (regulation text publication record)

**Publication date:** May 2022 (published 2022-05-30)

**Link:** <https://op.europa.eu/cs/publication-detail/-/publication/b3c148c3-e2d6-11ec-a534-01aa75ed71a1/language-en>

**Why it matters:** This is a core EU-level governance anchor explicitly aimed at “European data governance”, providing legal infrastructure that can reduce trusted-data-sharing friction and make interoperability and trust frameworks more realistic at scale (a key feasibility dependency for the ART). [\[5\]](#)

#### 2) European Data Governance Act (DGA) — OECD toolkit entry

**Organisation:** Organisation for Economic Co-operation and Development[\[6\]](#)

**Type:** authoritative policy/implementation summary (international organisation toolkit)

**Publication date:** April 2025 (15 Apr 2025)

**Link:** [https://www.oecd.org/en/publications/access-to-public-research-data-toolkit\\_a12e8998-en/european-data-governance-act-dga-regulation-eu-2022-868\\_920b8b28-en.html](https://www.oecd.org/en/publications/access-to-public-research-data-toolkit_a12e8998-en/european-data-governance-act-dga-regulation-eu-2022-868_920b8b28-en.html)

**Why it matters:** Provides an implementation-oriented synopsis (including entry-into-force/applicability framing) that helps evaluate maturity signals: the ART’s trust frameworks are not merely proposed—key elements have defined legal timelines and a governance narrative geared toward increasing *trust in data sharing*. [\[7\]](#)

#### 3) Regulation (EU) 2023/2854 (Data Act) (Text with EEA relevance)

**Organisation:** Publications Office of the EU (corporate authors: European Parliament;

Council of the European Union)

**Type:** authoritative legal instrument (regulation text publication record)

**Publication date:** December 2023 (published 2023-12-22)

**Link:** <https://op.europa.eu/en/publication-detail/-/publication/ef51c6ab-a06c-11ee-b164-01aa75ed71a1/language-en>

**Why it matters:** Establishes a broad legal framework for access/use of data and is directly relevant to the ART’s “portability” and “switching” promises; the existence of a final regulation is a strong maturity indicator that governments are *institutionalising* portability and interoperability requirements rather than leaving them purely voluntary. [8]

#### 4) Regulation (EU) 2024/1183 establishing the European Digital Identity Framework

**Organisation:** Publications Office of the EU (corporate authors: Council of the European Union; European Parliament)

**Type:** authoritative legal instrument (regulation text publication record)

**Publication date:** April 2024 (published 2024-04-30)

**Link:** <https://op.europa.eu/en/publication-detail/-/publication/459993a1-068e-11ef-a251-01aa75ed71a1/language-en>

**Why it matters:** A direct, high-authority driver for the “personal data wallet” component of the ART: it formalises an EU digital identity framework which (in practice) is pushing wallet-based identity/attribute presentation into regulated reality—critical for plausibility of cross-service reuse and interoperability. [9]

#### 5) UK digital identity and attributes trust framework (gamma 0.4)

**Organisation:** GOV.UK[10] / Department for Science, Innovation and Technology[11] (with Office for Digital Identities and Attributes[12])

**Type:** government trust framework / operational requirements (authoritative policy + compliance pathway)

**Publication date:** November 2024 (published 25 Nov 2024; last updated 1 Dec 2025)

**Link:** <https://www.gov.uk/government/publications/uk-digital-identity-and-attributes-trust-framework-04>

**Why it matters:** Shows a concrete, operational “trust framework” approach (including recognition and certification pathways) that maps closely to the ART’s governance/dispute/assurance layer and indicates real-world institutional readiness beyond ad-hoc identity checks. [13]

#### 6) EU Digital Identity Wallet milestone reached as Commission adopts implementing regulations

**Organisation:** European Commission[14] (EU Digital Identity Wallet programme pages)

**Type:** authoritative programme/governance update (implementing rules summary)

**Publication date:** December 2024 (created/dated 4 Dec 2024)

**Link:** <https://ec.europa.eu/digital-building-blocks/sites/spaces/EUDIGITALIDENTITYWALLET/pages/844759146/EU+Digital+Identity+Wallet+milestone+reached+as+Commission+adopts+implementing+regulations>

**Why it matters:** Reports adoption of **five implementing regulations** covering wallet core functionalities, security/reliability aspects, and certification—direct maturity evidence that the ecosystem is moving from “concept” to enforceable technical and assurance requirements. [15]

## 7) European Commission adopts new round of EU Digital Identity Wallet implementing regulations

**Organisation:** European Commission (EU Digital Identity Wallet programme pages)

**Type:** authoritative programme/governance update (implementing rules expansion)

**Publication date:** May 2025 (created 7 May 2025; last updated 21 May 2025)

**Link:** <https://ec.europa.eu/digital-building-blocks/sites/spaces/EUDIGITALIDENTITYWALLET/pages/896827698/European+Commission+adopts+new+round+of+EU+Digital+Identity+Wallet+implementing+regulations>

**Why it matters:** Evidence of ongoing standardisation *beyond* initial wallet specs—explicitly covers registration/certification of wallets and relying parties and references rules for handling security breaches, aligning with the ART’s need for governance plus operational security response. [16]

## 8) EU Digital Identity Wallet Pilot implementation (Large Scale Pilots overview)

**Organisation:** European Commission (DG CONNECT / Shaping Europe’s Digital Future)

**Type:** government programme page (pilot deployment evidence)

**Publication date:** February 2025 (last update 18 Feb 2025)

**Link:** <https://digital-strategy.ec.europa.eu/en/policies/eudi-wallet-implementation>

**Why it matters:** Direct maturity evidence of real-world piloting at EU level: pilots are “guided by technical specifications” and are scheduled to continue through 2025, indicating multi-party interoperability testing rather than purely laboratory prototypes. [17]

## 9) Digital Identity Guidelines (NIST SP 800-63-4)

**Organisation:** National Institute of Standards and Technology[18]

**Type:** authoritative government technical guidance (security/assurance architecture)

**Publication date:** July 2025

**Link:** <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-63-4.pdf>

**Why it matters:** Explicitly models a “federated digital identity” architecture with a **subscriber-controlled wallet** (including key generation/activation and attribute bundle issuance), and calls for phishing-resistant options at higher assurance levels—directly relevant to feasibility constraints around phishing/account takeover. [19]

## 10) Decentralized Identifiers (DIDs) v1.0

**Organisation:** World Wide Web Consortium[20]

**Type:** technical standard (W3C Recommendation)

**Publication date:** July 2022 (19 Jul 2022)

**Link:** <https://www.w3.org/TR/did-core/>

**Why it matters:** A foundational building block for wallet-centric ecosystems: DIDs provide a standard way to represent and resolve decentralised identifiers, supporting interoperable identity references across providers—critical for portability frameworks not locked to a single platform. [21]

## 11) Verifiable Credentials Data Model v2.0

**Organisation:** World Wide Web Consortium

**Type:** technical standard (W3C Recommendation)

**Publication date:** May 2025 (15 May 2025)

**Link:** <https://www.w3.org/TR/vc-data-model-2.0/>

**Why it matters:** Defines a standard data model for cryptographically verifiable claims (issuer/holder/verifier model) and explicitly treats credentials as machine-verifiable personal information; this is a central plausibility pillar for selective disclosure and portable attestations across services. [22]

## 12) OpenID for Verifiable Presentations 1.0

**Organisation:** OpenID Foundation[23]

**Type:** technical standard (final specification, standards track)

**Publication date:** July 2025 (published 9 Jul 2025; status: Final)

**Link:** [https://openid.net/specs/openid-4-verifiable-presentations-1\\_0.html](https://openid.net/specs/openid-4-verifiable-presentations-1_0.html)

**Why it matters:** Specifies a standard protocol for *requesting and presenting* credentials, directly aligning with the ART’s “consistent prompts” and interoperable permission/request flows across relying parties and wallet implementations. [24]

## 13) OpenID for Verifiable Credential Issuance 1.0

**Organisation:** OpenID Foundation

**Type:** technical standard (final specification, standards track)

**Publication date:** September 2025 (published 16 Sep 2025; status: Final)

**Link:** [https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0.html)

**Why it matters:** Defines an issuance API and OAuth-based flows for delivering verifiable credentials into wallets—evidence that the “portable data wallet” pattern is consolidating around interoperable, implementable interfaces rather than bespoke integrations. [25]

## 14) Selective Disclosure for JSON Web Tokens (RFC 9901)

**Organisation:** Internet Engineering Task Force[26]

**Type:** technical standard (RFC; Proposed Standard)

**Publication date:** November 2025

**Link:** <https://datatracker.ietf.org/doc/rfc9901/>

**Why it matters:** Standardises a concrete, deployable mechanism for **selective disclosure** of claims carried in JWT-like structures—directly supporting the ART’s goal of sharing “meets requirement” or only specific fields without giving full account-level access. [27]

## 15) Digital Credentials (Digital Credentials API)

**Organisation:** World Wide Web Consortium (Federated Identity Working Group)

**Type:** technical standard-in-progress (W3C Working Draft)

**Publication date:** February 2026 (19 Feb 2026)

**Link:** <https://www.w3.org/TR/digital-credentials/>

**Why it matters:** Indicates convergence at the *user agent / platform layer* (device makers, browsers, identity providers) to mediate credential issuance/presentation—exactly the kind of cross-actor standardisation needed for the ART’s “legible, reusable prompts” and “safe-by-default sharing” to become mainstream UX. [28]

## 16) ISO/IEC TS 27560:2023 — Privacy technologies — Consent record information structure

**Organisation:** International Organization for Standardization[29] / ISO/IEC JTC 1

**Type:** technical standard (ISO/IEC technical specification)

**Publication date:** August 2023 (publication date 2023-08)



**Link:** <https://www.iso.org/standard/80392.html>

**Why it matters:** Provides a standardised information structure for recording and exchanging consent records/receipts—directly matching the ART’s need for machine-readable consent receipts, portable permissions, and interoperability across systems. [30]

#### 17) Implementing ISO/IEC TS 27560:2023 Consent Records and Receipts for GDPR and DGA

**Authors:** Harshvardhan J. Pandit[31] et al.

**Type:** technical report / preprint (arXiv; label: preprint)

**Publication date:** May 2024 (1 May 2024)

**Link:** <https://arxiv.org/abs/2405.04528>

**Why it matters:** Demonstrates concrete, machine-readable implementations of ISO 27560 consent records/receipts and explicitly discusses exchange and interoperability; this is evidence that “consent receipts” can be engineered into reusable, standardised representations rather than bespoke UI screenshots. [32]

#### 18) Selective disclosure in digital credentials: A review

**Authors:** Šeila Bećirović Ramić[33] et al.

**Type:** peer-reviewed journal paper (ICT Express, open access)

**Publication date:** August 2024 (Volume 10, Issue 4, August 2024)

**Link:** <https://www.sciencedirect.com/science/article/pii/S2405959524000614>

**Why it matters:** Surveys selective disclosure approaches (including anonymous credentials, ZK-related strategies) and highlights method trade-offs and gaps—useful for plausibility assessment of the ART’s “share only what’s needed” claim and what is still technically hard. [34]

#### 19) Credential Issuance Transparency: A Privacy-preserving Audit Log of Credential Issuance

**Authors:** Edona Fasllija[35] et al.

**Type:** peer-reviewed conference proceedings paper (Springer LNCS; NSS 2024 proceedings)

**Publication date:** March 2025 (published 14 Mar 2025)

**Link:** <https://tugraz.elsevierpure.com/en/publications/credential-issuance-transparency-a-privacy-preserving-audit-log-o/>

**Why it matters:** Proposes and evaluates a transparency-log approach for credential issuance that preserves privacy while enabling auditability; reports *concrete feasibility metrics* (e.g., <2 ms overhead to showing; monitoring costs bounded by <1 GB/day download and <10 s compute), directly informing the ART’s “tamper-evident logs” plausibility. [36]

#### 20) Implementing regulation for European Digital Identity Wallets

**Organisation:** European Commission (Shaping Europe’s Digital Future library entry)

**Type:** authoritative government library/press linkage (implementation status anchor)

**Publication date:** November 2024 (press release dated 28 Nov 2024 on the page)

**Link:** <https://digital-strategy.ec.europa.eu/en/library/implementing-regulation-european-digital-identity-wallets>

**Why it matters:** Shows the Commission positioning implementing regulations as the mechanism “laying down rules for core functionalities and certification,” a key maturity signal that the wallet layer is being standardised with compliance hooks, not only built as optional apps. [37]

## Maturity score and reasoning

### A) Final maturity score: 5

**Score: 5 (post-PoC, multiple major actors racing toward production deployment).** [\[38\]](#)

### B) Evidence-to-rubric mapping

#### What rules out Levels 1–3 (theory only / lab validation / early prototype):

There is now a substantial base of *finalised* or near-final interoperable standards for key wallet/credential flows—e.g., W3C Recommendations for verifiable credentials (May 2025) and OpenID final specs for issuance/presentation (July/September 2025), plus an IETF Proposed Standard for selective disclosure (RFC 9901, November 2025). [\[39\]](#)

On the governance side, the EU has enacted major regulations (Data Governance Act published May 2022; Data Act published December 2023; European Digital Identity Framework regulation published April 2024) and is issuing implementing regulations for the wallet ecosystem (first round dated December 2024; additional round May 2025). [\[40\]](#)

This combination goes beyond laboratory plausibility: it indicates that interoperability is being *codified* and engineered for cross-organisation use, including certification and relying-party rules. [\[41\]](#)

#### What rules out Level 4 as the ceiling (i.e., why it’s not just a single PoC):

Multiple well-capitalised and institutionally powerful actors are concurrently standardising and operationalising the stack: EU-level regulation plus implementing acts and pilots, OpenID standards for protocols, and IETF/W3C standards for credential semantics and selective disclosure. [\[42\]](#)

The UK’s statutory trust-framework direction (with certification pathways) is another strong signal that trust frameworks are moving into enforceable operational regimes, not just pilots. [\[13\]](#)

Altogether, this aligns best with “several well-capitalised actors competing to develop a production prototype post-PoC” (rubric Level 5). [\[43\]](#)

#### What is still missing to justify Level 6 (products delivered in increasing amounts; scaling expanding by default):

The web/platform mediation layer that would make the ART feel like a universal “system capability” is still explicitly a **Working Draft** (W3C Digital Credentials API, February 2026), which suggests that browser/OS-level convergence is not fully locked in yet. [\[28\]](#)

The EU’s programme framing still highlights pilots continuing through 2025 and the stepwise rollout of implementing rules, implying ongoing integration/testing and not yet a stable, mass-scale operational equilibrium across sectors/services. [\[44\]](#)

On auditability, while concrete performance results exist for privacy-preserving issuance transparency, this remains research/proceedings-level evidence rather than widespread production deployment across issuers and relying parties. [\[36\]](#)

### Sub-score breakdown and aggregation rationale

Because this ART is a *bundle* (portability law + wallet/credential protocols + consent semantics + auditability), a single score is best treated as an **average-weighted** assessment of major sub-components, with emphasis on the bottleneck to broad adoption (cross-sector interoperability + governance + UX/security). [\[45\]](#)

- **Governance and regulatory forcing functions (EU + UK) → 5–6**

*Support:* Enacted EU regulations plus implementing regulations and certification framing; UK trust framework with certification pathway language. [46]

*Why not a clean 6:* still strongly framed as staged rollout/pilots, with additional implementing rounds continuing. [44]

- **Wallet/credential interoperability protocols (VC/DID/OpenID/SD-JWT) → 5**

*Support:* Final OpenID specs for issuance/presentations; W3C VC Recommendation; IETF SD-JWT Proposed Standard. [47]

*Why not 6:* platform-level mediation is still draft, and broad “default everywhere” relying-party adoption is not yet evidenced here. [48]

- **Consent receipts / machine-readable permission records → 4–5**

*Support:* ISO/IEC TS 27560 published and an implementation-focused preprint mapping it into interoperable consent records/receipts. [49]

*Why not 5–6:* evidence of widespread production deployment across major platforms/services is not established by these sources alone. [32]

- **Tamper-evident logs for accountability → 3–4**

*Support:* Peer-reviewed proceedings paper with quantified overhead and monitoring costs for privacy-preserving issuance transparency. [36]

*Why not 5+:* still at research-to-early-adoption stage rather than a widely mandated, interoperable production norm.

**Aggregation to one score:** These sub-components cluster around **Level 5** for the core wallet/protocol/governance elements, with consent and audit logging trailing; averaging yields a **Level 5** overall because the primary user-visible capability (portable, permissioned, standardised sharing via wallets/credentials with selective disclosure) is now backed by multiple final standards *and* active regulatory implementation, but is not yet unequivocally in broad, scaled production across sectors. [50]

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[1] [5] [33] [40] [46] <https://op.europa.eu/cs/publication-detail/-/publication/b3c148c3-e2d6-11ec-a534-01aa75ed71a1/language-en>

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<https://datatracker.ietf.org/doc/rfc9901/>

[4] [13] <https://www.gov.uk/government/publications/uk-digital-identity-and-attributes-trust-framework-04>

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## ART 12.095 Interoperable Digital Currency Payment Networks

### 1. ART extraction

- **Primary capability (claimed)**
- A protocol “inter-network” that can connect heterogeneous digital money systems (multiple CBDCs, cryptocurrencies, mobile money / fast payment rails) so value can be discovered, quoted, authorised and settled end-to-end across boundaries. [1]
- **Atomic cross-rail settlement** (payment-versus-payment / delivery-versus-payment style guarantees) so neither leg completes without the other, reducing counterparty/settlement risk in cross-currency transfers. [2]
- A practical, standards-driven approach: keep systems sovereign/independent, but enforce interoperability via common messaging/semantic rules, standard APIs, and well-defined roles for routing/liquidity providers and compliance checks. [3]
- **Key sub-components / sub-threads (technology bundle)**
- **Interoperability models & architecture choices** (compatible systems vs interlinked systems vs shared multi-currency platforms). [4]
- **Routing + discovery layer** (hub-and-spoke routers, gateways, minimising bilateral integrations; path selection/rate selection). [5]
- **Real-time quoting & FX/liquidity orchestration** (competition among FX providers; support for bridge/vehicle currencies). [6]

- **Atomic settlement primitives** (PvP coordination; HTLC-like constructions; smart-contract-mediated conditional settlement). [\[7\]](#)
- **Standardised data + messaging semantics** (ISO 20022 usage, harmonised minimum data set, end-to-end consistency). [\[8\]](#)
- **Wallet/API integration + delegated authorisation** (standard APIs/SDKs for account lookup, quotes, payment initiation; constrained delegation). [\[9\]](#)
- **Privacy + compliance controls** (selective disclosure / unlinkability options for “prove what’s required, reveal as little as possible”). [\[10\]](#)
- **Offline / low-connectivity operation** (offline transfers later reconciled; resilience against outages; double-spend risk controls). [\[11\]](#)
- **Governance, standard-setting, and cross-jurisdictional operating model** (roles, dispute resolution, rules, adoption timelines). [\[12\]](#)
- **Maturity indicators that would count as evidence for this ART**
- **Multi-party prototypes** that interoperate across at least two currency systems/rails (CBDC↔CBDC; CBDC↔existing payment systems) and demonstrate the full sequence: discovery → quote → authorise → settle. [\[13\]](#)
- **Real-value pilots** (not just simulated) and/or operational throughput/latency results that look production-relevant. [\[14\]](#)
- **Published standards/specifications** (message/data requirements, API specs, credential formats) with multi-stakeholder adoption plans and timelines. [\[15\]](#)
- **Move toward live scheme governance** (eg, scheme organisation established, rulebooks/implementation guides published). [\[16\]](#)
- **Offline/payment resilience demonstrations** with explicit security trade-offs, double-spend mitigation, and device/security model. [\[11\]](#)

## 2. Evidence (10–20 recent, reliable sources)

### [1] Options for access to and interoperability of CBDCs for cross-border payments (Report to the G20)

Organisation/authors: Bank for International Settlements[\[17\]](#); Committee on Payments and Market Infrastructures[\[18\]](#); BIS Innovation Hub[\[19\]](#); International Monetary Fund[\[20\]](#); World Bank Group[\[21\]](#) (joint report)

Venue/type: Authoritative roadmap/report (G20 deliverable)

Publication date: **July 2022**

Link: <https://www.bis.org/publ/othp52.pdf>

Annotation: Defines and compares cross-border CBDC access/interoperability options and explicitly highlights the need for coordinated standards (technical + governance) so domestic CBDC choices do not create barriers to cross-border interoperability. It also frames interoperability as technical/semantic/business compatibility and sets out evaluation criteria central to plausibility and maturity assessment. [\[22\]](#)

### [2] Project Dunbar: International settlements using multi-CBDCs (final report)

Organisation/authors: Reserve Bank of Australia[\[23\]](#); Bank Negara Malaysia[\[24\]](#); Monetary Authority of Singapore[\[25\]](#); South African Reserve Bank[\[26\]](#) (+ BIS Innovation Hub collaboration)

Venue/type: Authoritative technical report + prototype programme report



Publication date: **March 2022**

Link: <https://www.rba.gov.au/payments-and-infrastructure/central-bank-digital-currency/pdf/project-dunbar-report-2022-03.pdf>

Annotation: Reports building and testing **technical prototypes** of a shared multi-CBDC settlement platform (model-3 style) and explicitly targets direct cross-border settlement between participating central banks and financial institutions, tackling fragmentation across ledgers/message formats. The report documents a concrete engineering approach (including prototype builds on two DLT stacks) that strengthens plausibility beyond “concept only”. [27]

### [3] Project mBridge: connecting economies through CBDC (pilot report)

Organisation/authors: BIS Innovation Hub + Hong Kong Monetary Authority[28]; Bank of Thailand[29]; Digital Currency Institute of the People's Bank of China[30]; Central Bank of the United Arab Emirates[31] (joint report)

Venue/type: Authoritative pilot report (multi-central bank technical programme)

Publication date: **October 2022**

Link: <https://www.bis.org/publ/othp59.htm>

Annotation: Describes a purpose-built “mBridge Ledger” and a six-week pilot that settled **real value directly on-platform**, issuing **over US\$12m** and completing **160+ PvP payment/FX transactions totalling >US\$22m**—strong evidence for functional feasibility close to production requirements. It is direct maturity evidence that multi-CBDC interoperability is already operating beyond lab demo scale. [32]

### [4] HKMA press release on Project mBridge (real-value pilot details + roadmap language)

Organisation/authors: HKMA (press release)

Venue/type: Central bank technical programme announcement (public-sector deployment evidence)

Publication date: **October 2022**

Link: <https://www.hkma.gov.hk/eng/news-and-media/press-releases/2022/10/20221026-3/>

Annotation: Confirms the pilot as a **six-week, 20-bank, four-jurisdiction** exercise with **160+ payment and FX transactions totalling >HK\$171m**, and explicitly states intent to progress toward an MVP and “production-ready system” (useful maturity signalling). This independently corroborates the pilot scale and “real-value” claim for plausibility/maturity evaluation. [33]

### [5] Project mBridge reached minimum viable product stage (status update page)

Organisation/authors: BIS Innovation Hub (project status update)

Venue/type: Authoritative programme status update (roadmap/progress evidence)

Publication date: **Updated November 2024**

Link: [https://www.bis.org/about/bisih/topics/cbdc/mcbdc\\_bridge.htm](https://www.bis.org/about/bisih/topics/cbdc/mcbdc_bridge.htm)

Annotation: States that mBridge reached **MVP stage in mid-2024**, indicating movement from pilot toward a more productised platform and inviting wider participation—an important maturity marker for scaling efforts. Also documents the expanding multi-jurisdiction governance context (eg, additional central bank participation) showing growing institutional commitment. [34]

### [6] Project Icebreaker: breaking new paths in cross-border retail CBDC payments (final report)

Organisation/authors: Bank of Israel[35]; Norges Bank[36]; Sveriges Riksbank[37] + BIS

Innovation Hub Nordic Centre

Venue/type: Authoritative technical report (prototype architecture + risk analysis)

Publication date: **March 2023**

Link: <https://www.bis.org/publ/othp61.htm>

Annotation: Demonstrates a hub-and-spoke **interlinking model** where each rCBDC stays inside its domestic system, while cross-currency settlement is coordinated via **PvP using HTLCs**, materially addressing the “atomic settlement” requirement. Also implements competitive FX quoting (hub selects best rate submitted by FX providers), directly mapping to the ART’s discovery/quoting/routing functions. [38]

**[7] Project Mariana: cross-border exchange of wholesale CBDCs using automated market makers (final report landing page)**

Organisation/authors: BIS Innovation Hub + Bank of France[39]; Swiss National Bank[40]; Monetary Authority of Singapore

Venue/type: Authoritative proof-of-concept report (wholesale FX + settlement design)

Publication date: **September 2023**

Link: <https://www.bis.org/publ/othp75.htm>

Annotation: Reports a PoC showing technical feasibility of cross-border interbank FX trading/settlement in (hypothetical) wCBDCs using **automated market makers**, which directly supports the ART’s “quoting + liquidity + settlement integration” narrative. It matters because it explores a concrete mechanism for embedded FX conversion alongside settlement—often a key bottleneck for interoperable multi-currency networks. [41]

**[8] Project Rialto: improving instant cross-border payments using central bank money settlement (project page + technical report pointer)**

Organisation/authors: BIS Innovation Hub with Bank of France, Bank of Italy[42], Bank Negara Malaysia, Monetary Authority of Singapore

Venue/type: Authoritative proof-of-concept programme report (bridge between existing rails and tokenised settlement)

Publication date: **Updated December 2025**

Link: <https://www.bis.org/about/bisih/topics/cbdc/rialto.htm>

Annotation: States the PoC **successfully simulated** cross-border retail payments by combining **interlinked instant payment systems** with a tokenised wholesale central bank money settlement layer and modular FX (including a vehicle currency scenario). This is directly aligned with the ART’s “layered protocol stack” claim: connecting non-tokenised rails to tokenised settlement while preserving modularity and interoperability. [43]

**[9] Project Nexus: enabling instant cross-border payments (programme status + governance milestone)**

Organisation/authors: BIS Innovation Hub (programme page)

Venue/type: Authoritative programme status + scheme/governance progress

Publication date: **Updated August 2025**

Link: <https://www.bis.org/about/bisih/topics/fmis/nexus.htm>

Annotation: Describes standardising cross-border connectivity so a domestic instant payments system can “connect once” to reach others, with an ambition of cross-border payments **within ~60 seconds**, and notes establishment of the **Nexus Scheme Organisation** to manage live implementation stages. It matters as evidence that interoperability is moving

from prototypes to operational governance + technical documentation (API + ISO 20022 message specs), a key maturity criterion for real networks. [44]

#### **[10] Interlinking Fast Payment Systems for Cross-border Payments (RBA report)**

Organisation/authors: Reserve Bank of Australia

Venue/type: Central bank technical/report (design models + implementation considerations)

Publication date: **April 2024**

Link: <https://www.rba.gov.au/payments-and-infrastructure/pdf/report-interlinking-fast-payment-systems-for-cross-border-payments-april-2024.pdf>

Annotation: Provides a detailed breakdown of **four interlinking models** (single access point, bilateral link, hub-and-spoke, common platform) and highlights modern interoperability enablers like **ISO 20022** and **APIs** for real-time exchange. While not CBDC-only, it is strong “network engineering reality” evidence for the ART’s claim that interoperability resembles enterprise-grade middleware with significant legal/regulatory and operational alignment requirements. [45]

#### **[11] Harmonised ISO 20022 data requirements for enhancing cross-border payments (final report)**

Organisation/authors: Committee on Payments and Market Infrastructures (BIS) in collaboration with the private-sector Payments Market Practice Group

Venue/type: Standards/roadmap report (data semantics interoperability)

Publication date: **October 2023**

Link: <https://www.bis.org/cpmi/publ/d218.htm>

Annotation: Specifies **12 harmonised ISO 20022 end-to-end data requirements** intended to reduce fragmentation in cross-border message implementations, with a stated “begin preparations now” and align **by end-2027**. This is directly relevant to maturity because it provides a concrete, time-bound, multi-stakeholder interoperability artefact rather than a purely conceptual goal. [46]

#### **[12] G20 Roadmap for Enhancing Cross-border Payments: Consolidated progress report for 2024 (FSB)**

Organisation/authors: Financial Stability Board [47]

Venue/type: Authoritative roadmap/progress report (governance + adoption timelines)

Publication date: **October 2024**

Link: <https://www.fsb.org/uploads/P211024-1.pdf>

Annotation: Tracks implementation workstreams and milestones under the G20 roadmap, including the cross-border messaging migration context (ISO 20022 transition and follow-up actions after harmonised data requirements). This is critical for maturity assessment: even if technology works, scaling interoperable networks depends on coordinated adoption and governance across jurisdictions. [48]

#### **[13] Exploring multilateral platforms for cross-border payments (G20 programme analytical note/report)**

Organisation/authors: CPMI (BIS) with BIS Innovation Hub, IMF and World Bank (joint report)

Venue/type: Authoritative analytical report (design options + risks/barriers)

Publication date: **January 2023**

Link: <https://www.imf.org/-/media/files/publications/analytical-notes/2023/english/anea2023001.pdf>

Annotation: Defines “multilateral platforms” as multi-jurisdictional by design and evaluates potential benefits (shorter chains, improved standards usage) alongside legal/operational barriers and governance trade-offs. It is directly useful for plausibility/maturity because it frames interoperability as an institutional/operational design problem—not only a protocol problem—and outlines evolution pathways (“growth” vs “greenfield”). [49]

#### [14] Connecting digital islands: CBDCs (Swift Phase 2 experiments results report)

Organisation/authors: SWIFT[50] with Capgemini[51]

Venue/type: Industry technical results report (interoperability experiments)

Publication date: **October 2022**

Link:

[https://www.swift.com/sites/default/files/files/swift\\_cbdc\\_experiments\\_results-report\\_071022\\_final.pdf](https://www.swift.com/sites/default/files/files/swift_cbdc_experiments_results-report_071022_final.pdf)

Annotation: Reports Swift experiments interlinking CBDC networks with existing payment systems and explicitly summarises BIS multi-CBDC models (compatibility, interlinking, single multi-CBDC system), giving an industry perspective on “connect the islands” rather than replace them with one ledger. This matters for maturity because Swift is a major incumbent testing bridging approaches that could be deployed at scale if standardised and governed appropriately. [52]

#### [15] Project Polaris: A handbook for offline payments with CBDC (Part 1)

Organisation/authors: BIS Innovation Hub (Polaris programme)

Venue/type: Authoritative handbook/technical report (offline capability design space)

Publication date: **May 2023**

Link: <https://www.bis.org/publ/othp64.pdf>

Annotation: Provides definitions and technical/security framing for **offline CBDC systems** (payments without continuous connection to ledger systems), including risk concepts like offline authentication and the security trade-offs required to mitigate double-spend/counterfeiting. This is directly relevant to the ART’s “signed vouchers later reconcile” claim by mapping the offline design space and constraints. [53]

#### [16] Digital pound experiment report: Offline payments

Organisation/authors: Bank of England[54]

Venue/type: Central bank experiment report (engineering feasibility + trade-offs)

Publication date: **April 2025**

Link: <https://www.bankofengland.co.uk/report/2025/digital-pound-experiment-report-offline-payments>

Annotation: Concludes that offline functionality **might be technically feasible**, but highlights concrete trade-offs and security challenges (particularly double-spending/counterfeiting and user experience), showing the feature is still non-trivial for production. This is maturity-relevant because offline mode is often treated as optional “nice-to-have” but becomes a critical reliability requirement for a globally interoperable network. [55]

#### [17] Verifiable Credentials Data Model v1.1 (W3C Recommendation)

Organisation/authors: World Wide Web Consortium[56]

Venue/type: Standards recommendation (credential data model for claims/attestations)

Publication date: **March 2022**

Link: <https://www.w3.org/TR/vc-data-model-1.1/>

Annotation: Defines a standard data model for verifiable credentials (issuer–holder–verifier)

that can support interoperable “authorisation/eligibility proofs” across systems, aligning with the ART’s selective disclosure and credential-checking layer. While not a payments standard, it is a key building block for portable compliance/identity assertions (eg limits, residency, eligibility) without exposing full histories. [57]

#### **[18] Decentralized Identifiers (DIDs) v1.0 (W3C Recommendation)**

Organisation/authors: World Wide Web Consortium

Venue/type: Standards recommendation (decentralised identifier architecture)

Publication date: **July 2022**

Link: <https://www.w3.org/TR/did-core/>

Annotation: Specifies decentralised identifiers designed to be decoupled from central registries, enabling interoperable identity references and key material across multiple ecosystems. For the ART, DIDs are a plausible underpinning for cross-system discovery/authorisation where no single identity provider exists across all rails. [58]

#### **[19] Data Integrity BBS Cryptosuites v1.0 (W3C Candidate Recommendation Draft)**

Organisation/authors: World Wide Web Consortium

Venue/type: Standards draft (selective disclosure + unlinkability primitive)

Publication date: **April 2025**

Link: <https://www.w3.org/TR/vc-di-bbs/>

Annotation: Specifies BBS-signature-based data integrity mechanisms explicitly intended to support **selective disclosure** and **unlinkable derived proofs**, mapping closely to the ART’s privacy requirement (“prove required facts without exposing full history”). This matters for plausibility because it shows standardisation work is converging on interoperable cryptographic primitives rather than bespoke privacy schemes. [59]

#### **[20] Open Payments OpenAPI specifications (interledger/open-payments-specifications) — release v1.3.0**

Organisation/authors: Interledger Foundation[60] (open-source standard) hosted on GitHub[61]

Venue/type: Open-source API standard / reference specification (OpenAPI)

Publication date: **February 2026** (latest release shown)

Link: <https://github.com/interledger/open-payments-specifications>

Annotation: Defines an interoperable API stack with explicitly separated subsystems for **wallet address discovery**, **quotes**, and **payment initiation**, and includes an authorisation server aligned to G NAP-style grant negotiation—directly echoing the ART’s layered discovery/quoting/authorisation design. While not a CBDC standard, it demonstrates an actively maintained, implementation-oriented interoperability toolkit aimed at banks, digital wallets and mobile money providers. [62]

### **3. Maturity score (1–7) and reasoning**

#### **A) Final maturity score: 4**

#### **B) Why this score fits the rubric (explicit evidence → rubric mapping)**

The ART is clearly above levels 1–3 because multiple independent, well-resourced public-sector programmes have already demonstrated **functional cross-system prototypes and pilots**, including **real-value** settlement activity rather than purely theoretical models or limited laboratory demonstrations. In particular, Project mBridge reports a six-week, multi-jurisdiction pilot settling real-value transactions, including issuance of **>US\$12m** on-platform

and **160+** PvP payment/FX transactions totalling **>US\$22m**—evidence of a functioning prototype operating with multiple banks and currencies. [\[14\]](#)

The ART meets the rubric’s **level 4 (PoC)** definition because:

- Interoperability is demonstrated not merely as “message translation”, but with **end-to-end transaction logic** that includes routing/quoting and **atomic-like settlement risk reduction** mechanisms (eg Project Icebreaker’s PvP coordination using **HTLCs** and competitive FX rate selection). [\[38\]](#)
- Multiple architectures have been built and tested, including **shared multi-CBDC settlement platforms** (Project Dunbar prototypes) and **interlinked/hub models** (Icebreaker, Nexus), supporting the plausibility of a “protocol stack” approach rather than requiring a single global ledger. [\[63\]](#)
- Key “plumbing” components for maturity—standards and shared semantics—are being formalised, notably CPMI’s **harmonised ISO 20022 data requirements** with an explicit global alignment timeline (**end 2027**), which is the kind of adoption roadmap required for large-scale interoperability. [\[46\]](#)

### What is still missing for a score of 5 (next level up)

Level 5 would require clear evidence that interoperable digital-currency payment networks are in (or near) **production prototype** phase with funded deployment programmes, or that multiple actors are competing with near-launch production systems. The evidence here shows strong PoCs and some governance steps toward implementation (eg Nexus’s Scheme Organisation) but does not yet show broad, routine, customer-facing or institution-wide production usage across many jurisdictions and rails—especially not across the full scope of CBDCs + cryptocurrencies + mobile money systems as a single interoperable network. [\[64\]](#)

Additionally, critical “last-mile” requirements highlighted by central banks—offline operation trade-offs and double-spend/counterfeiting risks—remain challenging even when feasibility is demonstrated, suggesting remaining engineering/policy work before large-scale deployment. [\[65\]](#)

### C) Sub-component maturity breakdown (bundle → aggregated score)

- **Cross-border CBDC interoperability (shared platforms / multi-CBDC settlement) → 4** → Key evidence: Project Dunbar prototypes and design goals; mBridge real-value pilot and reported transaction volumes; mBridge MVP milestone. [\[66\]](#)
- **Cross-border retail CBDC interlinking with atomic settlement-risk reduction (hub, FX quoting, HTLC/PvP) → 4** → Key evidence: Project Icebreaker’s hub-and-spoke interlinking and PvP via HTLC; competitive FX rate selection. [\[38\]](#)
- **Interlinking “non-CBDC” payment rails (fast/instant payment systems as adjacent interoperable rails) → 4–5 (leaning 4 overall)** → Key evidence: Nexus governance milestone (Scheme Organisation) and published technical documentation; RBA’s modelling of interlinking architectures and live bilateral link examples (not CBDC, but proves multi-rail interoperability patterns are implementable). [\[67\]](#)
- **Standards layer (cross-border data/messaging semantics) → 6 (mature standard + adoption programme underway)** → Key evidence: CPMI harmonised ISO 20022 data requirements with end 2027 alignment timeline; FSB consolidated roadmap progress tracking. [\[68\]](#)



- **Privacy-preserving credentials / selective disclosure** → 3–4 → Key evidence: W3C VC Data Model (Recommendation) plus BBS cryptosuites standardisation toward unlinkable selective disclosure; however, operational integration into cross-border payment compliance regimes is not yet evidenced at scale within these sources. [10]
- **Offline / low-connectivity operation** → 3–4 → Key evidence: Project Polaris handbook (design space) and Bank of England experiment finding feasibility but emphasising trade-offs and hard security problems—suggesting pre-production maturity rather than product scale. [11]

**Aggregation rationale:** the ART’s “headline capability” requires the **end-to-end interoperable network** (discovery + quoting + authorisation + settlement across heterogeneous systems). While parts of the stack (messaging standards) are mature, the integrated cross-rail network capability is best characterised as **PoC demonstrated with real-value pilots**, but not yet widely deployed or scaled—so the overall score is **4** rather than taking the maximum sub-score. [69]

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[27] [31] [35] [51] [63] [66] <https://www.rba.gov.au/payments-and-infrastructure/central-bank-digital-currency/pdf/project-dunbar-report-2022-03.pdf>

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## ART 12.096 Machine-Readable Regulation (Rules as Code)

### ART extraction

#### Primary capability the ART claims

- Publish regulation in a **machine-consumable form** alongside authoritative human-readable legal text, so software can interpret and apply requirements consistently at scale. [1]
- Distribute “rules packages” via **APIs/toolkits** with **versioning, test cases, and auditable traces** so downstream systems can validate compliance decisions and update quickly when rules change. [2]
- Enable **simulation/sandboxing** (policy impact and “what-if” testing) as well as **production compliance checking** with transparent explanations of which clauses/parameters were applied. [3]

#### Key sub-components or variants

- **Authoritative publishing workflow** for dual outputs: legal text + formal model (definitions, thresholds, exceptions, procedures). [4]
- **Representation formats and engines** (e.g., computation models in Python/DSLs; decision-tree-to-code pipelines; consultation-style rule engines). [5]
- **Version control, traceability, and change management** (auditability, historical rebuild, links back to legal sources). [6]
- **Validation & testing harnesses** (test cases, edge cases, regression checks) to keep machine interpretations aligned with policy intent. [7]
- **Secure distribution & integration** into external software ecosystems (developer-facing rule files, APIs, sandboxes, embedded guidance in “natural systems”). [8]
- **Semi-automation of rule extraction** (NLP/grammar parsing, assisted drafting, human-in-the-loop approval), acknowledging limits of determinism and discretion. [9]
- **Governance and accountability** (who certifies the legal component; how errors are handled; transparency/appeal considerations). [10]

#### Maturity indicators that would constitute strong evidence

- **Operational government deployments** where rule artefacts are published as reusable machine-readable assets (files/models) and consumed by third-party systems. [11]
- **Standardised packaging and interfaces**: published APIs, version histories, traceability back to legal sources, and documented test suites. [12]
- **Evidence of scaling**: multi-agency programmes, “enterprise” offerings, or multiple jurisdictions implementing comparable approaches. [13]
- **Independent technical or peer-reviewed validation** of feasibility for translating legal text into computable logic (accuracy metrics, datasets, prototypes validated with domain experts). [14]
- **Clear articulation of limits and governance** (discretion, ambiguity, accountability), showing maturity beyond pure technical demos. [15]

#### Evidence (10–20 recent, reliable sources)

##### Government programme evidence and operational deployments

- **GovCMS Rules-as-Code Proof-of-Concept Whitepaper (v1.2)**  
 Authors/Org: GovCMS[16] / Australian Government Department of Finance[17] with Salsa Digital (whitepaper authors listed in document)  
 Type: Government programme technical whitepaper (PoC)

Date: September 2022 [18]

Link: <https://oecd-opsi.org/wp-content/uploads/2022/09/GovCMS-Rules-as-Code-Proof-of-Concept-Whitepaper-v1.2.pdf> [19]

Annotation: Documents a sponsored PoC that mapped COVID vaccination rules into a decision model, defined variables/parameters, and created **test cases**; it also reports an implemented **OpenFisca instance** plus **API management** and **source code management** considerations for “rules as code” operations. [20]

- **Introducing Rules as Code**

Org: GovCMS (Australian Government official site)

Type: Government programme documentation / deployment update

Date: Last updated June 2025 [21]

Link: <https://www.govcms.gov.au/introducing-rules-code> [21]

Annotation: Reports a completed **12-month pilot** delivering **14 experimental projects with 12 Australian Government agencies**, and states the programme is in **early stages of moving to production** plus offers purchasable “**sandpit**” **prototypes** via a procurement panel—indicative of scaling beyond a single demo into repeatable delivery. [21]

- **GovCMS announces enterprise adoption of Rules as Code**

Org: GovCMS

Type: Government programme announcement

Date: November 2023 [22]

Link: <https://www.govcms.gov.au/news-events/news/govcms-announces-enterprise-adoption-rules-code> [23]

Annotation: States intent to implement Rules as Code “at enterprise scale” for agencies on the platform; while not a technical spec, it is evidence of programme investment and institutionalisation beyond isolated pilots. [22]

- **Rules as Code Proof of Concept (PoC)**

Org: Australian Taxation Office [24]

Type: Government developer documentation (PoC)

Date: July 2025 (page date in search result) and describes active PoC collaboration [25]

Link: <https://softwaredevelopers.ato.gov.au/RulesasCodePoC> [26]

Annotation: Describes partnering with GovCMS and working with Digital Service Providers to embed tax guidance into software workflows—directly aligned with the ART’s “publish once, consume across tools” thesis. [27]

- **Tax Administration 2024 (Sweden – Rules as Code concept)**

Org: Organisation for Economic Co-operation and Development [28]

Type: Authoritative international report (comparative government operations)

Date: November 2024 (PDF path and publication series year; OECD report edition 2024) [29]

Link: [https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/11/tax-administration-2024\\_5c4606e4/2d5fba9c-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/11/tax-administration-2024_5c4606e4/2d5fba9c-en.pdf) [30]

Annotation: Reports that Sweden’s tax agency provides **rule-based machine-readable files** and written specs as open data; a rule editor converts decision trees to machine-readable code, and the authority has produced rule files in **three legal areas** plus an **API**, describing the concept as “already available and in production” (while still improving). [31]

- **Assessment of Rules as Code methods concerning the goal of assisting citizens personally with regulations**

Authors/Org: Digicampus for GovTech4All [32] (Bas Kaptijn & Jet Klaver)

Type: Government/consortium technical assessment report

Date: April 2024 [33]

Link: [https://regels.overheid.nl/cms/uploads/Ra\\_Cassessment\\_compressed\\_e48b7f7f95.pdf](https://regels.overheid.nl/cms/uploads/Ra_Cassessment_compressed_e48b7f7f95.pdf) [34]

Annotation: Proposes an evaluation framework for a “Personal Regulations Assistant” and concludes **no single current RaC solution** is viable alone, implying integration/standardisation gaps; it also defines practical adoption criteria (transparency, integration, affordability) and highlights the need for machine-consumable models tightly linked to official law. [33]

- **Computer-Readable Legislation Project: Introduction**

Org: States of Jersey Legislative Drafting Office

Type: Government project intro brief

Date: February 2023 [35]

Link:

<https://www.gov.je/SiteCollectionDocuments/Crime%20and%20justice/Introduction%20to%20the%20Computer-Readable%20Legislation%20Project.pdf> [35]

Annotation: Establishes a formal 2-year programme to produce computer-readable versions of the logical structure of legislative drafts, signalling sustained institutional effort (not a one-off demo). [35]

- **Government Plan 2023 to 2026 Annex (Jersey – “Legislative Drafters – Rules as Code”)**

Org: Government of Jersey / States Assembly budgeting annex

Type: Government plan and funding document

Date: December 2022 [36]

Link:

<https://www.gov.je/SiteCollectionDocuments/Government%20and%20administration/Government%20Plan%202023%20to%202026%20Annex.pdf> [37]

Annotation: Documents allocated funding and a stated goal to deliver publishable digital versions by end-2024, providing concrete signals of resourcing and timelines (a maturity indicator for public-sector tech rollouts). [38]

- **Digitalization and Other Opportunities to Improve Tax Administration (Committee of Experts on International Cooperation in Tax Matters; Co-Coordinator’s report)**

Org: United Nations [39] ([financing.desa.un.org](https://financing.desa.un.org))

Type: International organisation technical report

Date: 4 March 2024 [40]

Link: <https://financing.desa.un.org/sites/default/files/2024-03/CRP.%204%20Digitalization%20of%20Revenue%20Authorities%20and%20Annexes.pdf> [41]

Annotation: Describes an “ideal scenario” for tax digitalisation that explicitly includes incorporating “rules as code” with **transparency and testing frameworks**, and shifting implementation into taxpayers’ natural systems—directly matching the ART’s envisioned distribution and assurance model. [42]

## Strategy/roadmap and governance framing (what must exist for scaling)

- **Global Trends in Government Innovation 2023**

Org: OECD (Public Governance Reviews)

Type: Authoritative international report

Date: May 2023 [43]

Link: [https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/05/global-trends-in-government-innovation-2023\\_68d12bfa/0655b570-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/05/global-trends-in-government-innovation-2023_68d12bfa/0655b570-en.pdf) [44]

Annotation: Identifies “advancement of the Rules as Code concept” as a leading current

public-sector innovation theme and frames “Rules as Code 2.0” as an emerging horizon—supporting plausibility that governments are actively progressing from concept to practice. [45]

- **Governing with Artificial Intelligence: The State of Play and Way Forward in Core Government Functions**

Org: OECD

Type: Authoritative international report

Date: June 2025 [46]

Link: [https://www.oecd.org/content/dam/oecd/en/publications/reports/2025/06/governing-with-artificial-intelligence\\_398fa287/795de142-en.pdf](https://www.oecd.org/content/dam/oecd/en/publications/reports/2025/06/governing-with-artificial-intelligence_398fa287/795de142-en.pdf) [47]

Annotation: Positions rules as code as an “emerging approach” for automation that can improve accuracy and transparency in AI-enabled service delivery, while signalling that multiple governments are already engaging—useful for maturity assessment at policy-system level. [48]

- **Governing Digital Legal Systems: Insights on Artificial Intelligence and Rules as Code (release 2)**

Authors: Hamish Fraser[49] and Tom Barraclough[50]

Venue/type: MIT Computational Law Report (research report)

Date: October 2024 [51]

Link: <https://law.mit.edu/pub/governingdigitallegalsystems/release/2> [51]

Annotation: Defines concrete governance requirements for “digital legal systems” (transparency, explainability, monitoring, documentation, accountability) and argues that the *legal component* needs explicit assurance/permissioning/version control—critical constraints to make machine-readable regulation scalable and trustworthy. [51]

- **Rules as Code for a More Transparent and Efficient Global Economy**

Authors: Jess Rapson et al. (Think7 Canada 2025 / Task Force 2)

Type: Policy brief with technical orientation (G7/Think tank)

Date: April 2025 [52]

Link: [https://www.cigionline.org/static/documents/T7\\_TF2\\_Rapson\\_et\\_al.pdf](https://www.cigionline.org/static/documents/T7_TF2_Rapson_et_al.pdf) [53]

Annotation: Synthesises current “rules as code” engines and use cases and frames RaC as enabling interoperable policy execution via APIs; helpful as a cross-sector snapshot showing multiple well-resourced actors and pathways beyond single-jurisdiction experiments. [54]

- **Augmented LEOS with smart functionalities (final report)**

Org: European Commission interoperability ecosystem (report hosted on interoperable-europe portal)

Type: Government/consortium technical report

Date: June 2024 (document path) [55]

Link: <https://interoperable-europe.ec.europa.eu/sites/default/files/document/2024-06/Augmented%20LEOS%20with%20smart%20functionalities%20final%20report.pdf> [55]

Annotation: Describes an EU lawmaking tooling ecosystem using structured formats (Akoma Ntoso/AKN4EU) and explores “machine computable law” and smart drafting/analysis functions—evidence that upstream “digital-ready lawmaking” infrastructure (a prerequisite for rules-as-code publishing) is being specified and evaluated. [55]

## **Academic and technical feasibility (formalisation, explainability, semi-automation)**

- **Integrating NLP and Context-Free Grammar for Complex Rule Interpretation towards Automated Compliance Checking**

Authors: Yu-Cheng Zhou, Zhe Zheng, Jia-Rui Lin, Xin-Zheng Lu (Tsinghua University)

Venue/type: Peer-reviewed paper (author manuscript; published in *Computers in Industry* in



2022 per citation trail)

Date: July 2022 (PDF date on author site) [56]

Link: <https://linjiarui.net/files/2022-07-12-integrating-NLP-and-CFG-for-rule-interpretation-towards-ACC.pdf> [57]

Annotation: Demonstrates a generalised NLP+CFG pipeline that parses regulatory sentences into a computable tree structure, reporting **99.6% parsing accuracy for single-requirement** and **91.0% for multi-requirement sentences**, plus publishes a regulation dataset—evidence that partial automation of rule formalisation is technically feasible (but still scoped). [56]

- **Explainable AI (XAI) in Rules as Code (RaC): The DataLex approach**

Authors: Andrew Mowbray, Philip Chung, Graham Greenleaf

Venue/type: Peer-reviewed journal article (*Computer Law & Security Review*)

Date: April 2023 [58]

Link: <https://www.sciencedirect.com/science/article/abs/pii/S0267364922001145> [58]

Annotation: Specifies explainability requirements for RaC (transparency, traceability, links to legal sources, accountability) and evaluates how an open environment (DataLex) supports those needs—directly relevant to the ART’s demand for auditable traces and governance. [58]

- **Representing legislative Rules as Code: Reducing the problems of ‘scaling up’**

Authors: Andrew Mowbray, Philip Chung, Graham Greenleaf

Venue/type: Peer-reviewed journal article (*Computer Law & Security Review*)

Date: April 2023 [59]

Link: <https://www.sciencedirect.com/science/article/abs/pii/S0267364922001157> [59]

Annotation: Proposes representing legislation as propositions in a quasi-natural language coding approach (“yscript”), discusses a pathway for automating conversion and for drafting legislation that is both human-readable and machine-usable—evidence aimed squarely at the “versioned package of text + formal model” vision, while foregrounding the scale-up challenge. [59]

- **Building Blawx**

Author: Jason Morris

Venue/type: Technical paper in workshop proceedings (CEUR-WS)

Date: 2023 (workshop proceedings publication) [60]

Link: <https://ceur-ws.org/Vol-3437/paper5GDE.pdf> [61]

Annotation: Reports concrete engineering progress in a rules-as-code tool aimed at non-programmers, including defeasibility, event reasoning, improved natural-language explanations, and date/time handling—capabilities that map to the ART’s need to handle exceptions, temporal clauses, and explainable outputs. [61]

- **AI-Powered Rules as Code: Experiments with Public Benefits Policy**

Org/Authors: Georgetown/Beeck Center team (authors listed on page)

Type: Applied research report with evaluation rubrics and results

Date: March 2025 [62]

Link: <https://digitalgovernmenthub.org/publications/ai-powered-rules-as-code-experiments-with-public-benefits-policy/> [62]

Annotation: Runs four experiments on using LLMs to translate benefits policies into summaries, pseudocode, and usable code; reports quantitative scoring (e.g., state-specific applicability/completeness/relevance) and concludes that LLMs can assist but **still require external knowledge and human oversight** for complex logic—direct evidence for the ART’s constraint that not all legal language is deterministically encodable. [62]

- **Computer-Readable Legislation: progress and prospects (pre-print chapter manuscript)**

Author: Matthew Waddington (Jersey Legislative Drafting Office; personal views)

Type: Preprint / technical discussion with worked examples

Date: Pre-print as at March 2024 [63]

Link:

[https://www.researchgate.net/publication/378894845\\_Digitising\\_legislation\\_progress\\_and\\_prospects](https://www.researchgate.net/publication/378894845_Digitising_legislation_progress_and_prospects) [63]

Annotation: Provides detailed discussion of modelling the logical structure of legislative provisions and includes explicit worked examples mapping “if-then” structures into spreadsheet-like logic, illustrating practical pathways and pitfalls for turning legislative drafting into structured, testable representations. [63]

## **Maturity score (1–7) and reasoning**

**Final maturity score: 5**

[64]

**Why this score fits the rubric (evidence-to-rubric mapping)**

### **What evidence rules out Levels 1–3 (theory → lab demonstration → lab prototype)?**

Multiple sources show that rules-as-code is not merely theoretical or confined to lab prototypes: government programmes have produced functional PoCs and operational artefacts, including a detailed GovCMS PoC with decision models, variables/parameters and test cases, plus an implemented rules engine instance and API/process considerations. [20] The Swedish tax administration example goes further, describing rule-based machine-readable files and an API being made available and “in production” in several legal areas, supported by an internal rule editor to translate decision trees into machine-readable code. [31]

### **What evidence supports Level 5 (multiple well-capitalised actors; production prototypes and investment; fast-paced progress)?**

There is clear evidence of multiple well-resourced public-sector actors moving beyond single pilots toward repeatable programmes: GovCMS reports a 12-month pilot with 14 projects across 12 agencies and states it is moving into production and offering a procurement pathway for “sandpit” implementations. [21] National agencies are also partnering to embed guidance into third-party software ecosystems (ATO + GovCMS + Digital Service Providers), consistent with a scaling trajectory. [27] International bodies (OECD and UN) explicitly position rules-as-code as an emerging governmental approach, reinforcing that multiple jurisdictions are investing and learning simultaneously rather than it being a niche one-off. [65]

### **What evidence is still missing to justify Level 6 (products delivered in increasing amounts; financed scaling; expanding applications)?**

While there is “in production” language for Sweden’s rule files and substantial pilot activity in Australia, the evidence set does not (within the strict 4-year window) provide hard indicators of **broad, growing adoption volumes**, cross-jurisdiction standardisation, or repeated large-scale “rules packages” being published as a routine legal standard with stable liability/assurance frameworks. [66] The Dutch GovTech4All assessment also suggests current solutions are not yet sufficient “on their own” for ambitious citizen-facing regulation assistants, implying interoperability and completeness gaps remain before widespread scaling. [33]

### Sub-component maturity breakdown (and aggregation)

- **Operational rule publication for compliance (tax) → 6 (domain-limited)** → Supported by the Swedish tax administration case describing rule files and an API “available and in production” (but still developing). [31]
- **Government platformisation (multi-agency capability + procurement path) → 5** → Supported by GovCMS programme evidence of multi-agency pilots and “moving to production,” plus enterprise adoption announcements. [67]
- **Cross-government experimentation and institutional learning → 4–5** → Supported by Canada’s experiments/lessons-learned report (structured experiments rather than full production scaling). [68]
- **Automated/semi-automated formalisation from text (NLP/LLMs) → 3–4** → Strong feasibility results exist (high parsing accuracy in a constrained domain) and applied evaluations show usefulness but persistent need for human oversight. [14]
- **Governance, assurance, and standardisation frameworks → 3–4** → Governance requirements are clearly articulated, but evidence of widely adopted formal assurance regimes for “authoritative code” is still emerging. [69]

**Aggregation to one score:** These sub-components serve largely the same functional goal (machine-consumable rules used for compliance and service delivery), but their maturity varies by domain. Taking a pragmatic average weighted toward the most deployment-relevant strands (government platformisation + operational tax use) yields an overall **5**, reflecting active investment and early production in bounded areas, without yet reaching broad, market-wide scaling that would justify 6. [70]

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[1] [3] [4] [10] [15] [51] [69] <https://law.mit.edu/pub/governingdigitallegalsystems/release/2>

<https://law.mit.edu/pub/governingdigitallegalsystems/release/2>

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<https://oecd-opsi.org/wp-content/uploads/2022/09/GovCMS-Rules-as-Code-Proof-of-Concept-Whitepaper-v1.2.pdf>

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## ART 12.097 Open Metaverse Interoperability Protocols

### 1. ART extraction

- **A) Primary capability (claimed)**
- Open, implementation-agnostic **interoperability protocols** that let many independent immersive/3D environments interconnect (analogous to how the internet scaled via shared rules), reducing fragmentation and lock-in.
- **Portable user continuity** across worlds: authentication and persistent identity (including privacy-preserving credentials), plus portability of inventories, settings, social graphs, reputation signals, and data-sharing controls.
- **Standardised creator/operator interfaces** for cross-engine asset exchange/rendering, permissions/royalties/usage rights portability, real-time interaction semantics (e.g., physics/animation), moderation/safety signals, and transaction settlement.
- **B) Key sub-components / sub-threads implied by the ART**

- Cross-platform **identity and authentication**: decentralised identifiers, verifiable credentials, selective disclosure / privacy-preserving proofs, token/session security, trust/assurance levels.
- **3D asset & scene interchange**: compact runtime delivery formats; high-fidelity scene composition formats; conversion pipelines; materials/shading interchange; animation/rig semantics; (future) interactivity/physics declarations.
- **XR device/runtime access APIs**: unified device input/display/runtime interfaces; compatibility and conformance testing across platforms.
- **Web-based immersive interoperability**: browser-facing XR APIs and modules; test suites and interoperability reports.
- **Provenance, permissions, and rights metadata**: cryptographic provenance manifests; attachment/binding of usage assertions; tamper-evidence; auditability.
- **Governance and compliance scaffolding**: standards roadmaps, architectures, reference points, conformance/certification, and multi-jurisdiction policy alignment.
- Operational constraints: **latency/bandwidth/compute**, security review overhead, and ongoing validation/certification costs.
- **C) Maturity indicators that would count as evidence**
  - **Ratified standards** and stable versioning from recognised standards bodies (e.g., ISO/IEC, W3C Recommendations, IETF RFCs) rather than aspirational whitepapers.
  - **Reference implementations + toolchains** (validators, auditors, SDKs) that demonstrate implementability and reduce switching costs.
  - **Conformance test suites and registries** with multiple independent implementations passing tests (evidence of real interoperability, not just paper standards).
  - **Multi-actor adoption** across device vendors, engines, DCC tools, cloud pipelines, and open-source consortia (not a single-vendor stack).
  - **Cross-platform demonstrations** showing identity/credential portability, asset round-tripping, and policy/rights metadata survival across toolchains.
  - Explicit acknowledgement of what is **not yet deployed** (e.g., “scenarios not fully implemented”) to avoid over-scoring maturity.

## 2. Evidence (10–20 recent, reliable sources)

### 1) ISO/IEC 12113:2022 — “Information technology — Runtime 3D asset delivery format — Khronos glTF™ 2.0”

- **Org**: International Organization for Standardization[1] / ISO/IEC JTC 1
- **Type**: International standard (ISO/IEC)
- **Date**: 07/2022
- **Link**: <https://www.iso.org/standard/83990.html>
- **Why it matters**: glTF’s publication as an ISO/IEC standard is hard evidence that at least one “content format” layer of metaverse interoperability has reached formal standardisation suitable for broad multi-vendor adoption and long-term stability. [2]

### 2) “Khronos Releases OpenXR 1.1 to Further Streamline Cross-Platform XR Development”

- **Org**: The Khronos Group[3]
- **Type**: Standards body press release (XR runtime/device API standard)



- **Date:** 04/2024
- **Link:** <https://www.khronos.org/news/press/khronos-releases-openxr-1.1-to-further-streamline-cross-platform-xr-development>
- **Why it matters:** The release describes OpenXR 1.1 consolidating widely used extensions into the core spec to reduce fragmentation—directly aligned with the ART’s thesis that shared rules reduce ecosystem fragmentation. [4]

### 3) OpenXR Conformant Products Registry (OpenXR)

- **Org:** Khronos Conformance programme
- **Type:** Conformance registry (deployment evidence + compliance mechanism)
- **Date:** Continuously updated; entries include **2022–2026** conformance dates (e.g., multiple products listed with dates in 2023–2026)
- **Link:** <https://www.khronos.org/conformance/adopters/conformant-products/openxr>
- **Why it matters:** A public, date-stamped conformance listing is strong maturity evidence: it demonstrates multi-vendor implementations that have passed a shared test process (a key prerequisite for real interoperability at scale). [5]

### 4) OpenXR Conformance Test Suite (CTS) release evidence (Git tag / release entry)

- **Org:** Khronos OpenXR Working Group (open-source CTS)
- **Type:** Open-source conformance test suite release (implementation-enabling infrastructure)
- **Date:** Example approved CTS release **04/2024** (OpenXR CTS 1.1.47.0 dated 2024-04-24)
- **Link:** <https://github.com/KhronosGroup/OpenXR-CTS/releases>
- **Why it matters:** Interoperability protocols mature faster when they ship with conformance tooling; dated CTS releases show an operational pathway to certify implementations, not just a paper standard. [6]

### 5) W3C Recommendation: “Decentralized Identifiers (DIDs) v1.0” (did-core)

- **Org:** World Wide Web Consortium [7]
- **Type:** Web standard (W3C Recommendation)
- **Date:** 07/2022
- **Link:** <https://www.w3.org/TR/did-core/>
- **Why it matters:** A W3C Recommendation for decentralised identifiers provides a mature building block for portable, consent-based identity across services—directly relevant to the ART’s “persistent identity” and cross-world authentication claims. [8]

### 6) W3C Recommendation: “Verifiable Credentials Data Model v2.0”

- **Org:** W3C
- **Type:** Web standard (W3C Recommendation)
- **Date:** 05/2025
- **Link:** <https://www.w3.org/TR/vc-data-model-2.0/>
- **Why it matters:** A ratified credential data model supports portable claims (e.g., age/entitlements/reputation signals) across platforms—core to plausible cross-metaverse identity portability without each platform inventing bespoke formats. [9]

### 7) W3C Recommendation: “Verifiable Credential Data Integrity 1.0”

- **Org:** W3C
- **Type:** Web standard (W3C Recommendation; cryptographic integrity for credentials)
- **Date:** 05/2025

- **Link:** <https://www.w3.org/TR/vc-data-integrity/>
- **Why it matters:** Interoperable identity requires interoperable verification; a Recommendation-level integrity mechanism reduces ambiguity about how credentials should be secured and verified across independent implementations. [10]

#### 8) W3C Candidate Recommendation Draft: “Data Integrity BBS Cryptosuites v1.0”

- **Org:** W3C (Verifiable Credentials workstream)
- **Type:** Standards-track draft (privacy-preserving / unlinkable disclosure mechanism)
- **Date:** 04/2025
- **Link:** <https://www.w3.org/TR/vc-di-bbs/>
- **Why it matters:** This draft explicitly targets unlinkability and selective disclosure—evidence that privacy-preserving credential portability is being standardised, though still not at full Recommendation maturity. [11]

#### 9) Final specification: “OpenID for Verifiable Credential Issuance 1.0”

- **Org:** OpenID Foundation [12]
- **Type:** Identity protocol specification (Final; OAuth-protected issuance API)
- **Date:** 09/2025
- **Link:** [https://openid.net/specs/openid-4-verifiable-credential-issuance-1\\_0.html](https://openid.net/specs/openid-4-verifiable-credential-issuance-1_0.html)
- **Why it matters:** The ART’s portability narrative depends not just on credential formats but also interoperable issuance flows; a “Final Specification” indicates an implementation-ready step toward ecosystem-wide interoperability. [13]

#### 10) IETF RFC 9449: “OAuth 2.0 Demonstrating Proof of Possession (DPoP)”

- **Org:** Internet Engineering Task Force [14]
- **Type:** Internet standard (RFC; Proposed Standard)
- **Date:** 09/2023
- **Link:** <https://datatracker.ietf.org/doc/rfc9449/>
- **Why it matters:** Cross-platform identity/data portability increases token replay and session hijack risks; DPoP is concrete, standards-track security machinery for sender-constraining tokens—supporting the ART’s security-review and trust requirements. [15]

#### 11) W3C Candidate Recommendation Draft: “WebXR Device API”

- **Org:** W3C (Immersive Web)
- **Type:** Web standard (Candidate Recommendation Draft; browser-based XR interoperability)
- **Date:** 10/2025 (CRD dated 1 Oct 2025)
- **Link:** <https://www.w3.org/TR/webxr/>
- **Why it matters:** WebXR is relevant to “implementation-agnostic” access for immersive experiences via browsers; its Candidate Recommendation status shows progress but also signals that web-layer interoperability is still stabilising. [16]

#### 12) Linux Foundation press release: “Pixar, Adobe, Apple, Autodesk, and NVIDIA Form Alliance for OpenUSD (AOUSD)”

- **Org:** The Linux Foundation [17]
- **Type:** Consortium launch announcement (3D scene description standardisation)
- **Date:** 08/2023
- **Link:** <https://www.linuxfoundation.org/press/announcing-alliance-for-open-usd-aousd>
- **Why it matters:** The ART assumes multiple well-capitalised actors converge on shared

rules; this alliance is direct evidence of coordinated standardisation efforts around a key “world description” layer (scene composition/interchange). [18]

### 13) AOUSD Working Group Charter: “USD Core Specification Working Group Charter — Approved”

- **Org:** Alliance for OpenUSD[19] (hosted under Linux Foundation/JDF)
- **Type:** Authoritative governance/standards work-plan document (scope + deliverables)
- **Date:** 03/2024
- **Link:** <https://www.linuxfoundation.org/hubfs/AOUSD/Charters/24.03.06%20AOUSD%20Core%20Spec%20Working%20Group%20Charter%20-%20Approved.pdf>
- **Why it matters:** The charter defines an explicit interoperability scope (composition model, file formats, data model) and a versioned deliverables pathway—key maturity indicators that a spec is being engineered for implementability and multi-implementation compatibility. [20]

### 14) AOUSD announcement: “Alliance for OpenUSD Announces Core Specification 1.0”

- **Org:** Alliance for OpenUSD
- **Type:** Standards milestone announcement (core spec + compliance tooling availability)
- **Date:** 12/2025
- **Link:** <https://aousd.org/news/core-spec-announcement/>
- **Why it matters:** The announcement frames Core Spec 1.0 as a normative baseline and explicitly links it to testing/compliance tooling and future domain-specific specs (e.g., geometry/materials/physics), matching the ART’s “connective tissue” notion for cross-tool interoperability. [21]

### 15) OpenPBR specification: “OpenPBR Surface”

- **Org:** Academy Software Foundation[22]
- **Type:** Technical specification (materials/shading model interoperability)
- **Date:** 06/2024
- **Link:** <https://academysoftwarefoundation.github.io/OpenPBR/>
- **Why it matters:** Materials/shading portability is a practical blocker for cross-engine asset interoperability; an open, published shading model spec is concrete progress toward shared “rendering semantics” across toolchains. [23]

### 16) MaterialX release notice: “MaterialX Library v1.39.0 has been released”

- **Org:** MaterialX project (ASWF ecosystem)
- **Type:** Open standard release note (materials interchange tooling)
- **Date:** 07/2024
- **Link:** <https://materialx.org/>
- **Why it matters:** A dated release demonstrates ongoing evolution of a shared material interchange stack; the release explicitly references OpenPBR support, signalling integration between standards rather than isolated formats. [24]

### 17) C2PA Technical Specification PDF: “Content Credentials — C2PA Technical Specification 2.3”

- **Org:** Coalition for Content Provenance and Authenticity[25]
- **Type:** Technical specification (provenance manifests; signed assertions)
- **Date:** 01/2026 (spec PDF shows 2.3 dated 2026-01-05)
- **Link:**

[https://spec.c2pa.org/specifications/specifications/2.3/specs/\\_attachments/C2PA\\_Specification.pdf](https://spec.c2pa.org/specifications/specifications/2.3/specs/_attachments/C2PA_Specification.pdf)

- **Why it matters:** The ART highlights provenance/permissions portability and auditability; C2PA provides a concrete, cryptography-based mechanism for portable provenance assertions that can travel with digital assets across tools and platforms. [26]

**18) ITU FG-MV Technical Specification: “FGMV-19 — Service scenarios and high-level requirements for metaverse cross-platform interoperability”**

- **Org:** International Telecommunication Union [27] (Focus Group on Metaverse)

- **Type:** Standards body technical specification (requirements + scenarios)

- **Date:** 12/2023

- **Link:** [https://www.itu.int/dms\\_pub/itu-t/opb/fg/T-FG-MV-2023-19-PDF-E.pdf](https://www.itu.int/dms_pub/itu-t/opb/fg/T-FG-MV-2023-19-PDF-E.pdf)

- **Why it matters:** This is directly on-point: it enumerates service scenarios and explicitly states that scenarios are not fully implemented because cross-platform interoperability capability is not yet provided, which is strong negative evidence for over-claiming maturity while still supporting plausibility. [28]

**19) ITU FG-MV Technical Specification: “FGMV-43 — High-level interoperability architecture for cross-platform metaverse”**

- **Org:** ITU FG-MV (WG on interoperability)

- **Type:** Standards body technical specification (architecture + reference points + information flows)

- **Date:** 06/2024

- **Link:** [https://www.itu.int/dms\\_pub/itu-t/opb/fg/T-FG-MV-2024-43-PDF-E.pdf](https://www.itu.int/dms_pub/itu-t/opb/fg/T-FG-MV-2024-43-PDF-E.pdf)

- **Why it matters:** Provides an explicit functional architecture (e.g., components for identity, asset, avatar, content interoperability) and recognises “bridge” models, aligning with the ART’s protocol-layer concept while underscoring that much work is still architectural/standardisation rather than mass deployment. [29]

**20) ETSI Group Report: “ETSI GR ARF 012 V1.1.1 — consolidated insights on Virtual Worlds standardisation processes, standards and the role of standards bodies”**

- **Org:** European Telecommunications Standards Institute [30]

- **Type:** Standards body report (multi-SDO landscape + process)

- **Date:** 11/2025

- **Link:**

[https://www.etsi.org/deliver/etsi\\_gr/ARF/001\\_099/012/01.01.01\\_60/gr\\_ARF012v010101p.pdf](https://www.etsi.org/deliver/etsi_gr/ARF/001_099/012/01.01.01_60/gr_ARF012v010101p.pdf)

- **Why it matters:** A European SDO consolidating virtual-world standardisation insights is evidence that interoperability is being treated as an engineering/process problem across standards ecosystems (not only vendor initiatives), supporting plausibility of multi-jurisdiction governance and compliance considerations. [31]

**3. Maturity score (1–7) and reasoning**

- **A) Final maturity score: 5**
- **B) Evidence-to-rubric mapping**
- **What rules out lower levels (1–3):**

- Multiple core building blocks are not merely theoretical; they are **ratified standards** (ISO/IEC glTF, W3C DID, W3C VC DM v2.0, W3C VC Data Integrity, IETF RFC 9449) with implementable specifications. [32]
- The XR runtime/device interface layer (OpenXR) has moved beyond “prototype”: it has a **conformance process**, frequent CTS releases, and a **public conformant products registry** with date-stamped entries (including many within 2022–2026), showing operational interoperability mechanisms and deployment by multiple independent implementers. [33]
- Several layers show mature standardisation + tooling (e.g., OpenUSD core spec governance documents, C2PA technical spec, Materials standards like OpenPBR/MaterialX), which is substantially beyond lab demos and aligns with production-facing interoperability engineering. [34]
- **Why the ART is not yet a 6 (or 7): what is still missing**
  - The ART describes **end-to-end cross-world portability** (identity + social graph + inventory + rights + moderation + settlement). The best “metaverse cross-platform interoperability” sources from an international SDO explicitly indicate that many cross-platform scenarios are **not yet implemented** because interoperability capabilities are not yet provided between platforms—strong evidence the integrated system is still emerging. [35]
  - Some key parts remain at **standards-track draft / stabilisation** rather than fully deployed global infrastructure (e.g., WebXR still at Candidate Recommendation; privacy-preserving credential cryptosuites still Candidate Recommendation). [36]
  - Evidence of **cross-platform adoption** is strongest for specific layers (XR device API, asset delivery formats) but weaker for the full protocol suite described (especially portable moderation signals, rights/royalties enforcement across worlds, and universally adopted transaction settlement interfaces). The dossier above supports plausibility and partial maturity, but does not yet support broad “products delivered in increasing amounts” for the *complete* interoperability stack as a unified market offering.
- **C) Sub-component maturity breakdown (bundle scoring)**
- **XR runtime/device interoperability (OpenXR) → 6–7**
  - Rationale: Standard release cadence + conformance programme + conformant product registry and CTS releases indicate real deployments across multiple implementers. [37]
- **3D asset delivery format interoperability (glTF as ISO standard) → 6–7**
  - Rationale: ISO/IEC publication is a strong signal of standard maturity suitable for broad adoption and long-term stability. [2]
- **High-fidelity scene interchange standardisation (OpenUSD / AOUSD core spec) → 5**
  - Rationale: Formation of a major cross-industry alliance and a formalised charter + Core Spec 1.0 milestone show late-stage spec engineering and governance, but broad cross-platform conformance/deployment evidence (in

the strict “products delivered at scale” sense) is less directly documented here. [38]

- **Identity portability primitives (DIDs/VCs + issuance + verification) → 5–6**
  - Rationale: W3C Recommendations and a Final OpenID issuance spec demonstrate mature building blocks; however, the *metaverse-specific* integration into cross-world identity portability remains largely architectural/requirements-driven in SDO documents rather than evidenced as widely deployed cross-platform practice. [39]
- **Privacy-preserving credentials (unlinkable disclosure) → 4**
  - Rationale: Standards-track Candidate Recommendation indicates a workable approach exists, but not fully stabilised and broadly deployed. [11]
- **Provenance and portable audit assertions (C2PA) → 5**
  - Rationale: A current, detailed technical specification (v2.3 dated 01/2026) is evidence of serious standardisation for portable provenance metadata; the dossier here does not, by itself, prove cross-metaverse universal adoption at scale. [26]
- **Cross-platform “metaverse interoperability” as an integrated, user-facing reality → 3–4**
  - Rationale: ITU FG-MV documents provide scenarios, requirements, and architecture, but also explicitly note that scenarios are not fully implemented due to missing interoperability capability—indicating the integrated system is not yet market-mature. [35]
- **Aggregation method and justification:**
  - This ART is a **technology bundle** whose subcomponents differ materially in deployment maturity. Using an average-leaning judgement (with higher weights on the “integrated cross-platform metaverse interoperability” layers rather than already-mature adjacent standards like OpenXR/gLTF), the overall maturity is best represented as **5**: beyond PoC due to ratified standards, conformance infrastructure, and multiple large consortia, but not yet at widespread end-to-end market delivery of the full interoperability vision described. [40]

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[3] [16] [25] [36] <https://www.w3.org/TR/webxr/>

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## ART 12.098 Content Authenticity Infrastructure

### ART extraction

#### A) Primary capability (core claim)

- Establish a shared, interoperable infrastructure that attaches tamper-evident provenance (“content credentials”) to digital media at capture/generation and preserves a verifiable edit lineage across common workflows (capture → edit → export → publish).
- Enable offline/verifier-side checking of provenance integrity (cryptographic validation) and provide user-facing and machine-readable signals (summaries/APIs) distinguishing attributable, traceable media from copies lacking provenance.
- Support privacy and selective disclosure so creators can demonstrate integrity and tool lineage without necessarily exposing all personally identifying details.

#### B) Key sub-components / sub-threads

- Standards and file-format binding for provenance manifests (cryptographic structures embedded in media containers across images/video/audio/documents), centred on the Coalition for Content Provenance and Authenticity[1] specifications (often surfaced as “Content Credentials”).
- Trust model and governance: certificate policies, trust lists, key lifecycle (issuance, expiry, revocation), and conformance/certification programmes; plus parallel work to separate identity/rights assertions (e.g., CAWG-style extensions).
- Capture-side signing anchored in secure hardware (camera chipsets, device security modules, hardware-backed key storage) by vendors such as Sony[2], Nikon[3], and Leica Camera[4].
- Editing and transformation-chain retention (e.g., CDN/image pipeline transformations that preserve credentials and append signed transformation actions), including deployments by Cloudflare[5].
- Platform/service-side automatic credential attachment for synthetic media and AI-assisted editing by major ecosystem actors (e.g., Google[6], Microsoft[7], Adobe[8], OpenAI[9]).
- Durability and recovery mechanisms when embedded metadata is stripped (soft binding via watermark/fingerprint plus manifest repositories/lookup).

- International standards alignment and formalisation (e.g., International Organization for Standardization[10] / ISO/IEC work; “JPEG Trust”), and media-sector pilots/guidance via bodies like the European Broadcasting Union[11] and International Press Telecommunications Council[12].

### **C) Maturity indicators that would constitute strong evidence**

- Stable, versioned, interoperable technical specifications covering multiple media modalities, with explicit trust model, embedding rules, and validation behaviour; plus a published version history showing iterative hardening (security, validation, media types).
- Demonstrated production deployments in widely used capture devices, creator tools, CDNs, and AI generation services (automatic signing at scale; credential preservation through transformations; real-world newsroom workflows).
- Existence of conformance/certification and assurance-level frameworks (not just “spec published”), including trust lists and security requirements.
- Cross-organisation adoption and standardisation trajectory (e.g., ISO/IEC standards or committee drafts aligned with the core architecture).
- Evidence of handling key constraints: key/certificate management, offline verification/time-stamping, durability/metadata-stripping recovery, and privacy-by-design mechanisms.

#### **Evidence (10–20 recent, reliable sources)**

##### **1) Content Credentials: C2PA Technical Specification (v2.2)**

- **Org:** C2PA
- **Type:** standards specification (technical; normative)
- **Date:** May 2025 (2025-05-01)
- **Link:**  
[https://spec.c2pa.org/specifications/specifications/2.2/specs/\\_attachments/C2PA\\_Specification.pdf](https://spec.c2pa.org/specifications/specifications/2.2/specs/_attachments/C2PA_Specification.pdf)
- **Why it matters:** Defines the core “manifest/claim/signature/assertions” architecture, hard bindings (hashes) and trust concepts needed for tamper-evident provenance across media workflows—direct plausibility evidence grounded in established cryptography and file-format embedding rules. [13]

##### **2) C2PA Soft Binding API (v2.2)**

- **Org:** C2PA
- **Type:** standards specification (supplementary technical spec)
- **Date:** May 2025 (part of the v2.2 spec set)
- **Link:**  
<https://spec.c2pa.org/specifications/specifications/2.2/softbinding/Decoupled.html>
- **Why it matters:** Specifies recovery/lookup of manifests when embedded metadata is stripped, using “soft binding” identifiers (e.g., watermark or fingerprint) and manifest repositories—direct evidence for durability beyond brittle metadata carriage. [14]

##### **3) Content Credentials: C2PA Technical Specification (v2.3) – version history highlights**

- **Org:** C2PA
- **Type:** standards specification update (technical)
- **Date:** Dec 2025
- **Link:**

[https://spec.c2pa.org/specifications/specifications/2.3/specs/C2PA\\_Specification.html](https://spec.c2pa.org/specifications/specifications/2.3/specs/C2PA_Specification.html)

- **Why it matters:** Shows expansion to new asset contexts including **live video streaming** support and broader embedding/validation refinements, signalling an active standards trajectory towards higher-throughput, real-world distribution channels. [15]

#### 4) **Content Credentials Explained: Addressing Common Questions and Updates**

- **Org:** C2PA Technical Working Group

- **Type:** authoritative technical explainer / report

- **Date:** Sep 2025

- **Link:** [https://c2pa.org/wp-](https://c2pa.org/wp-content/uploads/sites/33/2025/10/content_credentials_wp_0925.pdf)

[content/uploads/sites/33/2025/10/content\\_credentials\\_wp\\_0925.pdf](https://c2pa.org/wp-content/uploads/sites/33/2025/10/content_credentials_wp_0925.pdf)

- **Why it matters:** Explicitly states the limits (“provenance is not truth”), details the trust model (X.509 chains, trust lists), and describes conformance programmes and security levels—key maturity evidence that governance and operational assurance are being formalised, not merely specified. [16]

#### 5) **ISO/IEC 21617-1:2025 — Information technology — JPEG Trust — Part 1: Core foundation**

- **Org:** ISO/IEC (via ISO catalogue entry)

- **Type:** international standard catalogue record (standards body)

- **Date:** Jan 2025

- **Link:** <https://www.iso.org/standard/86831.html>

- **Why it matters:** Demonstrates formal international standardisation of media trust/provenance frameworks (authenticity/provenance/integrity annotation through lifecycle), supporting interoperability and governance beyond a single consortium. [17]

#### 6) **ISO/CD 22144 — Authenticity of information — Content credentials**

- **Org:** ISO

- **Type:** standards-body committee draft record (roadmap/standardisation pipeline)

- **Date:** Oct 2024 (project approved / CD approved for DIS registration)

- **Link:** <https://www.iso.org/standard/90726.html>

- **Why it matters:** Shows “content credentials” entering ISO’s formal pipeline (fast-track style progression through committee stages), a strong maturity signal that the approach is converging towards interoperable, internationally governed standards. [18]

#### 7) **JPEG Trust White Paper version 2 (ISO/IEC JTC1/SC29/WG1) – meeting document**

- **Org:** JPEG (ISO/IEC JTC1/SC29/WG1)

- **Type:** standards working-group whitepaper (authoritative)

- **Date:** Apr 2025 (meeting document header)

- **Link:** <https://ds.jpeg.org/whitepapers/jpeg-trust-whitepaper.pdf>

- **Why it matters:** States JPEG Trust (ISO/IEC 21617) publication and explicitly positions a multi-part roadmap including watermarking, while aligning with existing ecosystems; it evidences ongoing work to connect provenance annotation with durability techniques and broad format support. [19]

#### 8) **Preserve Content Credentials — Cloudflare Images documentation**

- **Org:** Cloudflare

- **Type:** vendor technical doc (product documentation)

- **Date:** Feb 2025 (Last updated: 3 Feb 2025)
- **Link:** <https://developers.cloudflare.com/images/transform-images/preserve-content-credentials/>
- **Why it matters:** Documents a production CDN/image-pipeline feature that preserves embedded credentials through transformations and **appends cryptographically signed actions**, directly addressing a major bottleneck (credentials being stripped during re-encoding/resizing pipelines). [20]

#### 9) How we're increasing transparency for gen AI content with the C2PA

- **Org:** Google
- **Type:** technical product/engineering blog (deployment roadmap)
- **Date:** Sep 2024
- **Link:** <https://blog.google/innovation-and-ai/products/google-gen-ai-content-transparency-c2pa/>
- **Why it matters:** Describes product-level integration plans, validation against a trust list, and adoption of newer standard versions to harden provenance against tampering—evidence of large-platform commitment moving beyond pilots. [21]

#### 10) How Pixel and Android are bringing a new level of trust to your images with C2PA Content Credentials

- **Org:** Google Online Security Blog (Android Security / C2PA core team)
- **Type:** technical architecture and deployment documentation (security engineering)
- **Date:** Sep 2025
- **Link:** <https://security.googleblog.com/2025/09/pixel-android-trusted-images-c2pa-content-credentials.html>
- **Why it matters:** Reports a shipping device ecosystem approach: Content Credentials attached across every Pixel Camera photo, Assurance Level 2 (per C2PA conformance definitions), privacy-by-design certificate management (one-time keys/certs) and offline trusted timestamps—high-confidence evidence of hardware-rooted production deployment and privacy engineering. [22]

#### 11) Content Credentials — Generative AI on Vertex AI (Google Cloud docs)

- **Org:** Google Cloud (Vertex AI)
- **Type:** vendor technical doc (cloud product documentation)
- **Date:** Feb 2026 (Last updated 2026-02-18 UTC)
- **Link:** <https://docs.cloud.google.com/vertex-ai/generative-ai/docs/content-credentials>
- **Why it matters:** Documents automatic attachment and signing of Content Credentials for supported generative models, and clearly frames the “provenance ≠ truth” limitation—evidence of operationalised provenance for AI outputs in a major cloud platform. [23]

#### 12) Content Credentials in Azure OpenAI (Microsoft Learn)

- **Org:** Microsoft Learn / Azure OpenAI
- **Type:** vendor technical doc (service documentation)
- **Date:** Jan 2026 (Last updated 2026-01-30)
- **Link:** <https://learn.microsoft.com/en-us/azure/ai-foundation/openai/concepts/content-credentials?view=foundation-classic>
- **Why it matters:** States that all AI-generated images from Azure OpenAI include Content Credentials with cryptographically signed manifests (fields like “AI Generated Image”,

software agent, timestamp) traceable to Azure OpenAI—strong maturity evidence for automated at-scale credential issuance in a commercial AI service. [24]

### 13) Nikon releases firmware v2.00 for Nikon Z6III — image provenance function compliant with C2PA

- **Org:** Nikon (corporate news release)
- **Type:** vendor technical/product release note (deployment evidence)
- **Date:** Aug 2025
- **Link:** [https://www.nikon.com/company/news/2025/0827\\_imaging\\_01.html](https://www.nikon.com/company/news/2025/0827_imaging_01.html)
- **Why it matters:** Describes a camera workflow where a certificate is loaded via Nikon Imaging Cloud and provenance metadata plus a digital signature are added at capture, with additional provenance appended through C2PA-compliant editing—evidence of capture-side signing entering mainstream camera firmware. [25]

### 14) New: Leica M11-P — chain of authenticity with Content Credentials

- **Org:** Leica Camera (press release PDF)
- **Type:** vendor technical/product announcement (deployment evidence; contains architecture details)
- **Date:** Oct 2023
- **Link:** [https://leica-camera.com/sites/default/files/2023-10/press\\_release\\_leica\\_m11p\\_october\\_2023\\_final\\_.pdf](https://leica-camera.com/sites/default/files/2023-10/press_release_leica_m11p_october_2023_final_.pdf)
- **Why it matters:** Claims capture-time signing with a CAI-compliant certificate and a dedicated chipset storing certificates (German Federal Printing Office), indicating a hardware-root approach to provenance at the point of capture—important plausibility/maturity evidence for secure capture-device identity. [26]

### 15) Sony Electronics and The Associated Press complete testing of advanced in-camera authenticity technology

- **Org:** Sony Professional press centre
- **Type:** vendor report / prototype-to-field testing announcement
- **Date:** Nov 2023
- **Link:** [https://pro.sony/ue\\_US/press/ap-in-camera-authenticity-solution](https://pro.sony/ue_US/press/ap-in-camera-authenticity-solution)
- **Why it matters:** Reports multi-round testing with a major newsroom partner (AP) and describes a hardware-chipset in-camera signature at point of capture to reduce undetected manipulation at the origin—evidence of early field testing bridging prototype into professional workflows. [27]

### 16) Sony launches “Camera Verify” feature (beta) for Camera Authenticity Solution for News Organisations

- **Org:** Sony Europe press centre
- **Type:** vendor technical/product announcement (deployment expansion)
- **Date:** Jun 2025
- **Link:** <https://www.sony.eu/presscentre/sony-launches-camera-verify-feature-for-its-camera-authenticity-solution-for-news-organisations>
- **Why it matters:** Describes embedding C2PA digital signatures (plus Sony depth signals) at capture and enabling third-party verification via dedicated URLs from a validation site—evidence of operational verification services, not just embedded metadata. [28]



### 17) C2PA + CAWG walkthrough (Creator Assertions Working Group)

- **Org:** CAWG / ecosystem presentation
- **Type:** technical briefing deck (standards extension + governance/identity model)
- **Date:** Jan 2025
- **Link:** [https://cawg.io/meeting-notes/\\_attachments/2025-01-27/c2pa-cawg-walkthrough.pdf](https://cawg.io/meeting-notes/_attachments/2025-01-27/c2pa-cawg-walkthrough.pdf)
- **Why it matters:** Documents an explicit separation of identity/rights assertions from the core C2PA claim generator signal (identity, endorsement, metadata, training/data-mining permissions), and clarifies that X.509 certificates typically identify the implementation (hardware/software) rather than the human author—direct evidence that selective disclosure and rights signalling are being engineered into the ecosystem. [29]

### 18) EBU joins early implementers of new standard to track media content provenance (News Pilot integration)

- **Org:** European Broadcasting Union (EBU)
- **Type:** industry consortium deployment note (pilot in newsroom platform)
- **Date:** Dec 2024
- **Link:** <https://tech.ebu.ch/news/2024/12/ebu-joins-early-implementers-of-new-standard-to-track-content-provenance>
- **Why it matters:** Reports that an electronically signed C2PA manifest is attached to new images published on the EBU News Pilot platform, including an explicit opt-out preventing AI training use—strong evidence of real-world newsroom workflow integration and policy signalling via provenance metadata. [30]

### 19) IPTC releases guide helping news publishers to implement C2PA

- **Org:** IPTC
- **Type:** standards-adjacent implementation guide announcement (workflow guidance)
- **Date:** Jun 2025
- **Link:** <https://iptc.org/news/c2pa-implementation-guide/>
- **Why it matters:** Describes concrete implementation steps for publishers: obtain certificates, join verified publisher lists, and sign content—evidence that the ecosystem is translating standards into operational newsroom deployment playbooks. [31]

### 20) Content Credentials: Strengthening Multimedia Integrity in the Generative AI Era

- **Org:** U.S. Department of Defense Cybersecurity Information (CSI)
- **Type:** government technical report / guidance
- **Date:** Jan 2025
- **Link:** <https://media.defense.gov/2025/Jan/29/2003634788/-1/-1/0/CSI-CONTENT-CREDENTIALS.PDF>
- **Why it matters:** Provides an authoritative threat-and-mitigation framing for content provenance and explicitly describes Content Credentials as cryptographically signed metadata; it also discusses “durable” approaches (e.g., watermark/fingerprint-based recovery to retrieve credentials after stripping), clarifying both feasibility and remaining operational gaps. [32]

### Maturity score (1–7) and reasoning

#### A) Final maturity score: 6

#### B) Justification mapped to the rubric

### What rules out lower levels (≤5):

- This ART is clearly beyond lab prototype/PoC because multiple independent, well-capitalised actors have integrated content credentials into **shipping products and services** that automatically attach and/or preserve cryptographically signed provenance data.

Examples include:

- A consumer smartphone capture pipeline with hardware-backed key protection, privacy-oriented certificate management, and offline timestamping (Pixel 10 / Android implementation) described at an engineering level. [\[22\]](#)
- Commercial AI image-generation services that automatically embed signed manifests (Azure OpenAI and Vertex AI documentation). [\[33\]](#)
- Capture devices and professional solutions that sign at point of capture or support provenance functions via certificates (Nikon Z6III firmware; Leica M11-P; Sony/AP testing and Camera Verify). [\[34\]](#)
- Production distribution/infrastructure retaining credentials through transformations and appending signed actions (Cloudflare Images documentation). [\[20\]](#)
- Standards maturity is also beyond “competing prototypes” because the core technical approach is codified in a detailed, versioned specification (C2PA v2.2 and v2.3), with explicit mechanisms for hard bindings, trust lists, and durability via soft binding/manifest recovery. [\[35\]](#)
- International standardisation momentum exists in parallel (JPEG Trust as an ISO/IEC International Standard; ISO work item for content credentials), reinforcing ecosystem-wide interoperability rather than isolated vendor silos. [\[36\]](#)

These collectively satisfy rubric **level 6**: “Products are being delivered to customers ... application areas are expanding,” with evidence across capture devices, cloud AI generation, distribution tooling, and newsroom platforms. [\[37\]](#)

### What is still missing to justify level 7:

- Level 7 would require clearer evidence of **broad, rising customer demand and competitive growth** across multiple competing end-to-end provenance stacks (e.g., widespread default verifier UI across major social/messaging platforms; pervasive retention across common editing/export/share paths; strong evidence of market pull rather than primarily standards- and policy-driven push). The sources here show accelerating deployment, but also underscore that provenance is not synonymous with truth and that durability/adoption challenges remain central (e.g., need for durability mechanisms and ecosystem adoption). [\[38\]](#)

- A further requirement for level 7 is a demonstration that high-assurance governance is routine at scale across a wide range of products (consistent certificate practices, trust list reliance, revocation handling, and interoperable UX norms). The ecosystem is moving in that direction (conformance framing, assurance levels, and trust-list concepts appear), but the evidence base here is stronger for “delivered products expanding” than for “fully mature, widely relied upon across the mainstream internet.” [\[39\]](#)

### C) Sub-component maturity breakdown (bundle) and aggregation

- **Core technical standard (manifests, assertions, hard binding, trust model): 6** — Detailed, versioned specifications used in real deployments; active evolution (v2.2 → v2.3) including broader media contexts. [\[40\]](#)

- **Durability & recovery (soft binding, manifest recovery): 4–5** — Standardised mechanisms exist (soft binding API; “durable content credential” definitions), but large-scale, consistent “survives all sharing” durability is still an adoption/implementation challenge rather than a solved, ubiquitous capability. [41]
- **Capture-side hardware roots (camera/phone signing): 6** — Shipping camera and smartphone approaches with secure hardware elements and capture-time signing are documented across multiple vendors. [42]
- **Creator/editing and distribution-chain retention (CDN, newsroom platforms): 6** — Concrete deployments preserve and extend provenance through transformations and real-time newsroom aggregation. [43]
- **Identity/rights extensions and selective disclosure mechanics: 4–5** — Architectural separation and assertion standards exist (CAWG walkthrough; opt-out signalling in newsroom pilots), but broad cross-platform reliance is not yet evidenced at “default everywhere” maturity. [44]
- **International standardisation alignment: 5–6** — ISO/IEC published standard (JPEG Trust) plus ISO committee work on content credentials indicates strong institutionalisation, but global harmonisation across all media modalities and platforms is still in progress. [45]

**Aggregation to one score:** The ART’s primary function—cryptographically verifiable provenance attached at creation and carried through workflows—has multiple production deployments across devices, cloud AI services, and distribution infrastructure, which supports a **score of 6** despite some sub-threads (durability/soft-binding ubiquity; privacy/identity norms; ecosystem-wide verifier UX) still tracking closer to 4–5. [46]

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[31] <https://iptc.org/news/c2pa-implementation-guide/>

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[32] <https://media.defense.gov/2025/Jan/29/2003634788/-1/-1/0/CSI-CONTENT-CREDENTIALS.PDF>

<https://media.defense.gov/2025/Jan/29/2003634788/-1/-1/0/CSI-CONTENT-CREDENTIALS.PDF>

## ART 12.099 Privacy-Preserving Collaboration Protocols

### 1. ART extraction

- **Primary capability (core claim)**
- Enable *multiple independent organisations* to compute shared analytics (and some model-training-like workloads) over combined data **without disclosing underlying records** to one another or to an intermediary compute operator.
- Provide a **neutral collaboration layer** (an “MPC network” style fabric) that supports familiar analyst interfaces (SQL-like queries, dashboards, APIs) while enforcing *machine-checkable* privacy/security policies and auditable logging.
- Make collaboration feasible where **legal, competitive, or trust constraints** block conventional data pooling, by keeping each party’s data behind its own boundary and exchanging only cryptographic computation fragments.
- **Key sub-components / variants**
- **Secure Multi-Party Computation (MPC)** for relational analytics (joins, group-by/aggregations, sorting) and multi-party protocols (semi-honest vs malicious security).
- **Secure collaborative query platforms** translating SQL (or SQL-like) to secure computation plans and primitives (e.g., secret sharing based operators).
- **Output protection / “safe output” mechanisms**, notably **differential privacy (DP)** budgeting, DP summaries/synopses, and mechanisms that bound privacy loss under continual querying.

- **Privacy-preserving measurement/telemetry aggregation** (two-server or multi-server aggregation protocols; standardisation track protocols).
- **Governance + interoperability stack**: identities/authentication, policy description languages, node selection/trust assumptions, auditing, and compliance artefacts that regulators and counterparties can accept.
- **Performance engineering**: reducing worst-case costs of secure joins/sorts, data-parallel execution, WAN-aware communication layers, and controlled leakage/approximation where permitted.
- **Maturity indicators that count as evidence**
- Peer-reviewed **end-to-end prototypes** executing realistic multi-party analytics workloads (e.g., full SQL operators, complex joins, TPC-H-scale benchmarks) with concrete performance results.
- Demonstrations of **bounded privacy loss** for iterative/continual analytics (DP budgeting, synopses) integrated with secure computation.
- Evidence of **realistic deployment assumptions**: multi-cloud/WAN experiments, geographically distributed nodes, integration into existing systems, operational logging, and key-management/role separation.
- **Standards / interoperability progress** (published standards, standards-track specifications) and **regulatory guidance** that explicitly contemplates PET deployment and compliance.
- “Network/compute layer” directionality: reference architectures for **MPC-as-a-service / secure private computing-as-a-service**, and integration into federated “data space” architectures.

## 2. Evidence (10–20 recent, reliable sources)

### 1) **SECRECY: Secure collaborative analytics in untrusted clouds**

- **Authors/Org**: John Liagouris[1] et al.
- **Venue/type**: Peer-reviewed systems paper (USENIX Association[2] NSDI)
- **Publication date**: April 2023 (presentation dated 18 Apr 2023)
- **Link**: <https://www.usenix.org/system/files/nsdi23-liagouris.pdf>
- **Why it matters (concrete progress)**: Demonstrates a relational MPC system for collaborative analytics-as-a-service, reporting **>1000×** query performance improvements vs prior approaches and showing complex analytics on **millions of rows with a single thread per party**, including multi-cloud evaluation—direct plausibility evidence for MPC-based “neutral compute layer” workflows. [3]

### 2) **Orq: Complex Analytics on Private Data with Strong Security Guarantees**

- **Authors/Org**: Eli Baum[4] et al.
- **Venue/type**: Peer-reviewed systems paper (Association for Computing Machinery[5] SOSP)
- **Publication date**: October 2025
- **Link**: <https://cs-people.bu.edu/vkalavri/assets/pdf/orq-sosp25.pdf>
- **Why it matters (concrete progress)**: Reports performance for the **full TPC-H workload entirely under MPC**, including **Scale Factor 10** where queries operate on **~58M rows on average** and up to **75M-row inputs** for the most expensive query—strong evidence that secure collaborative analytics is pushing beyond toy workloads toward production-sized analytics. [6]



### 3) CoVault: Secure, Scalable Analytics of Personal Data

- **Authors/Org:** Rodrigo De Viti[7] et al.
- **Venue/type:** Peer-reviewed systems/security paper (USENIX Security Symposium)
- **Publication date:** 13 Aug 2025 (publisher record)
- **Link:**  
<https://www.usenix.org/system/files/conference/usenixsecurity25/sec25cyclic1-prepub-657-de-viti.pdf>
- **Why it matters (concrete progress):** Proposes an architecture that **scales actively-secure MPC horizontally** by combining server-aided MPC with TEEs; provides a quantified scaling claim: continuous epidemic analytics for a **country of 80M people (~11.85B records/day)** needing **~one core pair per 30,000 people**—evidence of an approach toward practical scaling economics. [8]

### 4) SecretFlow-SCQL: A Secure Collaborative Query pLatform

- **Authors/Org:** Wenjing Fang[9] et al.
- **Venue/type:** Peer-reviewed database systems paper (PVLDB)
- **Publication date:** 2024 (PVLDB 17(12); month not stated in the paper’s reference block)
- **Link:** <https://www.vldb.org/pvldb/vol17/p3987-fang.pdf>
- **Why it matters (concrete progress):** Establishes a collaborative query platform with **comprehensive SQL operator support** and an explicit MPC translation pipeline using **additive secret sharing**, including redesign/optimisation of sorting as a key bottleneck for **GROUP-BY**—direct evidence that “SQL-like queries → MPC” interfaces are being engineered toward usability and scale. [10]

### 5) SPECIAL: SynoPsis AssistEd Secure Collaborative AnaLytics

- **Authors/Org:** Chenghong Wang[11] et al.
- **Venue/type:** Peer-reviewed database systems paper (PVLDB)
- **Publication date:** Dec 2024 (publisher listing); PVLDB reference year 2024
- **Link:** <https://www.vldb.org/pvldb/vol18/p1035-wang.pdf>
- **Why it matters (concrete progress):** Introduces DP “synopses” with a bounded privacy-loss model for continual processing and reports large empirical gains: up to **80× faster** query times, **900× smaller** memory usage, and up to **89× reduction in privacy loss**—direct evidence of “policy modules + safe output checks” improving practicality. [12]

### 6) Longshot: Indexing Growing Databases Using MPC and Differential Privacy

- **Authors/Org:** Yanping Zhang[13] et al.
- **Venue/type:** Peer-reviewed database systems paper (PVLDB)
- **Publication date:** 2023 (the PVLDB issue is cited as April 2023 in later PVLDB bibliographies; the paper itself emphasises “growing DB” operations and evaluation)
- **Link:** <https://www.vldb.org/pvldb/vol16/p2005-zhang.pdf>
- **Why it matters (concrete progress):** Combines MPC with DP synopses/indexes so that query/update work can drop from linear to **poly-logarithmic** portions of data; reports an update optimisation achieving **~5× efficiency improvement** (even for <200 updates) and evaluates on a real-world dataset (NYC taxi), demonstrating feasibility of DP-bounded “safe leakage” to accelerate secure computation. [14]

### 7) Secure Sampling for Approximate Multi-party Query Processing

- **Authors/Org:** Qiyao Luo[15] et al.
- **Venue/type:** Peer-reviewed database paper (Proc. ACM on Management of Data / SIGMOD)

track)

- **Publication date:** September 2023 (stated in the paper header)
- **Link:** <https://yilei.aqua.hk.cn/paper/SecureSampling.pdf>
- **Why it matters (concrete progress):** Builds **MASQUE**, an MPC-AQP system that pre-generates batches of samples offline to achieve  $\sim \tilde{O}(s)$  amortised online query cost, while maintaining the MPC guarantee that nothing is revealed beyond the result (which can be further protected by DP)—clear evidence that performance constraints are being attacked with system-level redesigns. [16]

#### 8) Multiparty Private Set Intersection Cardinality and Its Applications

- **Authors/Org:** Jiahui Gao[17] et al.
- **Venue/type:** Peer-reviewed privacy/security paper (PoPETs)
- **Publication date:** 2024 (PoPETs 2024(2))
- **Link:** <https://petsymposium.org/popets/2024/popets-2024-0041.pdf>
- **Why it matters (concrete progress):** Provides an implemented multi-party PSI-CA protocol; reports that for **n=16 parties** with datasets of **2<sup>20</sup> items**, the **serverless** setting completes in **~7 seconds** (and a server-aided variant in 71s), showing that some collaboration primitives can be fast enough for practical workflows. [18]

#### 9) DPrio: Efficient Differential Privacy with High Utility for Prio

- **Authors/Org:** Dana Keeler[19] et al.
- **Venue/type:** Peer-reviewed privacy/security paper (PoPETs)
- **Publication date:** 2023 (Volume 2023, Issue 3)
- **Link:** <https://petsymposium.org/popets/2023/popets-2023-0086.pdf>
- **Why it matters (concrete progress):** Adds DP guarantees to Prio-style multi-server aggregation by having clients submit secret-shared noise and uses minimal MPC to select noise contributions; reports utility gains vs prior noise-generation designs with only minimal/batchable server communication—evidence that “safe output” can be engineered into MPC-style aggregation. [20]

#### 10) SCIF: Privacy-Preserving Statistics Collection with Input Validation and Full Security

- **Authors/Org:** Jianan Su[21] et al.
- **Venue/type:** Peer-reviewed privacy/security paper (PoPETs)
- **Publication date:** 2025 (PoPETs 2025(3))
- **Link:** <https://petsymposium.org/popets/2025/popets-2025-0106.pdf>
- **Why it matters (concrete progress):** Designs and implements a “ready-to-use” secure aggregation platform with **malicious-adversary** resilience and input validation; notes SCIF is written in Go for scalability/ease-of-use and demonstrates integration into a private Tor deployment, plus geographically distributed experimental setup (cloud regions, TLS). [22]

#### 11) Distributed Aggregation Protocol (DAP) for Privacy Preserving Measurement

- **Authors/Org:** Internet Engineering Task Force[23] (PPM working group), Internet-Draft authors listed on the spec
- **Venue/type:** Standards-track Internet-Draft (protocol specification)
- **Publication date:** 30 Jan 2026
- **Link:** <https://www.ietf.org/archive/id/draft-ietf-ppm-dap-17.html>
- **Why it matters (concrete progress):** Specifies a multi-party protocol in which two aggregators compute statistics over client measurements without learning individual

measurements (privacy holds as long as at least one aggregator is honest), providing a standardising foundation for “neutral compute layer” aggregation services. [24]

#### 12) ISO/IEC 4922-1:2023 — Information security — Secure multiparty computation — Part 1: General

- **Authors/Org:** International Organization for Standardization[25] / ISO/IEC JTC 1/SC 27
- **Venue/type:** International standard
- **Publication date:** 2023-07
- **Link:** <https://www.iso.org/standard/80508.html>
- **Why it matters (concrete progress):** Establishes MPC terminology/taxonomy and processes explicitly aimed at enabling interoperability—foundational evidence that MPC is moving from bespoke implementations toward standardised integration and assurance. [26]

#### 13) ISO/IEC 4922-2:2024 — Information security — Secure multiparty computation — Part 2: Mechanisms based on secret sharing

- **Authors/Org:** ISO/IEC JTC 1/SC 27
- **Venue/type:** International standard
- **Publication date:** 2024-03
- **Link:** <https://www.iso.org/standard/80514.html>
- **Why it matters (concrete progress):** Specifies concrete secret-sharing MPC mechanisms (e.g., addition/subtraction/multiplication primitives and shared randomness) and how to perform secure function evaluation—evidence of codifying the “compute fragments exchanged and recombined” model into interoperable mechanisms. [27]

#### 14) National Strategy to Advance Privacy-Preserving Data Sharing and Analytics

- **Authors/Org:** White House Office of Science and Technology Policy[28] / National Science and Technology Council (reporting body)
- **Venue/type:** Authoritative government roadmap/report
- **Publication date:** March 2023
- **Link:** <https://www.nitrd.gov/pubs/National-Strategy-to-Advance-Privacy-Preserving-Data-Sharing-and-Analytics.pdf>
- **Why it matters (concrete progress):** Frames privacy-preserving data sharing/analytics as needing both PET capabilities and **strong governance**, positioning the field as a coordinated public/private roadmap area—relevant to the ART’s emphasis on compliance evidence, governance rules, and regulator-acceptable controls. [29]

#### 15) Privacy-enhancing technologies (PETs) guidance

- **Authors/Org:** Information Commissioner's Office[30]
- **Venue/type:** Regulator guidance
- **Publication date:** Updated 19 Jun 2023
- **Link:** <https://ico.org.uk/for-organisations/uk-gdpr-guidance-and-resources/data-sharing/privacy-enhancing-technologies/>
- **Why it matters (concrete progress):** Provides structured PET guidance (including for technical audiences) focused on practical application and compliance framing—evidence that regulator-facing interpretation and operationalisation of PETs is advancing alongside engineering work. [31]

#### 16) Beyond the lab: How Multi-Party Secure Private Computing-as-a-service (MPSPCaaS) can foster adoption of Input Privacy technologies in the ESS

- **Authors/Org:** Fabio Ricciato[32], Eurostat[33]
- **Venue/type:** Technical presentation / architecture framing (official statistics context)
- **Publication date:** 23 Mar 2023
- **Link:** [https://cros.ec.europa.eu/system/files/2023-12/item5\\_wgm2023\\_pet\\_v8.pdf](https://cros.ec.europa.eu/system/files/2023-12/item5_wgm2023_pet_v8.pdf)
- **Why it matters (concrete progress):** Explicitly develops an “SPC/MPSPC-as-a-service” model with roles for controllers/auditors and multiple institutions, and positions MPC/TEE/HE as “input privacy” components—strongly aligned with the ART’s “neutral compute layer” and governance module concept. [34]

#### 17) UNECE Project on Input Privacy Preservation: Final Report

- **Authors/Org:** United Nations Economic Commission for Europe[35] HLG-MOS (authors listed as UNECE HLG-MOS)
- **Venue/type:** Authoritative report (open access on Zenodo)
- **Publication date:** 28 Mar 2023
- **Link:** <https://zenodo.org/records/10400296>
- **Why it matters (concrete progress):** Documents official-statistics work on “input privacy preservation” and (per the report description) defines the concept of **MPSPCaaS** and an open consultation—evidence of a real governance+infrastructure path toward multi-party secure computing networks between independent institutions. [36]

#### 18) Integrating Secure Multiparty Computation into Data Spaces

- **Authors/Org:** Veronika Siska[37] et al., Austrian Institute of Technology[38]
- **Venue/type:** Peer-reviewed conference proceedings paper
- **Publication date:** May 2024 (recorded as 2024/5/4)
- **Link:** <https://publications.ait.ac.at/en/publications/integrating-secure-multiparty-computation-into-data-spaces/>
- **Why it matters (concrete progress):** Systematically identifies *non-crypto* blockers for MPC networks—authentication/identity management, policy description, node selection, system parameters, access control—and argues for standardisation to ensure interoperability, mapping directly onto the ART’s “policy modules + governance + compliance evidence” requirements. [39]

### 3. Maturity score (1–7) and reasoning

**Final maturity score: 4**

#### Why levels 1–3 are ruled out

The ART is beyond “principle only” (levels 1–2) because multiple peer-reviewed systems demonstrate end-to-end secure collaborative analytics with concrete performance results on realistic workloads, including WAN/multi-cloud evaluations and SMB/enterprise-like SQL workloads. [40]

It is beyond a narrow lab prototype (level 3) because several works demonstrate **platform-like** characteristics aligned with commercial requirements: SQL/operator completeness and automatic MPC translation (SCQL), bounded privacy loss mechanisms for continual queries (SPECIAL; Longshot), and scaling architectures for large populations and high-throughput ingestion (CoVault). [41]

Additionally, implemented systems for privacy-preserving aggregation with adversarial

robustness and validation (SCIF) show an emerging “deployable building block” direction, including integration into existing systems and explicit operational setups. [42]

### Why level 4 fits best

Level 4 (“PoC: functional prototype meeting commercialisation requirements in functionality and viability”) is the best overall fit because the strongest evidence shows:

- **Functionality completeness approaching production needs:** full relational analytics and SQL-style workflows under MPC (e.g., join/aggregation/sorting support and query planning), and system-level optimisations to make these workflows faster. [43]
- **Demonstrated scalability progress:** full TPC-H under MPC up to SF10 (Orq) and large-population operational modelling with quantified resource needs (CoVault). [44]
- **Policy/safety modules becoming concrete:** DP synopses and bounded privacy loss in secure collaborative analytics (SPECIAL; Longshot), plus DP augmentation of multi-server aggregation (DPrio). [45]
- **Governance + interop are no longer hypothetical:** ISO MPC standards (taxonomy + secret-sharing mechanisms), standards-track protocol work for multi-party aggregation (DAP), and regulator/government roadmaps that explicitly talk about PET deployment, governance, and compliance framing (OSTP strategy; ICO guidance; Eurostat/UNECE MPSPCaaS framing). [46]

Collectively, this is consistent with “recent and clear PoC capability” rather than only isolated prototypes.

### What is still missing for level 5

Level 5 requires clear evidence that **several well-capitalised market actors are competing to develop production prototypes post-PoC** or that production prototypes are in a finishing phase with visible investments. The current evidence base here is strong on *research prototypes, standardisation, and public-sector reference architectures*, but it does not (within the strict “technical, non-marketing” sourcing constraints) show widespread, competitive **production-grade** offerings delivering general-purpose “MPC network” functionality with repeatable deployments, procurement patterns, and scaling playbooks. [47]

Separately, the performance challenge remains material: even papers aiming to reduce costs note that MPC SQL systems can be orders of magnitude slower than plaintext baselines, motivating approximation/offline sampling approaches (i.e., the gap is still actively being engineered away). [16]

### Sub-scores and aggregation

- **Secure collaborative SQL analytics engines (MPC-based query engines + planners) → 4** → evidence: SECRECY; SCQL; SPECIAL; Orq. [48]
- **“Safe output” modules: DP budgeting/synopses + DP-enabled aggregation → 3–4** → evidence: SPECIAL (bounded privacy loss + synopses); Longshot (DP synopses/indexes); DPrio (DP for Prio-style aggregation). [45]
- **Deployment-oriented secure aggregation / measurement protocols → 4** → evidence: SCIF (implemented platform with validation/malicious security); IETF DAP draft on standards track. [49]

- **Governance / interoperability foundations → 4–5 (enablers, not products) →** evidence: ISO/IEC 4922 series; OSTP strategy; ICO guidance; Eurostat/UNECE MPSPCaaS framing and data-spaces integration work. [50]

**Aggregation method:** average-weighted by “delivered capability in the ART’s core functionality” (secure collaborative computation over combined data with policy/safe-output controls). Because the core functionality is dominated by the analytics engines + the policy/safety layer—and both sit around **4** with some components still at **3–4**—the overall maturity consolidates to **4** rather than 5. [51]

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[1] [3] [5] [17] [21] [40] [43] [48] [51] <https://www.usenix.org/system/files/nsdi23-liagouris.pdf>

<https://www.usenix.org/system/files/nsdi23-liagouris.pdf>

[2] [19] [22] [32] [37] [42] [49] SCIF: Privacy-Preserving Statistics Collection with Input Validation and Full Security

<https://petsymposium.org/popets/2025/popets-2025-0106.pdf>

[4] [6] [44] <https://cs-people.bu.edu/vkalavri/assets/pdf/orq-sosp25.pdf>

<https://cs-people.bu.edu/vkalavri/assets/pdf/orq-sosp25.pdf>

[7] [27] <https://www.iso.org/standard/80514.html>

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[14] <https://www.vldb.org/pvldb/vol16/p2005-zhang.pdf>

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[15] [18] <https://petsymposium.org/popets/2024/popets-2024-0041.pdf>

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[34] [https://cros.ec.europa.eu/system/files/2023-12/item5\\_wgm2023\\_pet\\_v8.pdf](https://cros.ec.europa.eu/system/files/2023-12/item5_wgm2023_pet_v8.pdf)

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[35] [36] <https://zenodo.org/records/10400296>

<https://zenodo.org/records/10400296>

## ART 12.100 Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

### ART extraction

- **Primary capability (what the ART claims)**
- A cross-organisation framework of **standardised performance/quality/safety metrics** plus **repeatable conformance tests**, so that advanced manufacturing machines and processes become *comparable, auditable, and contractable* across sites and suppliers.
- A **certification and evidence “supply chain”** (test artefacts + digital test procedures + accredited labs/on-site verification) that reduces qualification time and integration risk by making claims depend on traceable measurement rather than reputation.

- **Machine-readable certification outputs** (tamper-evident certificates linked to configs/recipes/batch records) with software interfaces so procurement/compliance systems can automatically verify status.
- **Key sub-components / sub-threads implied by the ART**
- Common **test artefacts / benchmark jobs** and measurement datasets (reference builds, reference parts, reference measurement procedures).
- **Standardised data models** for production/measurement evidence (metadata schemas, identifiers, links to calibration/traceability, “digital thread” linkage).
- **Conformance suites** for machines, controllers, and industrial software interfaces (automated test tools, interoperability workshops, accredited test labs).
- **Digital certificates / attestations** for calibration, accreditation status, and (eventually) process and machine configuration states; cryptographic integrity and verification mechanisms.
- **Qualification standards** for processes, materials/feedstock, equipment installation/operation/performance (IQ/OQ/PQ), operators/coordination personnel, and acceptance criteria.
- Governance and update mechanisms (standards bodies + metrology institutes + accreditation bodies) that keep requirements current without freezing innovation.
- **Maturity indicators that would constitute strong evidence**
- Published and maintained **standards** defining metrics, test procedures, and qualification/acceptance requirements (including frequent revisions and new work items).
- Operational **certification programmes** (test labs, compliance tools, interoperability test events) with evidence of ongoing certifications and expanding scope.
- **Machine-readable, verifiable certificates** demonstrably used in real workflows (e.g., digital calibration certificates, digital accreditation symbols) and supported by tooling/APIs.
- **Reference datasets/benchmarks** used by multiple organisations (public repositories, structured metadata, repeatable measurement pipelines).
- Evidence of **scaling signals**: broad adoption across regions, procurement requirements, cross-recognition between accreditation systems, and integration into enterprise software routines.

#### Evidence (10–20 recent, reliable sources)

##### 1) Digital Calibration Certificate (DCC) – PTB overview page

- **Organisation:** Physikalisch-Technische Bundesanstalt<sup>[1]</sup> (PTB)
- **Type:** Metrology institute technical explainer / programme page
- **Publication date:** Dec 2024 (page timestamp)
- **Link:** <https://www.ptb.de/cms/en/metrological-services/dkd/dkd-dcc.html> <sup>[2]</sup>
- **Why it matters:** PTB describes DCCs as **structured, machine-readable calibration results** grounded in SI/VIM/GUM conventions—directly supporting the ART’s “repeatable measurement + machine-readable certificates” layer and showing an authoritative metrology institute is operationalising it. <sup>[2]</sup>

## 2) Digital accreditation symbol and digital calibration certificate: DAkkS and PTB prepare introduction

- **Organisation:** DAkkS[3] (German accreditation body)
- **Type:** Accreditation body press release
- **Publication date:** Sep 2023
- **Link:** <https://www.dakks.de/en/pressrelease/digital-accreditation-symbol-and-digital-calibration-certificate-dakks-and-ptb-prepare-introduction.html> [4]
- **Why it matters:** Announces a **machine-readable, tamper-proof, verifiable digital accreditation symbol** with applications starting March 2024—clear evidence that formal conformity infrastructure is moving from concept into a regulated operational rollout. [4]

## 3) Trustworthy chains of evidence at the international level with the digital accreditation symbol

- **Organisation:** European co-operation for Accreditation[5]
- **Type:** Accreditation network article / implementation update
- **Publication date:** Jun 2024
- **Link:** <https://european-accreditation.org/trustworthy-chains-of-evidence-at-the-international-level-with-the-digital-accreditation-symbol/> [6]
- **Why it matters:** Reports that the digital accreditation symbol was introduced after a pilot and positions it as support for **digitised supply chains**—evidence of cross-border recognition ambitions (a key maturity test for certification infrastructure). [6]

## 4) Forum on Metrology and Digitalization (FORUM-MD) – report of the 1st meeting

- **Organisation:** Bureau International des Poids et Mesures[7] (BIPM)
- **Type:** International metrology governance report
- **Publication date:** 2024 (meeting March 2024; report published 2024)
- **Link:** [https://www.bipm.org/documents/20126/252964004/Report%2B1st%2BFORUM-MD%2B2024\\_FINAL/7be58bf1-e556-ca80-bd62-243d7c3d3486](https://www.bipm.org/documents/20126/252964004/Report%2B1st%2BFORUM-MD%2B2024_FINAL/7be58bf1-e556-ca80-bd62-243d7c3d3486) [8]
- **Why it matters:** Documents that DCCs and **data integrity/authenticity mechanisms (e.g., digital signatures)** are being handled at the international metrology coordination level, including references to harmonisation and regional implementation efforts—supporting plausibility and governance maturity. [8]

## 5) DCC2GO – Supporting the implementation of Digital Calibration Certificates in the European metrology community

- **Lead author:** David Balslev-Harder[9] et al.
- **Type:** Peer-reviewed paper (Measurement: Sensors)
- **Publication date:** May 2025
- **Link:** <https://www.sciencedirect.com/science/article/pii/S2665917424004756> [10]
- **Why it matters:** Describes a capacity-building project producing **validated, shareable implementation materials** to help more institutes/labs adopt DCCs—evidence of scaling work beyond a single-country prototype into broader community deployment. [10]

## 6) Harmonisation processes and practical implementation of machine-interpretable digital calibration certificates

- **Lead author:** Shanna Schönhals[11] et al.

- **Type:** Peer-reviewed paper (Measurement: Sensors)
- **Publication date:** May 2025
- **Link:** <https://www.sciencedirect.com/science/article/pii/S266591742400446X> [12]
- **Why it matters:** Focuses on **global format harmonisation** and practical implementation steps for machine-interpretable DCCs—directly aligned with the ART’s “shared framework pursued to reduce bespoke audits” claim. [12]

#### 7) Design and Implementation of Digital Calibration Certificate for RFID Tag Storage

- **Lead author:** Kai Kan[13] et al.
- **Type:** Peer-reviewed paper (Sensors, MDPI)
- **Publication date:** Oct 2024 (published 14 Oct 2024)
- **Link:** <https://www.mdpi.com/1424-8220/24/20/6626> [14]
- **Why it matters:** Demonstrates an engineering pathway to **attach machine-readable calibration evidence physically to instruments** (RFID “DCC-Lite”), with experimental validation in a measurement system—supporting feasibility of “certificates that travel with equipment and are machine-consumable”. [14]

#### 8) ISO/ASTM 52920:2023 – Qualification principles for industrial additive manufacturing processes and production sites

- **Organisation:** International Organization for Standardization[15] / ASTM International[16]
- **Type:** International standard (requirements for industrial process/site qualification)
- **Publication date:** Jun 2023
- **Link:** <https://www.iso.org/standard/76911.html> [17]
- **Why it matters:** Sets **criteria and quality assurance measures** across the AM production site and operations, explicitly aiming at consistent requirements beyond local practice—strong evidence that “standardised qualification/assurance” is becoming codified and contractable in at least one advanced manufacturing domain. [17]

#### 9) ISO/ASTM TR 52917:2022 – Round robin testing (general guidelines)

- **Organisation:** ISO/ASTM
- **Type:** Technical report standard (inter-lab comparability methodology)
- **Publication date:** Aug 2022
- **Link:** <https://www.iso.org/standard/75757.html> [18]
- **Why it matters:** Focuses on managing round-robin studies to quantify variability across feedstock, machines, controls, and post-processing—directly matching the ART’s need for **repeatable, comparable measurement regimes** rather than ad hoc site-by-site judgement. [18]

#### 10) ISO/ASTM 52925:2022 – Qualification of materials for laser-based powder bed fusion of polymers

- **Organisation:** ISO/ASTM
- **Type:** International standard (feedstock qualification guidance)
- **Publication date:** Apr 2022
- **Link:** <https://www.iso.org/standard/76910.html> [19]
- **Why it matters:** Provides a standardised pathway for **material/feedstock qualification**, a prerequisite for any certification regime that aims to make process results comparable across organisations and time. [19]

#### 11) ISO/ASTM TS 52949:2025 – IQ/OQ/PQ of PBF-EB equipment

- **Organisation:** ISO/ASTM
- **Type:** Technical Specification (equipment qualification / process validation elements)
- **Publication date:** Jan 2025
- **Link:** <https://www.iso.org/standard/85660.html> [20]
- **Why it matters:** Standardises **installation qualification, operational qualification, and performance qualification** for a specific AM equipment class—exactly the sort of “conformance suite” and auditable evidence structure the ART forecasts for advanced machines. [20]

#### 12) ISO/ASTM FDIS 52951 – Data packages for AM parts (final draft, under development)

- **Organisation:** ISO/ASTM
- **Type:** Draft standard (data package models for design-to-acceptance workflow)
- **Publication date:** Project approved Dec 2023 (standard still under development)
- **Link:** <https://www.iso.org/standard/76828.html> [21]
- **Why it matters:** Explicitly targets **structured “data packages”** and a referenceable information workflow (digital thread) for communicating acceptance evidence—highly aligned with the ART’s claim that certification becomes machine-checkable and travels with configs/batches. [21]

#### 13) Research Results and Recommendations for Universally Unique Identifiers in Product Data Standards (NIST AMS 300-12)

- **Organisation:** National Institute of Standards and Technology [22]
- **Type:** Government lab technical report (Advanced Manufacturing Series)
- **Publication date:** Jul 2024
- **Link:** <https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.300-12.pdf> [23]
- **Why it matters:** Analyses how persistent identifiers (UUIDs) are (and are not) supported across manufacturing data standards and explicitly discusses **data tampering and the need for digital signatures**—supporting feasibility of machine-readable certificates linked to production evidence with integrity guarantees. [23]

#### 14) Compliance Corner – December 2024 (year-end OPC certification update)

- **Organisation:** OPC Foundation [24]
- **Type:** Standards/industry consortium compliance update
- **Publication date:** Dec 2024
- **Link:** <https://opccconnect.opcfoundation.org/2024/12/compliance-corner-december-2024/> [25]
- **Why it matters:** Reports that OPC test labs are **actively certifying products**, that certification requirements are becoming mandatory in some initiatives, and describes expanding automated conformance testing (including safety-related work undergoing assessment by TÜV [26])—strong evidence that conformance suites + certification labs are already operational in industrial automation ecosystems. [25]

#### 15) OPC UA Online Reference – released specifications list (including Machinery and Machine Tools companion specs)

- **Organisation:** OPC Foundation
- **Type:** Authoritative specification registry / release log
- **Publication date:** Ongoing; includes dated releases (e.g., 2022–2025 entries)
- **Link:** <https://reference.opcfoundation.org/> [27]

- **Why it matters:** Provides a traceable record of **versioned companion specifications** (e.g., machine tools, machinery building blocks, job management), which is foundational to “software-defined machines” being conformance-testable against a common interface contract. [27]

#### 16) umati information brochure (common OPC UA interface for machine tools)

- **Organisation:** umati[28]

- **Type:** Industry consortium technical overview (interoperability adoption artefact)

- **Publication date:** Apr 2024

- **Link:** [https://umati.org/wp-content/uploads/umati\\_info-brochure\\_04-2024\\_web.pdf](https://umati.org/wp-content/uploads/umati_info-brochure_04-2024_web.pdf) [29]

- **Why it matters:** Describes the goal of a **common interface across machine tool manufacturers and model series** based on an OPC UA companion specification—direct evidence of multi-actor alignment to reduce integration friction and enable plug-in procurement/integration routines. [29]

#### 17) A generic interface and a framework designed for industrial metrology integration for the Internet of Things

- **Lead author:** João Sousa[30] et al.

- **Type:** Peer-reviewed paper (Computers in Industry)

- **Publication date:** Jun 2022

- **Link:**

<https://www.sciencedirect.com/science/article/abs/pii/S0166361522000276> [31]

- **Why it matters:** Proposes and experimentally validates an integration framework using **open standards (QIF + OPC UA)** for quality operations/measurement data exchange—supporting the plausibility of standardised, data-driven conformance evidence flowing into higher-level enterprise systems. [31]

#### 18) Identifying machine times with OPC UA for Equipment as a Service (EaaS) and OEE determination

- **Lead author:** Dimitri Evcenko[32] et al.

- **Type:** Peer-reviewed conference paper (Procedia CIRP; CIRP CMS 2024)

- **Publication date:** 2024

- **Link:** <https://publica.fraunhofer.de/bitstreams/3affde77-d6b6-4c41-b520-ac1e9d887dbd/download> [33]

- **Why it matters:** Shows how standardised OPC UA information models can be mapped to **ISO-defined KPI structures (OEE per ISO 22400-2)** and quantifies uncertainty when only equipment data are available—directly relevant to building standard performance metrics and testable claims across organisations. [33]

#### 19) Outcomes and Conclusions from the 2022 AM Bench Measurements, Challenge Problems, Modeling Submissions, and Conference

- **Lead author:** Lyle Levine[34] et al.

- **Type:** Peer-reviewed paper (Integrating Materials and Manufacturing Innovation)

- **Publication date:** Jul 2024

- **Link:** <https://link.springer.com/article/10.1007/s40192-024-00372-4> [35]

- **Why it matters:** Documents a large, multi-organisation benchmark effort with **rigorous in-situ/ex-situ measurements**, a substantial increase in blind modelling submissions, and



explicit data-management infrastructure—strong evidence that “standard test artefacts + benchmark jobs + comparable metrics” are already functioning in a high-value manufacturing domain. [35]

## 20) Laser Beam Metrology for AM-Bench 2022: Approaches, Results, and Lessons Learned (NIST AMS 100-67)

- **Organisation:** NIST
- **Type:** Government lab technical report (Advanced Manufacturing Series)
- **Publication date:** Apr 2025
- **Link:** <https://www.nist.gov/publications/laser-beam-metrology-am-bench-2022-approaches-results-and-lessons-learned> [36]
- **Why it matters:** Provides concrete metrology methods and uncertainty analysis for a key AM parameter (laser beam power density distribution), explicitly documenting challenges at very high power densities—supporting feasibility of robust instrumentation and traceable measurement needed for conformance and certification regimes. [36]

## 21) Additive Manufacturing Benchmark 2022 Schema (XML schema/data model for benchmark metadata)

- **Organisation:** NIST (via Data.gov catalogue)
- **Type:** Government dataset + technical metadata standardisation artefact
- **Publication date:** Sep 2023 (last modified 12 Sep 2023)
- **Link:** <https://datagov-catalog-dev.app.cloud.gov/dataset/additive-manufacturing-benchmark-2022-schema> [37]
- **Why it matters:** Implements a structured **XML Schema metadata model** with identifiers and links for builds/specimens/measurements—an unusually concrete example of the ART’s “standardised digital test artefacts + machine-readable evidence packages” concept in active use. [37]

### Maturity score (1–7) and reasoning

**Final maturity score: 5**

### Why this rules out lower levels

- **Not level 1–3 (pure theory / lab principle / lab prototype only):** Multiple elements of the ART already exist as **operational infrastructures**, not just experiments—e.g., active industrial certification and test-lab activity for OPC UA conformance, and national accreditation work moving to machine-verifiable digital attestations. [38]
- **Not merely level 4 (single PoC prototype):** The evidence shows **multi-actor ecosystems** (standards bodies + accreditation/metrology organisations + industrial consortia) producing maintained standards, certification tooling, and rollouts that go beyond one-off demonstration. [39]

### What is still missing to justify the next higher level (6)

Level 6 would require clear evidence that this integrated, manufacturing-specific “standards + conformance + certification” stack is being **delivered and adopted at increasing scale across many industries and geographies**, with routine procurement integration and broad mutual recognition.

From the sources above, key gaps remain:

- **Scale and breadth evidence is uneven.** Many components are strong but domain-specific (notably additive manufacturing and industrial communications), and the evidence set does not quantify broad uptake (e.g., numbers of certified machine configurations, widespread enterprise API verification integration, or cross-border recognition at large scale). [\[40\]](#)
- **Some critical “certificate travels with configuration/batch record” elements are still standardisation-in-progress.** For example, structured data-package standards for AM acceptance evidence are still under development, signalling that end-to-end machine-readable certification plumbing is not fully mature. [\[21\]](#)
- **Global harmonisation is still an active workstream rather than a finished, universally recognised mechanism.** Multiple papers emphasise harmonisation efforts for DCCs, implying the ecosystem is still converging on formats and processes. [\[41\]](#)

#### Sub-component maturity breakdown and aggregation

- **Digital certificates for metrology + accreditation (DCCs, digital accreditation symbol) → ~5**
- **Why:** Evidence of pilot-to-rollout steps (digital accreditation symbol) and peer-reviewed work on implementation and harmonisation, but no clear proof yet of global, high-volume routine industrial usage across sectors. [\[42\]](#)
- **Interoperability conformance suites + certification labs for manufacturing communication standards (OPC UA ecosystem) → ~6**
- **Why:** Certification test labs are active; automated conformance tooling and new compliance areas (including safety tooling under assessment) show expansion. The evidence does not provide adoption volumes, so it is difficult to argue **7**, but it plausibly meets “products being certified and delivered into market” dynamics consistent with a mature certification ecosystem. [\[43\]](#)
- **Domain qualification/acceptance standards for advanced processes (AM qualification, IQ/OQ/PQ, round-robin comparability) → ~5**
- **Why:** Multiple ISO/ASTM standards now codify qualification requirements and equipment validation steps, but the dossier contains limited direct evidence of widespread, standard-driven certification replacing bespoke audits at scale. [\[44\]](#)
- **Reference test artefacts / benchmark datasets and measurement infrastructure (AM Bench) → ~4**
- **Why:** Highly functional and widely participatory benchmark infrastructure exists (measurements, metadata, data management systems), but it is primarily a benchmark/validation ecosystem rather than a general, market-wide certification layer integrated into procurement across manufacturing domains. [\[45\]](#)
- **Cross-standard identifiers and tamper-resistance for manufacturing data (digital thread linkage) → ~4–5**
- **Why:** NIST provides concrete recommendations around persistent identifiers and discusses tamper-resistance/digital signatures, but evidence of broad industrial

adoption as a default for certification evidence packaging is not yet demonstrated in this dossier. [23]

**Aggregation to a single score:** These sub-components cluster around **4–6**, with several operational infrastructures but incomplete integration and limited scale evidence. Using an average-weighted view (and discounting the most mature sub-ecosystem from dominating the whole ART), the overall maturity best fits **5**: multiple well-capitalised, multi-actor ecosystems are building and deploying key pieces post-PoC, but pervasive scaling and cross-domain standard certification-as-default are not yet evidenced. [46]

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[1] [12] [13] [41] <https://www.sciencedirect.com/science/article/pii/S266591742400446X>

<https://www.sciencedirect.com/science/article/pii/S266591742400446X>

[2] <https://www.ptb.de/cms/en/metrological-services/dkd/dkd-dcc.html>

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[4] [42] <https://www.dakks.de/en/pressrelease/digital-accreditation-symbol-and-digital-calibration-certificate-dakks-and-ptb-prepare-introduction.html>

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[8] [11] [https://www.bipm.org/documents/20126/252964004/Report%2B1st%2BFORUM-MD%2B2024\\_FINAL/7be58bf1-e556-ca80-bd62-243d7c3d3486](https://www.bipm.org/documents/20126/252964004/Report%2B1st%2BFORUM-MD%2B2024_FINAL/7be58bf1-e556-ca80-bd62-243d7c3d3486)

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[9] [23] [28] <https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.300-12.pdf>

<https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.300-12.pdf>

[10] <https://www.sciencedirect.com/science/article/pii/S2665917424004756>

<https://www.sciencedirect.com/science/article/pii/S2665917424004756>

[15] [25] [32] [34] [38] [40] [43] [46]

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<https://opccconnect.opcfoundation.org/2024/12/compliance-corner-december-2024/>

[16] [33] <https://publica.fraunhofer.de/bitstreams/3affde77-d6b6-4c41-b520-ac1e9d887dbd/download>

<https://publica.fraunhofer.de/bitstreams/3affde77-d6b6-4c41-b520-ac1e9d887dbd/download>

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[21] <https://www.iso.org/standard/76828.html>

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[22] [31] <https://www.sciencedirect.com/science/article/abs/pii/S0166361522000276>

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<https://datagov-catalog-dev.app.cloud.gov/dataset/additive-manufacturing-benchmark-2022-schema>

# Attachment 3.

## Anticipated GVN impacts of ARTs

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## GVN 1: Passenger Transport ART Impacts

### Group1. Sensing, Measurement & Connectivity

#### ART 01.001 — Global Broadband Connectivity

**Score:** 10 (Impact in GVN 1)

**Justification (4 sentences):**

Reliable near-ubiquitous connectivity materially expands where connected public transport, MaaS

orchestration, and autonomous or remotely supervised mobility services can work, especially outside dense corridors where the current regime under-serves passengers. First-order effects are better real-time routing, passenger information, dispatch, and safety monitoring; second-order effects include stronger dependence on telecom operators, app platforms, and digital identity/payment rails; third-order effects include new residential and service patterns once reliable on-demand mobility becomes available in more places. In a 5.5M-person society this can plausibly affect the weekly mobility of hundreds of thousands of people and shift annual time/cost outcomes well past the €1B-scale threshold, so the impact is transformative even though the ART is an enabler rather than the single keystone. The same pathway also raises concentration, outage, and surveillance risks, which keeps it below 20.

### Weak signals (9):

- (+) [rural accessibility] → MaaS operators stop excluding low-coverage districts from guaranteed service areas (coverage bottleneck easing)
- (+) [public transport punctuality] → regional bus contracts start requiring continuous high-bandwidth telemetry from every vehicle (operations becoming always-connected)
- (+) [passenger information] → shelters and stop apps publish live updates in previously offline corridors (service legibility rising)
- (+) [autonomous fleet operations] → permits reference satellite-plus-terrestrial connectivity redundancy for remote supervision (driverless service broadening)
- (+) [inclusive access] → mobility apps add offline-to-online handoff for low-income and elderly users in patchy areas (digital exclusion narrowing)
- (–) [market structure] → a few telecom-platform bundles dominate MaaS back-end contracts (bargaining power concentrating)
- (–) [resilience] → transport insurers add telecom outage clauses for connected fleet interruption losses (dependency being priced)
- (–) [privacy] → passenger groups challenge expanded trip-data collection from always-connected services (trust conflict surfacing)
- (–) [security] → outage or jamming incidents trigger temporary service suspensions across multiple operators (single-failure exposure visible)

## ART 01.002 — Ultra-Low Latency Networks

**Score:** 5 (Impact in GVN 1)

### Justification (4 sentences):

Ultra-low latency networks do not by themselves change why people travel, but they materially improve the feasibility of tightly coordinated, time-critical transport functions such as vehicle-to-infrastructure control, remote assistance, dynamic signal priority, and dense autonomous fleet management. First-order gains are smoother traffic flow, safer exception handling, and lower waiting time in high-utilization corridors; second-order effects include premium access for large operators that can buy deterministic network service levels; third-order effects include more centralized traffic control and stronger lock-in to network providers and edge-cloud vendors. In a 5.5M-person society the plausible impact is in the €100M–€1B / 50–500M person-hour band if low-latency coordination meaningfully reduces congestion, incidents, and buffer times across major corridors. The score stays at 5 because passenger transport can still electrify and digitize without universally deterministic networks.

**Weak signals (9):**

- (+) [traffic efficiency] → cities procure sub-10 ms service guarantees for signal priority corridors (control loop tightening)
- (+) [fleet safety] → autonomous shuttle permits require certified latency bounds for remote fallback links (exception handling formalizing)
- (+) [punctuality] → bus rapid transit lanes integrate edge-compute signal control instead of fixed timing plans (delay variance shrinking)
- (+) [rail/metro operations] → station control systems move computation from central data centers to corridor edge nodes (response time valued)
- (+) [MaaS coordination] → dispatch APIs expose latency classes for premium ride-pooling and microtransit services (network quality monetized)
- (–) [market access] → small operators report they cannot afford deterministic network tiers needed for advanced services (entry barriers rising)
- (–) [accountability] → incident investigations start tracing failures to edge-node timing faults rather than driver error (liability shifting)
- (–) [security] → regulators treat time-sync spoofing and latency attacks as transport-safety events (new attack surface acknowledged)
- (–) [labor] → remote assistance centers absorb more control authority from local operating staff (coordination power centralizing)

**ART 01.003 — Edge AI for Sensor Data****Score:** 10 (Impact in GVN 1)**Justification (4 sentences):**

Edge AI materially changes passenger transport because safety-critical perception and anomaly detection can happen on vehicles, at stops, and inside infrastructure without needing to stream everything to distant clouds. First-order effects include better collision avoidance, crowd management, accessibility assistance, and predictive maintenance; second-order effects include reduced dependence on centralized expertise but increased dependence on proprietary models and specialized chips; third-order effects include normalization of pervasive machine judgement in streets and stations. In a 5.5M-person society, if deployed across fleets and major transport nodes, this can clearly affect the weekly travel experience of hundreds of thousands while shifting annual safety, delay, and labor costs into the >€1B order of magnitude. Negative pathways are also large—false detections, biased intervention, and silent model failures—so the score captures high magnitude rather than unqualified benefit.

**Weak signals (9):**

- (+) [safety] → new buses, trams, and shuttles ship with on-board AI event detection rather than cloud-only video review (reaction loop localizing)
- (+) [station operations] → crowding and fall-detection systems at platforms move to on-camera processing with real-time alerts (faster intervention possible)
- (+) [accessibility] → vehicles add local speech/vision assistance for blind, deaf, and cognitively impaired passengers (support becoming ambient)
- (+) [maintenance] → depots use edge models to flag brake, door, tire, and suspension anomalies before scheduled inspections (downtime shifting earlier)



- (+) [privacy] → procurement language explicitly prefers on-device inference over raw video retention (social license improving)
- (–) [fairness] → complaints and audits begin targeting biased detections of loitering, fare evasion, or suspicious behavior (machine judgement contested)
- (–) [liability] → insurers require model version logs and edge inference traces after incidents (forensic burden rising)
- (–) [labor] → station staffing models are cut on the assumption that edge AI can replace observation roles (human presence thinning)
- (–) [security] → adversarial-signal or sensor spoofing incidents are logged as transport-safety events (new failure mode exposed)

## ART 01.004 — Quantum & High-Precision Sensing

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

The strongest passenger-transport pathway is precise positioning and inertial sensing where GNSS is unreliable, spoofed, or unavailable: tunnels, dense urban canyons, bad weather, and underground systems. That can improve safety margins, mapping accuracy, and continuity of service for autonomous and highly automated operations, but the effect is concentrated in specific modes and locations rather than system-wide. The plausible magnitude is therefore material but not transformative for the whole GVN.

**Weak signals (5):**

- (+) [navigation resilience] → metro, tunnel, and urban-autonomy pilots begin specifying GNSS-denied positioning performance in procurements (positioning risk prioritized)
  - (+) [safety certification] → regulators accept ultra-stable inertial references as redundancy for driverless operations (assurance stack broadening)
  - (+) [insurance] → premiums fall for fleets with certified spoof-resistant navigation packages (risk becoming quantifiable)
  - (–) [cost structure] → only premium fleets and critical corridors adopt high-precision sensing packages (benefit staying concentrated)
  - (–) [maintenance capability] → transport agencies create specialist calibration contracts for precision sensors (skills bottleneck appearing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 — Micro/Nano Sensor Networks

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

Dense low-cost sensor networks can make roads, bridges, platforms, depots, and vehicles far

more observable, reducing surprise failures and improving comfort and punctuality. The main impact is through maintenance, capacity management, and safety assurance rather than through a direct change in the passenger's travel mode. That points to a material but sub-transformative effect in the rubric.

#### **Weak signals (6):**

- (+) [infrastructure reliability] → bridges, tram tracks, and station structures get many-point strain and vibration monitoring rather than periodic manual checks (failure visibility increasing)
  - (+) [comfort] → fleet managers monitor seat vibration, cabin noise, and thermal gradients at many points inside vehicles (quality becoming granular)
  - (+) [capacity use] → micro-sensors start tracking queue build-up at escalators, gates, and curb zones (bottlenecks becoming measurable)
  - (+) [winter operations] → dense surface sensors are embedded in priority sidewalks, bike lanes, and bus stops (hazard response speeding up)
  - (–) [data overload] → operators procure new filtering layers because raw transport sensor data becomes unmanageable (action bottleneck shifting)
  - (–) [public acceptance] → municipalities face objections to invisible sensing in public space without visible notice (legibility problem surfacing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 01.006 — Privacy-Preserving Pervasive Sensing**

**Score:** 5 (Impact in GVN 1)

#### **Justification (4 sentences):**

Passenger transport increasingly depends on sensing people, vehicles, and infrastructure, but many useful applications are blocked by privacy, legal, and legitimacy constraints. Privacy-preserving sensing can unlock occupancy management, safety monitoring, accessibility assistance, and service optimization without centralizing raw personal data, while also shifting bargaining power toward actors that control the privacy stack and compliance rules. Third-order effects are substantial: if trusted sensing becomes normal, operators can optimize much more of the system in real time, but if poorly governed it can still normalize ubiquitous surveillance under a “privacy-safe” label. That supports a 5 rather than 3 because the institutional unlocking effect can plausibly move hundreds of millions of euros and large numbers of passenger-hours.

#### **Weak signals (9):**

- (+) [public trust] → transport agencies approve sensor projects only when vendors can prove on-device anonymization by design (privacy becoming procurement gate)

- (+) [service optimization] → occupancy, crowding, and dwell-time dashboards use aggregate outputs instead of raw video archives (data minimization operationalized)
- (+) [accessibility] → stations deploy local fall-detection and assistance triggers without storing identifiable imagery (support without raw retention)
- (+) [regulation] → transport regulators publish approved privacy patterns for station and vehicle sensing (compliance pathway clarifying)
- (+) [cross-border mobility] → MaaS services advertise privacy-preserving analytics as a condition for data-sharing partnerships (trust enabling interoperability)
- (–) [accountability] → safety investigators complain that privacy-minimized systems leave too little raw evidence after incidents (forensics trade-off surfacing)
- (–) [market power] → a few certified privacy-tech vendors become mandatory intermediaries for public-space sensing (control layer consolidating)
- (–) [labor relations] → unions challenge “privacy-safe” worker monitoring in depots and on vehicles (surveillance conflict persisting)
- (–) [social legitimacy] → civil society groups argue that aggregate sensing still expands behavioral control in public space (function creep debated)

## ART 01.007 — Quantum-Resilient and Secure Communication Networks

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

This ART matters in passenger transport mainly by protecting long-lived fleet, identity, payment, and infrastructure-control data as mobility systems become more software-defined and remotely managed. The effect is meaningful for trust and continuity, but most benefits come through reduced systemic risk rather than through visible changes in travel quality. That keeps the score in material-but-not-transformative territory for this GVN.

**Weak signals (6):**

- (+) [fleet cybersecurity] → transport control upgrades start requiring post-quantum cryptography in routers, depots, and chargers (long-lived control channels hardening)
  - (+) [ticketing and identity] → fare systems begin rotating to crypto-agile credential schemes with formal migration plans (future-proofing starting)
  - (+) [public procurement] → rail and metro contracts ask for quantum-resilient update paths over multidecade asset lives (lifecycle security valued)
  - (–) [cost and interoperability] → smaller operators delay upgrades because secure hardware and certification costs rise (security divide widening)
  - (–) [incident response] → regulators warn that algorithm migrations are creating temporary incompatibilities across mobility systems (transition fragility emerging)
  - (–) [governance] → suppliers use proprietary security stacks that reduce operator auditability (trust shifting to vendors)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 — Integrated Sensing and Communication (ISAC)

**Score:** 10 (Impact in GVN 1)

**Justification (4 sentences):**

ISAC can turn communication infrastructure along roads, stops, stations, and depots into a shared sensing layer, materially improving awareness of moving objects, crowd conditions, and corridor status without deploying entirely separate sensor stacks. First-order effects include safer vehicle movements, better traffic management, and improved support for automation; second-order effects include a shift of situational awareness power toward network operators and equipment vendors; third-order effects include denser rule-based management of public space as communication grids become ambient radar. In a 5.5M-person society, the technology can plausibly affect the weekly travel conditions of hundreds of thousands by changing how capacity, safety, and priority are managed in busy corridors, putting it in the 10 range. Risks around privacy, electromagnetic governance, and failure concentration are material but do not erase the magnitude.

**Weak signals (9):**

- (+) [street safety] → telecom and transport agencies run joint pilots where roadside communications nodes also detect near-misses (infrastructure becoming perceptive)
- (+) [autonomous operations] → driverless shuttle services use network-side object detection to extend line-of-sight beyond the vehicle (safety envelope widening)
- (+) [junction efficiency] → intersections start using shared radio sensing to allocate signal phases dynamically (flow control improving)
- (+) [station operations] → platforms use communication nodes to track crowd motion without dense camera build-outs (coverage cost dropping)
- (+) [winter reliability] → ISAC deployments begin advertising weather-robust detection compared with camera-only stacks (sensor diversity valued)
- (–) [privacy] → civil-liberty complaints target telecom infrastructure that now also tracks movement in public space (surveillance boundary blurring)
- (–) [governance] → disputes emerge over whether mobility agencies or network operators control corridor sensing outputs (institutional control contested)
- (–) [security] → spoofing or denial incidents against shared comms-sensing nodes are treated as transport-safety threats (dual-use risk recognized)
- (–) [equity] → high-density corridors receive ambient sensing upgrades first while peripheral areas lag (service quality diverging)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 — Compute-in-Memory & Neuromorphic Chips

**Score:** 5 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport increasingly depends on perception, anomaly detection, and local decision-making at the vehicle and infrastructure edge, where power, heat, and cost are tight constraints.

Compute-in-memory and neuromorphic chips can materially reduce those constraints, enabling richer always-on sensing in small vehicles, stations, curb equipment, and battery-powered accessibility devices. Second-order effects include lower dependence on remote clouds and fewer bandwidth bottlenecks, but also stronger dependence on specialized chip vendors and proprietary toolchains; third-order effects include wider deployment of machine judgement because the unit economics improve. That supports a 5-level impact: important and potentially system-shaping, but still one layer beneath the actual transport-service transformation.

#### **Weak signals (9):**

- (+) [autonomous fleet economics] → shuttle and delivery-platform procurements begin specifying low-power neuromorphic perception modules (edge cost dropping)
- (+) [battery range] → electric microtransit vehicles advertise safety/perception improvements without noticeable range penalties (compute energy shrinking)
- (+) [station safety] → platform and crossing equipment moves from cloud video analytics to always-on local event chips (latency and cost improving)
- (+) [accessibility devices] → wheelchairs, mobility scooters, and assistive station tools gain onboard hazard detection without daily charging burdens (assistive autonomy widening)
- (+) [maintenance] → compact edge devices in depots run continuous vibration and fault detection instead of bursty uploads (monitoring becoming persistent)
- (–) [vendor power] → a small set of chip-toolchain suppliers becomes embedded in fleet certification pathways (stack lock-in growing)
- (–) [auditability] → operators struggle to explain event-driven decisions from unfamiliar hardware architectures after incidents (forensics gap opening)
- (–) [skills] → transport tech hiring shifts toward rare accelerator-specific engineering skills (capability concentration increasing)
- (–) [security] → regulators start treating on-chip model tampering as a safety-relevant fleet risk (hardware trust boundary moving)

## **ART 02.010 — Novel transistor technologies and materials beyond silicon CMOS**

**Score:** 3 (Impact in GVN 1)

#### **Justification (3 sentences):**

More efficient and heat-tolerant device technologies would improve EV power electronics, sensor modules, chargers, and onboard compute across passenger transport. The impact is real but diffuse: it mainly improves the performance envelope and reliability of other transport technologies rather than creating a distinct new mobility model by itself. That fits the material-but-not-transformative anchor.

#### **Weak signals (6):**

- (+) [vehicle electronics] → new traction, sensing, and control modules advertise far lower heat loads and smaller cooling systems (packaging constraints easing)
- (+) [charging infrastructure] → fast chargers shrink in footprint or noise because power electronics run hotter and more efficiently (site economics improving)
- (+) [autonomy hardware] → perception/control units move closer to sensors in small vehicles and roadside equipment (compute placement changing)

- (+) [fleet uptime] → operators cite electronics lifetime gains in harsh weather or vibration-heavy duty cycles (reliability becoming bankable)
- (–) [supply chain] → transport OEMs face dependence on immature specialist fabrication ecosystems (component risk concentrating)
- (–) [cost] → premium fleets adopt first while mass transit procurement waits for standardized modules (benefits arriving unevenly)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 — Quantum Computing Platforms

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

The clearest passenger-transport pathway is high-end optimization: timetable design, multimodal assignment, fleet charging, pricing, and network planning under many constraints. That could create concrete savings for large operators, but the benefit remains indirect and contingent on very specific problem classes rather than on everyday service delivery. The linkage is therefore worth watching but limited in total magnitude for this GVN.

**Weak signals (4):**

- (+) [network planning] → large mobility operators begin buying quantum-optimization services for schedules, pricing, or depot charging (niche compute entering operations)
- (+) [public procurement] → transit agencies issue challenge tenders for combinatorial planning tasks framed as quantum-suitable (problem framing shifting)
- (–) [market structure] → only top-tier platforms can afford quantum access for planning advantages (optimization power concentrating)
- (–) [evidence quality] → transport pilots report no clear advantage over improved classical solvers (linkage remaining narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 — Photonic and Optical Computing

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Optical computing mainly affects passenger transport through cheaper or faster backend processing for simulation, mapping, demand forecasting, and large-scale AI training. Those gains matter to major mobility platforms and infrastructure operators, but they are one step removed from how passengers actually move. The likely impact is therefore concrete but limited.

**Weak signals (4):**

- (+) [mobility platforms] → large routing and mapping providers cite optical accelerators in traffic and demand modeling stacks (backend bottleneck shifting)
- (+) [autonomy development] → simulation farms for driverless systems adopt photonic hardware to cut training or validation times (testing throughput rising)



- (–) [operator access] → benefits stay concentrated in cloud vendors rather than public transport operators (capability centralizing)
  - (–) [service outcomes] → mobility KPIs improve only marginally despite major compute upgrades (translation to operations weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 — Next-Gen Memory & Storage

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Passenger transport generates large stores of maps, sensor logs, maintenance histories, and digital-twin states, so better memory/storage can reduce latency and retention costs. Still, the effect is mostly enabling and back-office rather than a direct change in mobility service design. That keeps the impact in the “worth considering but limited” band.

**Weak signals (4):**

- (+) [incident forensics] → fleets retain far longer high-resolution event histories because storage costs fall (evidence retention expanding)
  - (+) [digital twins] → operators keep live asset histories in place rather than archiving them offline (operational memory deepening)
  - (–) [privacy] → longer retention of passenger and vehicle traces triggers new data-minimization disputes (data stockpiles enlarging)
  - (–) [vendor lock-in] → specialized storage stacks become embedded in safety and maintenance software contracts (back-end dependence rising)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 — Molecular Computing

**Score:** 0 (Impact in GVN 1)

**Justification (3 sentences):**

No robust passenger-transport pathway is yet clear beyond very niche sensing or chemical-control uses in environments that are already better served by electronics. Even in a mature state, the technology does not obviously change the core operating model of moving people or a major value bottleneck in this GVN. For now the sensible stance is watchfulness rather than active weighting.

**Weak signals (4):**

- (+) [cabin air quality] → transport OEMs begin testing molecular-computing cartridges for onboard contamination detection and response (would create direct vehicle linkage)
  - (+) [fuel/chemical handling] → depots pilot molecular controllers in hydrogen or synthetic-fuel process safety systems (would create infrastructure linkage)
  - (–) [deployment evidence] → transport use cases remain confined to lab demonstrations rather than fielded assets (linkage still missing)
  - (–) [procurement] → no transit or shared-mobility tenders mention molecular computing as a required capability (demand absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 — Causal Learning & Reasoning

**Score:** 5 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport decisions are full of intervention questions—what happens if pricing changes, curb space is reallocated, a route is shortened, a signal plan is altered, or a safety rule is tightened. Causal learning can materially improve those decisions by reducing reliance on simple correlations, with first-order benefits in routing, pricing, safety policy, and network design; second-order effects in more defensible regulation and performance contracts; and third-order effects in more aggressive experimentation because impacts become easier to model and justify. In a 5.5M-person society that can plausibly move hundreds of millions of euros and tens to hundreds of millions of passenger-hours through better allocation and fewer policy mistakes. The score stops at 5 because causal reasoning is an important decision layer, not the transport regime shift itself.

**Weak signals (9):**

- (+) [network planning] → transport agencies start requiring counterfactual analysis for route cuts, fare changes, and curb reallocation (policy learning maturing)
- (+) [safety] → incident review systems move from descriptive dashboards to causal attribution models (intervention logic strengthening)
- (+) [MaaS pricing] → platforms advertise “what-if” engines that simulate demand and equity effects before price changes (pricing becoming intervention-aware)
- (+) [public legitimacy] → congestion and parking reforms are accompanied by publishable causal assumptions and sensitivity tests (policy contestability improving)
- (+) [operations] → control centers compare causal effects of bus priority, holding, and rerouting rather than chasing simple punctuality correlations (decision quality rising)
- (–) [accountability] → disputes focus on hidden assumptions in operator-owned causal models rather than on raw performance data alone (model politics deepening)
- (–) [equity] → vulnerable neighborhoods contest models that systematically undervalue indirect trip benefits (distributional blind spots surfacing)
- (–) [market power] → a few software vendors become trusted arbiters of “credible” mobility interventions (epistemic control concentrating)
- (–) [regulation] → authorities warn that causal-model outputs are being treated as automatic approval rather than expert support (decision laundering risk)

#### ART 03.016 — Federated & Privacy-Preserving Learning

**Score:** 5 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport data is fragmented across operators, municipalities, fleet OEMs, payment systems, mapping firms, and passenger devices, which blocks many useful learning loops. Federated and privacy-preserving learning can unlock shared safety, maintenance, demand, and accessibility models without pooling all raw data, materially improving system-wide learning while reducing some privacy and contractual friction. Second-order effects include new model-governance institutions and shared infrastructure providers; third-order effects include a winner-takes-most dynamic if one party controls the training stack and standard model updates. That puts

the likely impact in the significant-but-not-keystone range.

**Weak signals (9):**

- (+) [safety learning] → multiple fleet operators join shared model-training consortia without centralizing raw vehicle or passenger data (cross-operator learning unlocking)
- (+) [public transport] → cities require local retention of passenger data while still participating in regional demand-model updates (governance compromise emerging)
- (+) [maintenance] → OEMs and operators co-train fault models across many depots through federated pipelines (failure knowledge scaling)
- (+) [accessibility] → personal mobility devices and apps adapt locally while contributing privacy-protected updates to shared assistive models (local personalization broadening)
- (+) [regulation] → privacy authorities publish accepted templates for federated mobility analytics (legal certainty improving)
- (–) [market structure] → the entity hosting aggregation servers becomes the de facto control point for model performance and access (stack power centralizing)
- (–) [quality] → smaller operators complain that dominant fleets shape the shared model toward their operating conditions (bias from participation imbalance)
- (–) [labor] → unions challenge local worker data being used to improve supra-regional productivity models (employment surveillance concerns)
- (–) [security] → poisoning or model-inversion incidents are treated as transport-system integrity failures (new collaborative risk exposed)

## ART 03.017 — Trustworthy AI Systems

**Score:** 10 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport becomes structurally different once AI is trusted with safety-critical perception, routing, pricing, incident response, and accessibility assistance at scale. Trustworthy AI systems matter not just operationally but institutionally: they can lower regulatory hesitation, insurance premia, and public resistance by making automated decisions auditable, bounded, and reviewable, while also shifting power toward actors that control certification and assurance pipelines. Third-order effects are large because trustworthiness tooling can determine which operators, cities, and vendors are allowed to deploy advanced mobility functions at all. In a 5.5M-person society that is plausibly a >€1B and everyday-life scale effect, but still one layer below the keystone technology of driverless mobility itself, so 10 rather than 20.

**Weak signals (9):**

- (+) [autonomous deployment] → regulators require formal AI safety cases, fallback logic, and audit logs in mobility permits (assurance becoming gatekeeper)
- (+) [insurance] → insurers price autonomy and advanced driver-assist systems partly on documented monitoring and rollback capabilities (trust monetized)
- (+) [public transport] → transit agencies buy AI systems only with confidence indicators, human escalation paths, and provenance tracing (black-box tolerance falling)
- (+) [accessibility] → passenger-facing AI assistants are certified against explicit fairness and usability criteria (trust extending beyond safety)
- (+) [operations] → fleets adopt automatic safe-mode or human-review triggers when model uncertainty spikes (self-monitoring operationalized)

- (–) [market power] → a handful of approved assurance vendors become mandatory intermediaries for deployment (certification bottleneck forming)
- (–) [liability] → post-incident disputes hinge on whether the AI stayed inside its approved operating envelope (responsibility becoming formalized)
- (–) [labor] → operators use “trustworthy AI” branding to remove local discretion from drivers, dispatchers, or station staff (control centralizing)
- (–) [equity] → advocacy groups challenge whether “acceptable risk” thresholds differ across neighborhoods or user groups (fairness politics intensifying)

## ART 03.018 — Automated Machine Learning (AutoML)

**Score:** 5 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport depends on many prediction and control models that smaller operators and public agencies struggle to build and maintain consistently. AutoML can materially lower that specialist bottleneck across demand forecasting, maintenance, dispatch, accessibility, pricing, and incident triage, with second-order effects in vendor dependence and faster model churn. Third-order effects include more experimental and adaptive service management, but also more silent optimization of labor and passengers if objectives are poorly specified. That supports a 5: significant operational and institutional impact, but not a keystone shift on its own.

**Weak signals (9):**

- (+) [small-operator capability] → regional and municipal operators begin shipping production ML models without expanding in-house data-science teams (specialist bottleneck easing)
- (+) [service experimentation] → route, fare, and dispatch models are retrained frequently as a standard operating practice (adaptation speeding up)
- (+) [maintenance] → AutoML systems generate and deploy fault predictors across mixed fleets and depots from common telemetry feeds (model supply industrializing)
- (+) [MaaS competition] → platforms market configurable “mobility optimization factories” to smaller cities and operators (advanced analytics commodifying)
- (+) [governance] → procurement templates start demanding rollback and benchmarking features for automatically generated models (oversight catching up)
- (–) [labor] → workforce scheduling, performance scoring, or customer-priority models are deployed with little local scrutiny (optimization spilling into work control)
- (–) [safety] → authorities flag reward functions that optimize punctuality or utilization at the expense of comfort or risk margins (objective misspecification visible)
- (–) [market structure] → operators become dependent on a few AutoML platforms whose hidden defaults shape mobility choices (algorithmic dependence deepening)
- (–) [accountability] → incident investigations show no one can explain why a generated model dominated a dispatch or pricing decision (responsibility thinning)

## ART 03.019 — Collaborative Multi-Agent AI

**Score:** 10 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport is inherently multi-agent: vehicles, signals, stations, depots, chargers, dispatchers, passengers, and increasingly robots all need to coordinate under changing conditions.

Collaborative multi-agent AI can transform this coordination layer by enabling fleets and infrastructure to allocate tasks, share observations, and adapt jointly in real time, with first-order gains in throughput, waiting times, and disruption management. Second-order effects include centralization of operational control and new dependencies on common maps, communications, and safety protocols; third-order effects include much denser choreography of shared urban space than today's human-managed system allows. That is large enough to change how the GVN goal is realized, but it remains an enabler of broader autonomy and MaaS rather than the single indispensable linchpin.

#### **Weak signals (9):**

- (+) [traffic coordination] → fleets, signals, and curb systems begin exchanging machine-readable task and priority messages rather than isolated commands (coordination layer thickening)
- (+) [public transport reliability] → buses, trams, and feeder shuttles dynamically reassign holding, rerouting, and transfer-protection roles among themselves (joint strategy emerging)
- (+) [depot operations] → chargers, maintenance bots, and vehicles schedule themselves through shared task queues (infrastructure acting collectively)
- (+) [disruption response] → control centers supervise many semi-autonomous agents instead of micromanaging each asset (human role abstracting upward)
- (+) [accessibility] → passenger assistance agents coordinate elevators, vehicles, staff, and wayfinding services across the trip chain (service continuity improving)
- (–) [failure concentration] → a shared coordination protocol fault causes cascading service disruption across many assets (systemic coupling visible)
- (–) [labor] → dispatch roles shrink or consolidate as software agents negotiate assignments directly (coordination labor displaced)
- (–) [governance] → cities struggle to allocate priority when privately operated agents and public services share the same control layer (rule conflicts intensifying)
- (–) [security] → regulators classify spoofed agent-to-agent messages as critical transport-safety incidents (attack surface multiplying)

## **ART 03.020 — Quantum-Accelerated AI Systems**

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

The passenger-transport relevance is mainly a narrow extension of already indirect AI optimization use cases: route planning, resource allocation, or parameter search that happen in back-end systems. Even if useful for a few computationally hard problems, it does not obviously reshape how people are moved in most contexts. The linkage is therefore concrete but limited.

#### **Weak signals (4):**

- (+) [mobility platforms] → vendors market quantum-enhanced route or charging optimizers to major operators (niche premium tooling appearing)
- (+) [R&D] → driverless-system developers use quantum routines for complex planning subproblems in simulation (backend experimentation starting)
- (–) [evidence] → transport buyers see little performance gain over advanced classical AI stacks (incremental value staying uncertain)

- (–) [access] → benefits accrue only to operators with premium compute budgets (capability inequality widening)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 — AI-Driven Autonomous Scientific Discovery

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Its main impact on passenger transport would come through faster discovery of better batteries, materials, safety models, and traffic-control methods rather than direct use in mobility services. That can matter over time, but it is too indirect to dominate this GVN's operating model on its own. The score therefore stays at 1.

**Weak signals (4):**

- (+) [transport R&D] → OEMs and infrastructure agencies cite autonomous-discovery systems in battery, coating, or sensor procurement breakthroughs (indirect innovation channel opening)
- (+) [public programs] → transport innovation funds start buying AI-generated experiment pipelines for mobility materials and safety research (research workflow shifting)
- (–) [adoption chain] → promising discoveries do not translate into certified vehicle or infrastructure deployments (innovation pipeline gap persisting)
- (–) [market power] → a few firms control the discovery platforms feeding critical mobility technologies (upstream dependency concentrating)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 — Immersive Augmented & Virtual Reality

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

Immersive AR/VR can materially improve transport worker training, remote support, passenger wayfinding, station design, and rehearsal of disruptions or autonomous-service rollouts. Those benefits touch safety, accessibility, and maintenance quality, but they improve surrounding workflows more than they directly change the transport regime itself. That places the impact at a material but not transformative level.

**Weak signals (6):**

- (+) [skills bottleneck] → depots and control rooms replace parts of classroom training with VR rehearsals for incidents and new vehicle types (training throughput rising)
- (+) [maintenance] → field staff receive remote AR guidance for repairs on stations, elevators, and vehicles (expert presence virtualizing)
- (+) [passenger accessibility] → complex hubs begin offering AR indoor navigation for low-vision or cognitively impaired travelers (wayfinding becoming adaptive)
- (+) [planning] → cities and operators use shared immersive twins to test curb, stop, and station redesigns before construction (design-risk dropping)



- (–) [labor] → management uses immersive tools to centralize supervision instead of keeping local technical staff (control recentralizing)
  - (–) [equity] → premium passenger experiences get immersive overlays while basic accessibility improvements lag (attention skew emerging)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.023 — Brain-Computer Interfaces (BCI)

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

BCIs have a concrete but limited transport linkage through accessibility: they could help some passengers with severe motor impairments book, navigate, or use mobility services more independently. There is also a narrower pathway in hands-free control and monitoring for operators or teleoperators, but that is unlikely to scale broadly across passenger transport. The likely impact is therefore meaningful for a small population rather than system-wide.

**Weak signals (4):**

- (+) [accessibility] → mobility apps and ticketing systems begin supporting BCI-mediated input for users with severe motor impairment (independence channel opening)
  - (+) [paratransit] → public disability-transport programs fund BCI-compatible ride-request and wayfinding pilots (service inclusion widening)
  - (–) [privacy] → transport providers face objections to handling neural data in access-control or assistance systems (sensitive-data barrier rising)
  - (–) [cost] → BCI-enabled mobility support remains confined to specialized clinical or subsidy programs (scaling staying narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 — Advanced Prosthetics & Exoskeletons

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

The main passenger-transport relevance is improved mobility and participation for travelers and workers with reduced strength or limb function, plus worker support in maintenance and station operations. Those are valuable inclusion and labor effects, but they are not large enough to reshape the dominant operating model of moving people. The impact is concrete yet limited.

**Weak signals (4):**

- (+) [accessibility] → transport operators redesign vehicle boarding, seating, and charging spaces around advanced prosthetic and exosuit users (mobility norms broadening)
  - (+) [workforce] → depots and station services procure exosuits for lifting, cleaning, and repetitive maintenance tasks (injury risk shifting)
  - (–) [equity] → mobility benefits depend heavily on reimbursement and employer support rather than universal design (access remaining uneven)
  - (–) [service design] → operators substitute device-based access assumptions for broader barrier removal in infrastructure (inclusion burden privatizing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 — Haptic and Multi-Sensory Feedback Systems

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Richer haptic feedback could improve teleoperation fallback, accessibility interfaces, and navigation support for passengers in noisy or visually complex environments. The applications are real, but they are mostly niche layers on top of broader autonomy or accessibility systems rather than standalone transport transformations. That keeps the score at 1.

**Weak signals (4):**

- (+) [remote control] → teleoperation centers add force or tactile feedback for low-speed vehicle exception handling (human fallback improving)
  - (+) [accessibility] → navigation tools for blind and deafblind passengers adopt richer haptic guidance in stations and interchanges (wayfinding channel widening)
  - (–) [procurement] → transport agencies treat advanced haptics as optional add-ons rather than standard service elements (uptake remaining selective)
  - (–) [labor and safety] → operators discover that haptic systems need significant training and create new failure modes under stress (benefit staying bounded)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 — AI Understanding of Human Intent & Context

**Score:** 5 (Impact in GVN 1)

**Justification (4 sentences):**

Passenger transport involves constant interpretation of human intent: pedestrians about to cross, riders trying to board, anxious passengers needing assistance, crowds shifting under disruption, and people whose needs are not captured by simple commands. AI that can infer intent and context can materially improve safety and accessibility in both conventional and autonomous systems, while also changing the balance of attention between humans and machines. Second-order effects include more personalized services and more behavioral profiling; third-order effects include stronger sorting, nudging, and surveillance power in shared public space. The magnitude is significant because better intent/context inference can change accident rates, boarding friction, and service access across large user populations, but it is still an important enabling layer rather than the regime keystone.

**Weak signals (9):**

- (+) [street safety] → vehicle and roadside systems begin using pedestrian-intent prediction in certified safety functions (human behavior entering control loops)
- (+) [accessibility] → stations deploy assistants that infer confusion, missed transfers, or distress and offer help without explicit requests (support becoming anticipatory)
- (+) [public transport flow] → boarding, dwell, and crowd management systems start reacting to inferred passenger goals rather than simple counts (service adapting socially)
- (+) [shared mobility] → ride-pooling and pickup systems detect likely no-shows, wrong-side waiting, or family/group intent patterns (friction at curb dropping)
- (+) [customer service] → multimodal apps route users differently based on inferred mobility constraints or stress signals (journeys becoming context-aware)

- (–) [privacy] → operators face pushback over inference from gaze, voice, posture, and device signals in public-space mobility services (behavioral surveillance concern)
- (–) [fairness] → audits find intent models misread children, elderly users, migrants, or disabled travelers (context inference bias surfacing)
- (–) [labor] → frontline staff discretion is reduced because systems pre-classify passenger needs and risk levels (human judgement displaced)
- (–) [liability] → incident reviews focus on whether the system should have inferred intent earlier (expectations of machine interpretation rising)

## ART 04.027 — Brain-to-Brain Interfaces

**Score:** 0 (Impact in GVN 1)

**Justification (3 sentences):**

No strong passenger-transport pathway is presently visible beyond highly speculative coordination or accessibility use cases. Even if BBIs mature technically, they do not naturally address a major bottleneck in how passenger transport systems are organized. The technology is therefore outside the meaningful near-term weighting set for this GVN.

**Weak signals (4):**

- (+) [specialized accessibility] → transport services begin funding BBI-mediated communication for users unable to use speech or conventional input (would create narrow direct linkage)
  - (+) [control rooms] → experimental high-stress coordination settings test BBIs for team synchronization in transport operations (would create professional linkage)
  - (–) [deployment evidence] → no transport tenders mention BBI capability or interface support (demand absent)
  - (–) [ethics and privacy] → transport authorities explicitly exclude neural-sharing systems from mobility service pilots (social license missing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 — Memory Prostheses

**Score:** 0 (Impact in GVN 1)

**Justification (3 sentences):**

Memory prostheses could change some individuals' ability to navigate and live independently, but there is no strong system-level passenger-transport pathway beyond that general social effect. The technology does not target a transport bottleneck or core operating model directly. It therefore remains outside the meaningful impact set for this assessment.

**Weak signals (4):**

- (+) [independent travel] → transport accessibility services begin supporting users with neural memory aids in trip planning and wayfinding (would create direct inclusion linkage)
- (+) [driver licensing] → regulators consider whether memory prostheses alter eligibility for certain supervised mobility roles (would create governance linkage)
- (–) [system design] → mobility planning continues to assume conventional accessibility aids rather than neuroprosthetic support (transport linkage absent)

- (–) [market uptake] → no major passenger-transport operator adapts services around memory-prosthesis users (impact channel not forming)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 — Self-Driving Vehicles

**Score:** 20 (Impact in GVN 1)

**Justification (4 sentences):**

Self-driving vehicles are the clearest direct challenger-regime technology in this GVN because they can fundamentally change who provides passenger transport, how vehicles are utilized, how road space is allocated, and whether private car ownership remains the dominant means of access. First-order effects are major shifts in safety, travel time use, labor demand, cost structures, and accessibility for non-drivers; second-order effects include platform concentration, new liability and insurance regimes, labor displacement, and new forms of surveillance and remote control; third-order effects include land-use change, rebound traffic from deadheading or induced demand, and redefinition of driving as a skill and status marker. In a 5.5M-person society this comfortably exceeds the >€1B / hundreds-of-thousands-in-weekly-life threshold and is a direct candidate for changing how the GVN goal is realized. It is therefore a keystone rather than merely a strong enabler.

**Weak signals (10):**

- (+) [operating model] → driverless passenger services expand from pilots to recurring commercial routes without onboard safety staff (regime shift entering operations)
- (+) [cost structure] → providers begin pricing rides on the assumption of no full-time human driver cost (economics crossing threshold)
- (+) [accessibility] → services for children, elderly people, and non-drivers move from escorted exceptions to standard products (inclusion broadening structurally)
- (+) [asset utilization] → fleets increase daily vehicle-use hours well beyond private-car norms (underutilization bottleneck breaking)
- (+) [urban form] → cities convert parking and pickup space because persistent private-car storage demand falls (land use responding)
- (–) [labor] → unions and social partners negotiate large transition packages for displaced drivers and dispatch staff (labor shock becoming real)
- (–) [congestion] → regulators begin measuring or taxing empty repositioning kilometers from autonomous fleets (deadheading externality materializing)
- (–) [liability] → insurance and court cases shift from driver negligence toward software, operator, and map-provider responsibility (accountability relocating)
- (–) [market power] → a small number of fleet-platform operators gain leverage over access, routing, and data (mobility control concentrating)
- (–) [social acceptance] → neighborhoods or municipalities selectively resist driverless deployments despite national approval (spatial legitimacy becoming uneven)

## ART 05.030 — Drone Swarms & Aerial Robots

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

For passenger transport, the main impact is not flying passengers but improving inspection, mapping, incident response, and possibly temporary connectivity or traffic observation around transport corridors. That can materially improve safety, maintenance speed, and disruption handling, but it remains a support layer rather than a dominant way of moving people. The overall impact is therefore material but bounded.

**Weak signals (6):**

- (+) [infrastructure maintenance] → road, rail, and bridge operators move from periodic visual inspections to frequent autonomous aerial inspections (inspection cycle compressing)
- (+) [disruption response] → control centers routinely dispatch drone fleets to assess crashes, floods, and corridor blockages before crews arrive (situational awareness accelerating)
- (+) [rural reliability] → sparsely populated routes gain low-cost aerial monitoring of stops, crossings, and snow/ice conditions (coverage cost falling)
- (–) [airspace governance] → transport and aviation authorities create no-fly and priority rules around busy passenger hubs (space conflicts formalizing)
- (–) [privacy] → complaints rise over persistent aerial monitoring of roads, stations, and passengers (surveillance legitimacy weakening)
- (–) [security] → drone interference or spoofing is treated as a transport safety issue around major nodes (dual-use exposure rising)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.031 — Humanoid and General-Purpose Robots

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Humanoid and general-purpose robots are relevant mainly for station services, cleaning, routine maintenance, accessibility assistance, and depot work in spaces built for people. Those functions matter to cost and service quality, but they do not directly change the core mobility regime in most passenger transport settings. The score is therefore limited.

**Weak signals (4):**

- (+) [station operations] → transport hubs start procuring general-purpose robots for cleaning, inspection, and passenger assistance in existing facilities (human-space automation rising)
- (+) [service continuity] → smaller depots use remotely supervised robots to cover irregular maintenance shifts (labor scarcity workaround appearing)
- (–) [labor] → staff negotiations focus on robot substitution in customer-facing and maintenance roles (task displacement concern growing)
- (–) [safety] → regulators impose strict speed and force limits that confine robots to low-value tasks (impact remaining narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.032 — Soft Robotics & Bio-Inspired Machines

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Soft robots matter in passenger transport mainly for delicate cleaning, inspection, and handling tasks where rigid machines are awkward or unsafe. That may reduce maintenance costs and improve safety in constrained spaces, but it is not close to a core mobility-system driver. The impact is concrete but small.

**Weak signals (4):**

- (+) [maintenance safety] → operators pilot soft robots for cleaning and inspecting under seats, wheel wells, ducts, or tight infrastructure cavities (awkward tasks automating)
  - (+) [asset care] → transport interiors and sensitive components are serviced by compliant robots to reduce accidental damage (delicate handling valued)
  - (–) [deployment scale] → use remains confined to specialized maintenance vendors rather than mainstream fleet operations (linkage staying niche)
  - (–) [economics] → transport buyers treat soft robots as premium tools with weak payback outside narrow cases (scale threshold unmet)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 — Fully Autonomous Drones, Robots & Underwater Vehicles

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

This ART matters to passenger transport through inspection and intervention in hard-to-reach or hazardous infrastructure: tunnels, bridges, ferries, ports, drainage, embankments, and remote corridors. Better continuous monitoring and faster repair can materially improve safety and uptime, especially where human access is slow or risky. The impact is important but still supportive rather than regime-defining.

**Weak signals (6):**

- (+) [asset reliability] → transport authorities shift hazardous inspections of tunnels, bridge undersides, ferry hulls, and drainage systems to autonomous robots (human exposure dropping)
  - (+) [weather resilience] → remote corridors gain persistent robotic monitoring for landslides, flooding, snow loading, and washouts (early warning improving)
  - (+) [maintenance speed] → underwater and ground robots become standard in port, ferry, and bridge maintenance contracts (repair logistics changing)
  - (–) [governance] → service rules differentiate between autonomous infrastructure robots and passenger-facing autonomy (regulatory segmentation appearing)
  - (–) [security] → sabotage and spoofing concerns emerge for inspection robots working on critical transport assets (infrastructure attack surface widening)
  - (–) [market structure] → a few specialist service providers dominate robotic infrastructure inspection across regions (capability concentrating)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 05.034 — Supportive Infrastructure for Autonomy

**Score:** 10 (Impact in GVN 1)

**Justification (4 sentences):**

Autonomy-supportive infrastructure changes passenger transport by moving intelligence and legibility into streets, stations, curbs, and depots rather than expecting every vehicle or robot to solve everything alone. First-order effects are safer and cheaper deployment of driverless and robotic mobility services; second-order effects include capital-intensive retrofits, new public-private bargaining over standards and access, and the risk that upgraded corridors attract disproportionate investment; third-order effects include cities being redesigned around machine-readable, highly managed flows. In a 5.5M-person society this can affect how large parts of the network operate and what services are feasible at all, easily reaching transformative magnitude. It stays at 10 rather than 20 because autonomy can emerge through more than one pathway, even if this ART strongly accelerates and stabilizes it.

**Weak signals (9):**

- (+) [street design] → cities begin specifying machine-readable markings, localization aids, and docking interfaces in routine street renewals (environment adapting to robots)
- (+) [service feasibility] → driverless shuttle or delivery permits are tied to autonomy-ready corridors rather than generic road rights (deployment becoming place-based)
- (+) [public transport nodes] → stations and depots add standardized charging, cleaning, transfer, and machine-priority zones (robot support layers materializing)
- (+) [procurement] → infrastructure tenders require interoperability with multiple autonomy vendors instead of one-off integrations (platform neutrality becoming issue)
- (+) [safety] → shared traffic rules for robots, shuttles, and pedestrians are enforced through local coordination posts or digital beacons (mixed-use choreography formalizing)
- (–) [equity] → premium autonomy-native corridors receive upgrades first while lower-income areas keep legacy conditions (spatial inequality hardening)
- (–) [governance] → disputes intensify over whether public streets should be retrofitted for private fleet models (infrastructure politics sharpening)
- (–) [lock-in] → early corridor retrofits become optimized for one vendor's sensing or docking standard (path dependence forming)
- (–) [security] → tampering with local coordination posts or markers is treated as a safety-critical attack vector (infrastructure cyber-physical risk emerging)

## ART 05.035 — Optical/Microwave Power Beaming for Persistent Robotics

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

The main passenger-transport pathway is persistent inspection, monitoring, and emergency-response robotics around corridors and hubs. That may improve uptime and reduce servicing needs in some hard-to-reach areas, but it is a narrow support function rather than a broad transport transformation. The total impact is therefore limited.

**Weak signals (4):**

- (+) [corridor monitoring] → transport authorities pilot beamed-power support for persistent drones over bridges, tunnels, or major junctions (robot endurance constraint easing)

- (+) [incident response] → emergency aerial monitoring around critical hubs uses fixed power transmitters instead of frequent battery swaps (response persistence increasing)
  - (–) [safety regulation] → beam-exclusion rules around passengers and traffic sharply limit deployment zones (use staying constrained)
  - (–) [economics] → operators conclude batteries or wired solutions remain cheaper for most transport inspection tasks (linkage remaining niche)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 — Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Dry-adhesion systems matter mainly for inspection and repair on vertical, overhead, or delicate transport surfaces such as bridges, station roofs, train exteriors, and glazing. They can reduce scaffolding, closures, and worker exposure, but the effect is limited to specific maintenance tasks. That keeps the score at 1.

**Weak signals (4):**

- (+) [maintenance access] → operators test climbing robots on bridge pylons, noise barriers, station façades, and train exteriors (access cost dropping)
  - (+) [service continuity] → more repairs are performed without lane closures or heavy temporary fixtures (downtime burden shrinking)
  - (–) [surface limits] → performance problems on dirty, rough, or winter-exposed surfaces keep deployments narrow (environmental robustness limiting value)
  - (–) [procurement] → dry-adhesion tools appear only in specialist maintenance frameworks, not routine fleet or station contracts (adoption staying niche)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 — Multi-Material & Hybrid 3D Printing

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

The clearest passenger-transport pathway is faster production of spare parts, custom accessibility fixtures, lightweight interior modules, and low-volume specialty components. Those are useful for uptime and tailored service, but they sit well upstream of the actual transport operating model. The impact is therefore concrete yet limited.

**Weak signals (4):**

- (+) [fleet uptime] → operators print hard-to-source interior, sensor, or trim assemblies locally instead of waiting for supplier batches (spares lead times shrinking)
- (+) [accessibility] → customized handholds, boarding aids, and seating supports are fabricated per vehicle or user group (tailoring becoming cheaper)
- (–) [certification] → printed transport parts remain confined to non-critical applications because approvals lag (safety gate staying tight)

- (–) [economics] → mainstream fleet OEMs still rely on conventional mass production for most components (impact staying peripheral)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.038 — Digital Twin & Simulation-Driven Production

**Score:** 3 (Impact in GVN 1)

**Justification (3 sentences):**

Although production-focused, this ART can materially affect passenger transport by speeding vehicle, charger, and spare-part ramp-up, reducing defects, and improving resilience in the supply chain that keeps fleets operating. The benefits show up indirectly in fleet availability, maintenance quality, and cost control rather than in trip experience alone. That is enough for a material score, but not a transport-system transformation.

**Weak signals (6):**

- (+) [fleet availability] → vehicle and component suppliers cut recall and defect rates using live digital production twins (upstream reliability improving)
- (+) [electrification rollout] → charger and depot-equipment manufacturers shorten delivery and commissioning times through simulation-driven production control (infrastructure bottleneck easing)
- (+) [spare parts] → transport operators gain faster replenishment because suppliers predict production disruptions before they hit deliveries (supply resilience increasing)
- (–) [vendor dependence] → major transport buyers become tied to suppliers that own proprietary production twins and data (transparency weakening)
- (–) [small suppliers] → smaller local manufacturers struggle to meet twin-driven data requirements for transport procurement (market access tightening)
- (–) [cybersecurity] → cyber incidents at production-twin platforms begin spilling into fleet maintenance and availability problems (upstream digital fragility visible)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.039 — Reconfigurable & Agile Factories

**Score:** 1 (Impact in GVN 1)

**Justification (3 sentences):**

Reconfigurable factories matter to passenger transport mainly through more flexible production of vehicles, replacement parts, and infrastructure equipment. That can reduce procurement delays and support more customized vehicle types, but it remains an indirect supply-side effect. The linkage is worth watching, but limited.

**Weak signals (4):**

- (+) [fleet customization] → OEMs start offering short-run vehicle variants for niche accessibility, rural, or shared-mobility needs without long delays (product flexibility rising)
- (+) [supply resilience] → regional factories switch between transport components fast enough to cover import disruptions (local buffering increasing)
- (–) [capital barrier] → only large suppliers can afford the modular production infrastructure needed for transport contracts (supplier concentration rising)

- (–) [operator visibility] → transport buyers still treat factory agility as invisible supplier detail rather than a contract variable (linkage remaining upstream)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.040 — Circular & Sustainable Manufacturing

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

This ART affects passenger transport by changing the embodied emissions, repairability, and material security of vehicles, batteries, stations, and roads. Those lifecycle effects are meaningful, but they mostly change upstream supply conditions and environmental footprint rather than the service logic of moving passengers. The total impact is therefore limited but non-zero.

Weak signals (4):

- (+) [fleet procurement] → tenders begin rewarding recycled-content batteries, interiors, and structural components with verifiable passports (circularity entering purchasing)
- (+) [maintenance economics] → operators remanufacture more transport components locally instead of replacing them outright (replacement burden dropping)
- (–) [quality assurance] → recycled or bio-derived inputs trigger stricter performance and certification disputes for transport use (trust barrier surfacing)
- (–) [cost pass-through] → circular materials remain a premium feature rather than a mass-market transport standard (scale still limited)  
Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 06.041 — Bio-fabrication technologies

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Bio-fabrication does not have a strong direct pathway into passenger transport beyond highly speculative specialty materials or medical-support side effects. It does not address a core bottleneck in how passengers are moved or how the network operates. For this GVN the linkage is presently too weak to score above zero.

Weak signals (4):

- (+) [materials supply] → transport OEMs begin specifying bio-fabricated tissues or biomaterials for seat, safety, or acoustic applications (would create direct component linkage)
- (+) [workforce health] → transport injury-recovery programs adopt bio-fabricated clinical products at scale (would create labor-side linkage)
- (–) [procurement] → no mainstream transport tenders reference bio-fabricated products as required inputs (demand absent)
- (–) [R&D focus] → transport-sector innovation portfolios ignore bio-fabrication except in speculative design concepts (linkage not forming)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 — 4D Printed & Programmable Materials

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Programmable materials could appear in transport as adaptive signage, self-deploying barriers, climate-responsive surfaces, and components that change shape or stiffness with conditions. Those uses could reduce maintenance and improve safety in niche applications, but they do not yet indicate a broad regime change for passenger transport. The impact is therefore limited.

Weak signals (4):

- (+) [wayfinding and safety] → stations or vehicles pilot shape-changing or self-deploying warning elements that react to crowding or hazards (adaptive materials entering service)
  - (+) [winter operations] → transport surfaces or components use passive climate-responsive behavior to reduce icing or visibility problems (maintenance burden easing)
  - (–) [durability] → repeated cycling and harsh outdoor conditions keep programmable materials out of mainstream transport assets (reliability hurdle persisting)
  - (–) [certification] → safety approval processes struggle with components designed to change state over time (standards lagging behavior)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 — Volumetric Additive Manufacturing

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The passenger-transport linkage is faster local fabrication of small custom parts, fixtures, housings, and prototypes that help keep fleets and stations running. This can shorten downtime and experimentation cycles, but it remains an upstream production enabler rather than a system-level mobility shift. The impact therefore stays limited.

Weak signals (4):

- (+) [maintenance] → depots or regional suppliers use layerless printing for same-day replacement of small transport components (repair delay shrinking)
  - (+) [service design] → operators prototype custom passenger-interface and accessibility parts far faster than before (iteration cost dropping)
  - (–) [critical parts] → certification confines use to non-structural and low-risk components (value ceiling remaining low)
  - (–) [supply chain] → mass-produced parts remain cheaper for most transport applications despite faster printing (economic pull bounded)
- Signal density: LOW (linkage weak; additional signals would be speculative).

# 7. Advanced Materials & Nano-engineering

## ART 07.044 — Metamaterials for Novel Optics & Connectivity

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Metamaterials can matter in passenger transport through lighter, flatter lenses and antennas, better vehicle sensing, and more controllable connectivity along corridors and in vehicles. These improvements can reduce the size, energy use, and blind spots of autonomy and communications stacks, but they remain component-level advances rather than a mobility-system shift by themselves. The likely impact is therefore material but bounded.

Weak signals (6):

- (+) [vehicle sensing] → autonomous and assisted-driving systems adopt flat-lens or beam-shaping components that cut sensor bulk and exposure (sensor packaging improving)
  - (+) [connectivity] → transport corridors deploy reconfigurable reflecting surfaces to remove dead zones at stations, tunnels, or urban canyons (coverage becoming infrastructural)
  - (+) [vehicle design] → low-profile antennas and glazing-integrated wave-control surfaces enter buses, trains, and shuttles (form-factor constraints easing)
  - (–) [maintenance] → exposed wave-control surfaces show weathering or performance drift in transport environments (durability uncertainty surfacing)
  - (–) [market power] → a few specialized suppliers control critical wave-shaping components for autonomous and connected fleets (component dependency growing)
  - (–) [privacy/security] → better through-wall or around-corner sensing raises new concerns about monitoring in public space (sensing boundary blurring)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.045 — Room-Temperature Superconductors

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

If realized in practical transport-ready forms, room-temperature superconductors could materially improve traction, charging, power distribution, magnetic sensing, and perhaps some rail applications. The potential is large in theory, but passenger-transport impact within this GVN depends on slower infrastructure turnover and many complementary system changes. That supports a material score rather than a near-term keystone one.

Weak signals (6):

- (+) [electrified transport] → pilot rail, charging, or depot-power projects adopt ambient-superconducting conductors or devices (electrical-loss bottleneck tested)
  - (+) [vehicle weight and space] → transport OEMs advertise smaller high-current pathways or magnet systems enabled by new conductors (packaging value emerging)
  - (+) [grid interface] → depots and stations explore superconducting equipment for compact high-power interconnection (site constraints easing)
  - (–) [retrofit pace] → transport operators conclude existing conductors and power electronics remain good enough for most assets (turnover limiting diffusion)
  - (–) [reliability] → joining, strain, and field-management problems keep transport-grade applications narrow (engineering gap persisting)
  - (–) [capex] → only premium rail or infrastructure projects can justify adoption initially (benefits concentrating in niches)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 07.046 — Self-Healing & Smart Polymers

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Self-healing and adaptive polymers can reduce wear, cracking, corrosion, and maintenance in vehicle interiors, coatings, seals, road furniture, and some infrastructure components. That can improve comfort, reliability, and safety while lowering labor demand for small repairs, but it does not by itself change the core mobility model. The effect is material but not transformative.

Weak signals (6):

- (+) [fleet maintenance] → operators specify self-healing coatings, seals, or composites in vehicles with high abrasion and weather exposure (minor-damage burden shrinking)
  - (+) [station assets] → smart polymer surfaces begin self-reporting wear in gates, handrails, shelters, or glazing (condition visibility improving)
  - (+) [comfort] → interiors use adaptive materials that tune damping, grip, or thermal feel across weather conditions (quality becoming responsive)
  - (–) [certification] → repair claims from self-healing materials need new verification methods before critical use is allowed (assurance lag appearing)
  - (–) [recycling] → advanced polymer chemistries complicate end-of-life separation in transport assets (circularity trade-off surfacing)
  - (–) [procurement] → agencies treat smart polymers as premium add-ons rather than default specifications (scaling constrained)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 — Nano-Catalysts & Advanced Coatings

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

This ART has several concrete pathways into passenger transport: anti-icing, corrosion resistance, low-friction surfaces, air-quality treatment, easier cleaning, and improved catalyst performance in some fuel systems. The effects are distributed across maintenance, safety, and energy use rather than concentrated in a single transformational application. That makes the impact material but bounded.

Weak signals (6):

- (+) [winter safety] → anti-icing and low-wetting coatings appear in routine specs for stops, stairs, signals, and vehicle glazing (hazard management becoming passive)
- (+) [fleet lifetime] → buses, trains, and ferries adopt corrosion-resistant nanocoatings in high-salt or humid environments (asset life extending)
- (+) [cleanliness and turnaround] → easy-clean interior and exterior coatings reduce dwell time for cleaning and sanitation (service turnaround improving)
- (–) [durability] → agencies begin tracking when premium coatings fail earlier than promised under abrasion and grime (performance uncertainty exposed)
- (–) [health/environment] → concern rises over nanoparticle release from transport surfaces during wear or washing (externality scrutiny increasing)

- (–) [cost] → premium protective finishes remain targeted to high-value assets rather than mass fleets and local stops (benefit staying uneven)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 — High-Entropy Alloys & Advanced Metals

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Stronger, lighter, and more heat- or corrosion-tolerant metals can materially improve vehicle durability, reduce maintenance, and enable lighter structures in rail, buses, ferries, and supporting infrastructure. Those improvements matter across lifecycle cost and safety, but they remain component-level upgrades rather than a direct reorganization of passenger transport. The score is therefore 3.

Weak signals (6):

- (+) [vehicle efficiency] → transport OEMs begin substituting advanced alloys into weight-critical structural or thermal components (mass and durability trade-off shifting)
- (+) [infrastructure lifetime] → bridges, tracks, catenary components, and high-stress fasteners move to new alloy families in harsh climates (maintenance cycles lengthening)
- (+) [safety margins] → operators specify advanced metals to manage fatigue in autonomous or high-utilization fleets (asset intensity increasing)
- (–) [supply chain] → promising alloy grades depend on costly or concentrated elements, limiting public-procurement uptake (input risk surfacing)
- (–) [repairability] → maintenance providers need new joining and machining procedures for transport components (skills shift emerging)
- (–) [certification] → long qualification cycles delay use in safety-critical transport structures (adoption path slowing)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 — Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Passenger transport benefits mainly indirectly if better capture materials accelerate low-carbon fuel and industrial systems or help transport hubs manage local carbon accounts. That can matter for the environmental-responsibility value in the GVN, but it does not strongly change how passengers are moved. The linkage is therefore limited.

Weak signals (4):

- (+) [transport decarbonization] → airports, ports, depots, or fuel suppliers pilot modular CO<sub>2</sub> capture tied to transport-energy systems (carbon-accounting linkage forming)
- (+) [procurement] → mobility buyers start preferring fuels or materials whose embedded carbon is reduced through capture systems (indirect pressure rising)
- (–) [service model] → transport operators see capture as an upstream supplier issue rather than a mobility-system lever (operational pull weak)

- (–) [economics] → high capture costs keep effects outside mainstream passenger-transport budgets (direct influence staying small)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 — Graphene and Nanotube Composites for Lightweight Strength

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Lightweight-strength composites can significantly affect passenger transport by reducing vehicle mass, extending range, improving acceleration, and lowering wear while also enabling embedded condition monitoring. That matters especially for electric buses, shared fleets, active mobility devices, and lightweight rail or shuttle systems where every kilogram feeds into battery size, energy use, and maintenance. Second-order effects include shifts in vehicle design and supply chains, and third-order effects include new business models for highly utilized light electric fleets with continuous structural-health monitoring. This supports a significant score rather than a full transport-model transformation.

Weak signals (9):

- (+) [vehicle efficiency] → electric buses, shuttles, microcars, and micromobility fleets advertise major mass reductions from nanocomposite structures (energy-per-km falling)
- (+) [battery economics] → operators choose smaller packs or longer service intervals because lighter structures meet the same duty cycle (range-cost trade-off shifting)
- (+) [fleet safety] → structural parts begin self-reporting strain or delamination through embedded conductivity changes (condition monitoring becoming built-in)
- (+) [maintenance] → fleet managers move from calendar-based body inspections to sensor-informed composite health monitoring (inspection labor dropping)
- (+) [accessibility] → lighter vehicles and components enable lower-floor designs and more portable assistive mobility devices (access constraints easing)
- (–) [repair ecosystem] → local workshops struggle with composite-specific repair and end-of-life handling (service capability concentrating)
- (–) [supply chain] → nanoparticle handling and quality control push procurement toward a few qualified suppliers (industrial dependence increasing)
- (–) [equity] → lighter, premium vehicles first appear in private fleets or affluent service zones (benefits arriving unevenly)
- (–) [safety regulation] → agencies require new crash, fire, and recyclability evidence for nanocomposite-heavy transport assets (approval burden rising)

## ART 07.051 — Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Thermal control is a major hidden constraint in passenger transport because comfort, battery performance, electronics reliability, and station operations all depend on moving and storing heat well. Smart thermal materials can significantly reduce EV range penalties, improve winter and summer comfort, and lower hub energy costs, with especially strong value in climates where cabin

and battery conditioning consume large shares of energy. Second-order effects include redesign of vehicles, charging patterns, and depot energy systems; third-order effects include more resilient service during heatwaves and cold snaps. That is a significant impact, though not itself the main regime shift.

Weak signals (9):

- (+) [vehicle range] → OEMs and fleet operators highlight large winter-range or summer-HVAC gains from passive or semi-passive thermal materials (comfort-energy trade-off easing)
- (+) [battery health] → battery warranties improve as packs adopt smarter heat-spreading and heat-storage materials (lifetime becoming more predictable)
- (+) [station comfort] → shelters and stations add passive radiative or phase-change materials to stabilize temperatures without heavy HVAC (waiting environments improving)
- (+) [charging operations] → depots smooth peak loads by using thermal storage materials in charger and battery-conditioning systems (energy demand shifting)
- (+) [accessibility] → thermal comfort at stops and inside vehicles improves for heat- and cold-sensitive users (inclusive travel conditions improving)
- (–) [fire/safety] → regulators demand new certification for phase-change and advanced insulating materials in passenger spaces (safety review intensifying)
- (–) [maintenance] → operators discover performance drift after repeated thermal cycles in high-use fleets (durability question emerging)
- (–) [cost] → premium thermal packages initially appear only in higher-end vehicles or flagship corridors (benefit distribution uneven)
- (–) [recycling] → end-of-life handling for composite thermal systems complicates circular procurement goals (lifecycle trade-off appearing)

## ART 07.052 — Rare-Earth-Free Magnets for Sustainable Motors

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport's shift toward electrification makes motor supply a strategic bottleneck, and rare-earth-free magnets can significantly reduce exposure to concentrated supply chains while stabilizing motor cost and scalability. First-order effects are more secure production of EVs, rail auxiliaries, lifts, and many small mobility devices; second-order effects include changes in motor design, procurement, and geopolitical risk exposure; third-order effects include faster local or regional manufacturing because fewer constrained inputs are required. That is significant for the electrified operating model even if it does not by itself transform passenger behavior.

Weak signals (9):

- (+) [fleet procurement] → EV bus, shuttle, and rail tenders begin specifying magnet chemistries or supply-diversification criteria (motor inputs becoming strategic)
- (+) [industrial resilience] → local or regional motor suppliers market rare-earth-light designs to public transport buyers (supply security valued)
- (+) [cost stability] → operators cite smoother vehicle pricing because magnet volatility matters less (procurement risk falling)
- (+) [maintenance] → new motor families show better corrosion or demagnetization resistance in harsh duty cycles (lifetime becoming bankable)

- (+) [accessibility equipment] → lifts, escalators, and assistive devices adopt motors less exposed to material shortages (service continuity strengthening)
- (–) [performance trade-offs] → some routes or vehicle classes keep rare-earth motors for peak efficiency or compactness (technology split persisting)
- (–) [design lock-in] → changing magnet behavior forces proprietary motor-control software and redesign costs (transition friction surfacing)
- (–) [market concentration] → a small number of qualified suppliers dominate early transport-grade alternatives (new dependency forming)
- (–) [policy] → governments intervene in transport procurement to prioritize strategic-material independence over lowest upfront cost (politics entering specs)

## ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

The link to passenger transport is too indirect in most contexts, mainly running through water availability for broader energy or urban systems rather than transport operations themselves. Unless transport hubs become unusually water-constrained or hydrogen-dependent, this ART does not strongly affect how people are moved. It therefore remains outside the main impact set.

Weak signals (4):

- (+) [fuel supply] → hydrogen or synthetic-fuel projects serving passenger transport begin citing low-energy desalination as a critical enabling step (would create energy-water linkage)
  - (+) [remote hubs] → island or arid-region transport nodes deploy desalination as core operating infrastructure (would create direct resilience linkage)
  - (–) [mainstream transport] → most passenger-transport plans ignore desalination technology entirely (linkage absent)
  - (–) [budget exposure] → water treatment remains a municipal utility issue rather than a transport-system issue in operator accounts (impact not internalized)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 — Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score:** 10 (Impact in GVN 1)

Justification (4 sentences):

UWBG power semiconductors directly affect a core transport transition: electrification. By reducing losses, heat, size, and cooling needs in traction inverters, chargers, converters, and grid interfaces, they can materially improve vehicle efficiency, charging speed, depot design, and reliability across EV, rail, and charging ecosystems. Second-order effects include smaller, quieter, more distributed charging infrastructure and lower maintenance, while third-order effects include wider electrification of modes and routes previously constrained by power electronics, space, or cooling. In a 5.5M-person society that is plausibly a transformative-scale effect on how passenger transport is realized, even though it remains an enabling hardware layer below the full regime shift.

Weak signals (9):

- (+) [vehicle efficiency] → OEMs market visibly smaller, lighter traction inverters and auxiliary converters in passenger vehicles (powertrain packaging changing)
- (+) [charging infrastructure] → fast chargers become quieter, denser, and easier to site because cooling and passive-component needs shrink (site economics improving)
- (+) [rail and metro] → traction substations and onboard converters are upgraded for higher efficiency and higher-temperature operation (electrified corridors modernizing)
- (+) [depot design] → bus depots fit more chargers or more power into the same footprint thanks to compact modules (land-use pressure easing)
- (+) [reliability] → operators report lower failure rates in hot, cold, or vibration-heavy duty cycles (electronics robustness improving)
- (–) [supplier power] → a few module vendors become critical to transport electrification roadmaps (component bottleneck emerging)
- (–) [cost curve] → early benefits accrue to premium fleets and high-throughput corridors before mass transit retrofits (deployment unevenness visible)
- (–) [safety] → regulators update high-voltage maintenance and emergency-response protocols for new switching behaviors (operating practices shifting)
- (–) [grid interaction] → faster, denser switching creates new EMC and interoperability disputes at transport sites (power-quality governance tightening)

## ART 07.055 — Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

If hydrogen becomes relevant for buses, ferries, non-electrified rail, or remote fleets, safer and denser storage materials could materially improve handling, siting, and refueling. The impact is real but conditional on hydrogen winning meaningful shares in passenger transport, which is far from guaranteed across all modes. That supports a material but bounded score.

Weak signals (6):

- (+) [route feasibility] → bus, ferry, or rail pilots cite solid-storage cartridges as the reason hydrogen can be sited safely at depots or terminals (safety barrier easing)
  - (+) [public acceptance] → communities accept hydrogen fueling at passenger hubs more readily when pressure and cryogenic risks are reduced (social license improving)
  - (+) [remote services] → sparsely populated or island routes use swappable storage modules to avoid complex refueling infrastructure (logistics simplifying)
  - (–) [weight trade-off] → gravimetric penalties keep storage systems unattractive for many passenger vehicles (vehicle-level value bounded)
  - (–) [heat management] → depot operators face complexity in charge/discharge thermal control for transport duty cycles (operational friction surfacing)
  - (–) [technology split] → hydrogen storage improves but still loses most urban passenger segments to batteries and wire-based electrification (mode relevance staying partial)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion



## ART 08.056 — Fusion Energy Reactors

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Fusion would affect passenger transport primarily by changing the cost, reliability, and carbon intensity of electricity and high-temperature industrial energy rather than by altering mobility services directly. That could materially strengthen the electrified transport model and reduce climate-related legitimacy pressure, but it remains one layer removed from the transport operating model. The likely impact is therefore material but indirect.

Weak signals (6):

- (+) [electrification economics] → long-term fleet and charging strategies start assuming abundant low-carbon baseload from fusion projects (energy planning horizon shifting)
  - (+) [public transport finance] → major depot, rail, or charging investments are located or sized around future fusion-fed power access (infrastructure coupling emerging)
  - (+) [environmental responsibility] → transport decarbonization plans cite fusion-backed power supply for difficult high-throughput corridors (clean-power confidence rising)
  - (–) [timing risk] → transport planners continue treating fusion as too uncertain for core investment cases (linkage remaining hypothetical)
  - (–) [centralization] → benefits accrue mainly through wholesale power systems, not operator-controlled assets (transport leverage staying weak)
  - (–) [distribution] → cheap power does not automatically solve congestion, access, or platform concentration in mobility (energy not equal to regime change)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.057 — Small Modular Fission Reactors (SMRs)

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

SMRs could materially improve the reliability and carbon intensity of power for rail, charging depots, ferry electrification, and remote transport hubs, especially where grid reinforcement is difficult. The technology matters through energy-system resilience and siting flexibility, but not as a direct mobility-service redesign. That keeps it at 3.

Weak signals (6):

- (+) [remote accessibility] → isolated rail, ferry, or regional charging plans begin evaluating colocated SMR power supply (grid bottleneck being rethought)
- (+) [depot resilience] → large electrified depots or multimodal hubs study nuclear-backed microgrids for reliability (critical-node thinking changing)
- (+) [industrial policy] → transport decarbonization strategies pair fleet electrification with nearby nuclear build-out scenarios (cross-sector planning aligning)
- (–) [social legitimacy] → local opposition treats transport-linked reactor siting as politically harder than conventional energy siting (acceptance constraint surfacing)
- (–) [capex] → transport operators remain price takers on electricity rather than direct beneficiaries of SMR deployment (indirectness persisting)

- (–) [security] → high-security obligations limit use near dense passenger nodes (siting flexibility staying bounded)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.058 — Thin-film solar cells

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Thin-film solar can materially affect passenger transport by turning shelters, depots, façades, noise barriers, and some vehicles into local power-generating surfaces with lower installation friction. This supports electrification, resilience, and amenity upgrades, especially for distributed assets, but it is still an incremental energy layer rather than a core mobility transformation. The impact is therefore material but bounded.

Weak signals (6):

- (+) [distributed power] → shelters, stations, depots, and parking structures begin bundling solar skins into standard refurbishments (surface area monetizing)
- (+) [rural stops] → off-grid or weak-grid passenger nodes gain lighting, displays, and communications from integrated thin-film surfaces (service autonomy improving)
- (+) [vehicle design] → niche fleets adopt solar skins to support auxiliaries, sensors, or climate control rather than propulsion alone (auxiliary load offsetting)
- (–) [durability] → weathering, vandalism, and cleaning costs become central procurement criteria for transport-surface photovoltaics (real-world exposure testing value)
- (–) [equity] → premium hubs get energy-positive retrofits first while ordinary stops lag (amenity gap widening)
- (–) [maintenance] → operators find added power complexity burdensome on dispersed transport assets (operational payoff varying)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.059 — Bionic Leaf Technology

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Bionic-leaf systems could supply niche low-carbon molecules for remote or specialized transport energy uses, but the pathway into mainstream passenger transport is narrow compared with batteries, grid power, and more established power-to-X routes. The effect is therefore worth watching mainly as an option for hard-to-electrify edges of the system. Overall impact remains limited.

Weak signals (4):

- (+) [remote fuels] → small transport hubs or island services pilot bionic-leaf fuel production where grid and fuel logistics are weak (niche energy-autonomy linkage forming)
- (+) [decarbonization] → mobility strategies reference direct solar-to-molecule production for backup fuels or auxiliary energy (alternative pathway entering plans)
- (–) [competition] → batteries and conventional electrolysis continue to dominate transport-energy investment (comparative value staying low)

- (–) [operations] → transport operators avoid managing reactive-chemical production on mobility sites (organizational fit weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 — Grid-Scale Energy Storage

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Grid-scale storage significantly affects passenger transport because electrified mobility is constrained not only by vehicles but by charging peaks, grid volatility, and outage risk. Storage can smooth depot charging, support rail and station operations, reduce curtailment and price spikes, and make high-renewables transport systems more reliable, with second-order effects in power-market participation and infrastructure finance. Third-order effects include broader electrification of routes and service patterns that today look too risky for constrained grids. That is a significant GVN impact even though the storage plants sit outside vehicles.

Weak signals (9):

- (+) [depot operations] → bus and shared-vehicle depots add multi-hour storage specifically to avoid expensive grid upgrades (power bottleneck shifting)
- (+) [service resilience] → rail, metro, and major hubs pair storage with backup and islanding capability for continuity during outages (critical mobility nodes hardening)
- (+) [charging economics] → operators arbitrage charging schedules with storage to flatten demand charges and improve fleet availability (energy-cost structure changing)
- (+) [public planning] → transit electrification projects are approved only when paired with storage or flexible demand assets (storage becoming standard complement)
- (+) [rural accessibility] → remote charging corridors become viable because local storage bridges weak-grid conditions (peripheral electrification widening)
- (–) [land and safety] → communities contest large storage siting near passenger hubs over fire, land-use, or visual concerns (infrastructure politics sharpening)
- (–) [market concentration] → a few utility or platform actors control both storage dispatch and mobility charging access (system leverage concentrating)
- (–) [equity] → priority charging plus storage is built first for profitable fleets, not basic public services (benefits distributing unevenly)
- (–) [operational risk] → storage failures or thermal events are treated as mobility-system disruptions rather than just utility incidents (transport-energy coupling visible)

## ART 08.061 — Solid-State Batteries

**Score:** 10 (Impact in GVN 1)

Justification (4 sentences):

Solid-state batteries directly reshape the passenger-transport transition by improving safety, range, packaging, and potentially charging performance across EVs, micromobility, and highly utilized fleets. First-order effects include lower fire risk, longer range, lighter vehicles, and more usable interior or cargo space; second-order effects include new ownership and fleet-utilization models because downtime, insurance, and cooling burdens change; third-order effects include wider substitution of shared electric mobility for private ICE vehicles in segments that currently struggle with weight or safety. In a 5.5M-person society the technology can affect the weekly travel conditions of very large user groups and plausibly move costs/time at transformative scale. It is not

the single keystone because electrified transport can proceed without it, but it strongly accelerates and broadens the shift.

Weak signals (9):

- (+) [vehicle substitution] → mainstream fleet procurements move from pilot quantities to mass orders based on solid-state pack safety and range assumptions (technology crossing into operations)
- (+) [insurance] → insurers lower EV fleet premiums or parking restrictions where solid-state fire risk is demonstrably lower (risk economics changing)
- (+) [charging and uptime] → high-utilization fleets cite faster practical turnaround and lower thermal-management downtime (asset use intensifying)
- (+) [vehicle design] → buses, shuttles, and shared cars redesign cabin, floor, or weight distribution around smaller safer packs (packaging freedoms opening)
- (+) [accessibility] → lighter vehicles and devices expand practical ranges for mobility aids and low-floor service formats (inclusive electrification widening)
- (–) [supply chain] → early mass adoption depends on a narrow set of cell chemistries, materials, or licensed manufacturing routes (new bottlenecks forming)
- (–) [equity] → premium private vehicles and profitable fleets capture early benefits before ordinary public-service fleets (deployment skew appearing)
- (–) [recycling] → regulators race to define second-life and end-of-life rules for new solid electrolyte chemistries (lifecycle governance lagging)
- (–) [market power] → battery suppliers gain leverage over OEMs and fleet operators through proprietary pack architectures (platformization of hardware deepening)

## ART 08.062 — Green Hydrogen & Power-to-X

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Green hydrogen and power-to-X matter to passenger transport mainly for buses, ferries, non-electrified rail, remote corridors, and system balancing where direct electrification is awkward or slow. The direct operational impact is smaller than batteries for urban mass transport, but second-order effects can be significant by changing fuel security, seasonal energy storage, and infrastructure politics. Third-order effects include a contested split between battery-first and molecule-based transport strategies, with large consequences for who owns fueling networks and where capital is spent. That supports a significant score.

Weak signals (9):

- (+) [mode choice] → ferry, coach, and non-electrified rail programs begin selecting hydrogen or synthetic-fuel pathways on total-system grounds rather than only pilots (technology leaving demonstration stage)
- (+) [remote accessibility] → sparsely populated regions use power-to-X fuels to keep passenger services running where grid upgrades lag (energy geography widening options)
- (+) [depot planning] → multimodal hubs integrate electrolyzers, storage, or fuel-conversion modules into master plans (fuel production localizing)
- (+) [resilience] → operators treat stored molecules as strategic backup for power outages or winter stress periods (seasonal buffer value rising)
- (+) [environmental responsibility] → ticketing or procurement starts differentiating transport products by certified fuel origin and carbon intensity (traceable clean fuels monetizing)

- (–) [safety/governance] → communities and regulators contest hydrogen handling near passenger hubs and dense neighborhoods (siting politics intensifying)
- (–) [cost] → low utilization or poor electricity prices leave fuel plants stranded or underused (economics staying fragile)
- (–) [infrastructure lock-in] → platform battles emerge over who controls fueling, conversion, and certification infrastructure (new gatekeepers forming)
- (–) [equity] → public funds flow to visible hydrogen prestige projects while basic bus electrification still lacks support (resource allocation conflict sharpening)

## ART 08.063 — High-Efficiency Wind Turbines

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Like other generation technologies, high-efficiency wind affects passenger transport mainly by improving the cost and availability of clean electricity. It can materially support electrification and reduce long-run operating costs, especially for rail and charging-heavy fleets, but it does not directly restructure how passenger transport is organized. The impact is therefore material and indirect.

Weak signals (6):

- (+) [electrification economics] → large transport-power purchase agreements increasingly rely on high-yield wind output assumptions (clean-power supply stabilizing)
  - (+) [depot and rail supply] → operators co-invest in wind-backed energy contracts or dedicated generation for charging and traction power (mobility-energy coupling tightening)
  - (+) [resilience] → storage-plus-wind packages become common in transport decarbonization business cases (renewables becoming operationally credible)
  - (–) [variability] → transport operators still require expensive balancing despite better turbines (indirect value ceiling remaining)
  - (–) [siting politics] → conflicts over visual, land-use, or grid connection issues delay energy supply intended for transport electrification (deployment friction persisting)
  - (–) [ownership] → benefits accrue mostly to utilities and large asset owners rather than to transport operators or passengers directly (bargaining leverage limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 — Wireless & Space-Based Power Transfer

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The main passenger-transport relevance is power supply in remote, temporary, disrupted, or hard-to-wire settings rather than routine daily mobility. That could matter for emergency operations, remote hubs, or niche services, but it is unlikely to dominate the mainstream passenger network. The impact is therefore limited.

Weak signals (4):

- (+) [remote service continuity] → temporary transport hubs or emergency corridors begin using beamed power instead of fuel logistics or rushed cabling (niche energy-link emerging)

- (+) [disaster response] → critical passenger nodes include wireless power reception in resilience planning (outage-bridging value recognized)
  - (–) [safety and permitting] → beam-intensity limits keep public-space deployments rare near passengers and traffic (practical envelope staying tight)
  - (–) [economics] → wired upgrades and storage remain cheaper for almost all transport applications (mainstream pull weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 — Advanced geothermal technology

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Advanced geothermal affects passenger transport mainly as a steady low-carbon power and heat source for depots, stations, tunnels, and broader electrification systems. That can improve resilience and environmental performance, but it does not strongly alter transport operations compared with other energy sources. The impact is concrete yet limited.

Weak signals (4):

- (+) [hub resilience] → large stations, depots, or tunnel systems begin pairing electrification plans with deep geothermal heat or power (site energy autonomy rising)
  - (+) [remote corridors] → geothermal-rich regions market stable low-carbon energy as an advantage for charging or rail traction (energy geography influencing transport)
  - (–) [operator leverage] → transport providers remain mostly passive electricity buyers even where geothermal expands (direct control limited)
  - (–) [siting] → project complexity and geology keep benefits localized rather than network-wide (impact staying patchy)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 — Resilient microgrids

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Resilient microgrids significantly affect passenger transport because charging depots, stations, signaling, communications, elevators, and control centers are all vulnerable to wider grid disruption. Microgrids can protect service continuity, improve power quality, and let transport assets island during outages, with second-order effects in new local energy governance and ownership structures. Third-order effects include differentiated reliability between operators or neighborhoods that can and cannot fund local energy resilience. That is a significant effect on how reliably the GVN delivers mobility, even if it is not the main transformative shift.

**Weak signals (9):**

- (+) [service continuity] → major depots, stations, and control centers begin installing microgrids with islanding as a standard resilience feature (blackout vulnerability internalized)
- (+) [electrification rollout] → fleet electrification business cases increasingly bundle local generation, storage, and controls rather than assuming passive grid upgrades (energy architecture decentralizing)



- (+) [public safety] → accessible lifts, communications, ticketing, and emergency lighting at hubs are guaranteed through local microgrid backup (critical functions hardening)
- (+) [rural accessibility] → weak-grid communities use microgrids to make reliable charging and on-demand transport services possible (peripheral inclusion improving)
- (+) [operations] → transport operators start participating directly in local flexibility and energy markets through microgrid controls (new revenue and coordination layer)
- (–) [equity] → well-funded hubs and private fleets get resilient service first while ordinary stops remain outage-prone (reliability gap widening)
- (–) [governance] → disputes emerge over whether transport microgrids should prioritize public service, fleet revenue, or community loads during crises (allocation politics sharpening)
- (–) [cybersecurity] → local energy-control attacks are recognized as transport-service threats (critical infrastructure boundary expanding)
- (–) [market structure] → microgrid operators or vendors gain leverage over access to charging and power quality at mobility nodes (new gatekeepers forming)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Next-generation gene editing does not have a strong direct pathway into passenger transport operations, infrastructure, or service design. Any effect would be highly indirect through broad health or agricultural changes rather than through a transport bottleneck. It therefore stays outside the meaningful impact set for this GVN.

Weak signals (4):

- (+) [workforce health] → transport employers begin relying on gene-edited clinical interventions to sustain safety-critical staffing (would create labor-side linkage)
  - (+) [materials] → gene-edited organisms start producing transport-relevant biomaterials at scale (would create supply-side linkage)
  - (–) [policy] → no major passenger-transport strategies mention gene editing as a mobility-relevant lever (direct demand absent)
  - (–) [operations] → transport risk and resilience planning ignores gene-editing pathways except as generic public-health background (linkage not internalized)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 09.068 — mRNA Therapies & Vaccines

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The clearest link is system resilience during infectious outbreaks, when passenger confidence, staff availability, and public transport demand can change abruptly. Faster, more adaptable vaccines and therapies can reduce those shocks, but the effect is episodic and mediated through public health rather than transport design. That makes the impact concrete yet limited.

Weak signals (4):

- (+) [service continuity] → transport contingency plans explicitly assume rapid vaccine updates as part of outbreak recovery (health resilience entering mobility planning)
  - (+) [workforce availability] → public transport operators coordinate vaccination access for drivers, crews, and station staff as core continuity policy (staffing shock mitigation formalized)
  - (–) [demand sensitivity] → passenger behavior remains highly risk-sensitive even when medical tools improve (mobility confidence not automatically restored)
  - (–) [equity] → uneven access to rapid therapies leaves some user groups or workers exposed despite system-level readiness (resilience benefits uneven)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 — Cellular Agriculture & Cultured Meat

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

This ART has no strong direct transport pathway beyond broad land-use or food-system spillovers that are too indirect for this assessment. It does not clearly change passenger movement, transport infrastructure, or transport operations. The score is therefore zero.

Weak signals (4):

- (+) [travel demand geography] → major shifts in rural land use from cellular agriculture begin altering transport demand patterns (would create indirect spatial linkage)
  - (+) [station services] → transport hubs materially reconfigure food logistics around cultured products (would create minor service linkage)
  - (–) [mobility relevance] → transport agencies and operators do not treat cellular agriculture as a planning variable (linkage absent)
  - (–) [investment] → passenger-transport capital programs remain unaffected by cellular-agriculture growth (no operational pull)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 — Organoids & Tissue Engineering

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Organoids and tissue engineering mainly affect biomedical research and healthcare, not the operating model of passenger transport. Any link would be indirect through health outcomes or specialized materials. That is too weak to score above zero here.

Weak signals (4):

- (+) [workforce recovery] → transport injury and rehabilitation programs begin depending on tissue-engineered therapies (would create labor linkage)
- (+) [safety regulation] → driver or operator fitness standards shift because tissue-engineering treatments become common (would create governance linkage)

- (–) [transport planning] → mobility strategies do not reference organoid or tissue-engineering developments (linkage absent)
  - (–) [procurement] → no transport-sector procurements name these technologies as inputs or dependencies (operational relevance missing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 — Synthetic Biology & Designer Microbes

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Designer microbes could matter indirectly through bio-based fuels, coatings, waste treatment, and low-temperature material production relevant to transport assets. Those pathways are real but mostly upstream and substitutable by other technologies. The likely impact on passenger transport is therefore limited.

Weak signals (4):

- (+) [maintenance and materials] → transport suppliers begin using microbially produced coatings, polymers, or cleaners in fleet and station operations (bio-based inputs entering procurement)
  - (+) [fuel systems] → synthetic-biology routes appear in niche low-carbon fuels used for ferries, coaches, or backup generators (molecule pathway opening)
  - (–) [cost and certification] → transport buyers hesitate because biobased materials lack clear durability or safety evidence (qualification barrier persisting)
  - (–) [operational pull] → most passenger-transport decarbonization plans favor batteries and conventional electrofuels over bioengineered alternatives (competitive pressure limiting role)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 — Microbiome Engineering

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Microbiome engineering does not map strongly onto the core goal or operating model of passenger transport, beyond very indirect health or sanitation effects. Those pathways are too weak and too substitutable to justify a non-zero system score here. The technology remains outside the main relevance set.

Weak signals (4):

- (+) [cabin sanitation] → transport operators begin using microbiome-engineered surfaces or treatments in vehicles and stations (would create direct hygiene linkage)
  - (+) [worker health] → occupational-health programs in transport depend on targeted microbiome interventions for absenteeism reduction (would create labor linkage)
  - (–) [service design] → passenger-transport planning does not mention microbiome engineering as a mobility lever (relevance absent)
  - (–) [procurement] → no mainstream fleet or station tenders require microbiome-engineered solutions (demand not forming)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 — Precision Medicine & Genomic Diagnostics

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The most plausible transport pathway is better management of driver/operator health, passenger accessibility needs, and emergency-risk screening in high-safety roles. Those uses can produce concrete benefits, but they are narrow and ethically sensitive rather than system-transformative. The likely impact is therefore limited.

Weak signals (4):

- (+) [workforce safety] → transport occupational-health programs begin using genomics-informed screening or dosing for safety-critical staff (health management becoming individualized)
- (+) [accessibility] → mobility assistance services adapt trip planning or emergency protocols to richer passenger health profiles (care personalization increasing)
- (–) [privacy] → strong resistance emerges to genomic data use in licensing, employment, or insurance for transport roles (rights boundary hardening)
- (–) [equity] → better health-tailored mobility remains available mainly to insured or higher-income users (benefits staying stratified)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

This ART mainly affects research and biomedical testing, not passenger transport directly. Any transport linkage would be very indirect through occupational health, materials, or clinical progress. That is too weak for a non-zero score in this GVN.

Weak signals (4):

- (+) [worker safety] → transport toxicology and materials testing begin using organs-on-chips for cabin-air or chemical-exposure standards (would create narrow direct linkage)
- (+) [vehicle materials] → OEMs rely on bio-computational chip testing to qualify new interior materials for passengers (would create certification linkage)
- (–) [transport practice] → mainstream passenger-transport operations remain unaffected by the technology (linkage absent)
- (–) [policy] → mobility and infrastructure plans never mention organs-on-chips as a required capability (no demand signal)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 — Biological Aging & Longevity Barriers

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

If aging-related decline slows, it can modestly affect passenger transport through later-life travel patterns, continued driving, workforce participation, and demand for accessibility services. Those effects are real but diffuse, contested, and mediated through broader social change rather than

transport innovation itself. The impact therefore stays limited.

Weak signals (4):

- (+) [travel demand] → older age groups keep active travel and independent mobility patterns longer than current planning assumptions expect (age-mobility profile shifting)
  - (+) [labor supply] → transport operators retain older workers safely for longer in roles that now suffer shortages (workforce aging effects moderating)
  - (–) [accessibility planning] → demand for inclusive vehicle and station design does not fall despite healthier aging (basic design needs persisting)
  - (–) [inequality] → longevity-linked mobility gains appear first among wealthier groups, widening service and infrastructure disparities (benefits stratifying)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 — Engineered Living Materials

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Engineered living materials could directly affect passenger transport if roads, stations, barriers, or vehicle-adjacent structures become self-repairing, moisture-managing, or carbon-sequestering. That could materially reduce maintenance cycles, closures, and embodied emissions, especially for diffuse infrastructure that is expensive to inspect and repair manually. The impact is material but still focused on asset performance rather than the mobility regime itself.

Weak signals (6):

- (+) [infrastructure reliability] → pilot pavements, barriers, or station materials begin self-sealing small cracks or reporting damage conditions (maintenance cycle changing)
  - (+) [environmental responsibility] → public procurement starts valuing structural materials that measurably sequester carbon over their service life (low-carbon infrastructure logic strengthening)
  - (+) [winter/water management] → living composites are trialed where moisture handling and freeze-thaw cycles currently drive transport damage (climate resilience pathway opening)
  - (–) [durability] → agencies question whether living functions survive de-icing chemicals, abrasion, and pollution (environmental fit uncertain)
  - (–) [regulation] → biosecurity and maintenance rules slow approval for public-space structural use (governance friction appearing)
  - (–) [public acceptance] → visible “living” infrastructure provokes trust or hygiene concerns from passengers and workers (social legitimacy uncertain)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 — Gene Drive Pest Control

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The passenger-transport pathway is narrow but concrete in places where pests, disease vectors, or invasive species disrupt transport corridors, ports, stations, or public-health confidence. Even then, the effect is mediated through environmental management rather than transport-system design. The

likely impact is limited.

Weak signals (4):

- (+) [asset protection] → transport corridors and hubs begin appearing in vector-control or invasive-species programs using gene-drive approaches (transport environment entering scope)
  - (+) [public health resilience] → disease-control plans for ports, stations, or tourist mobility corridors cite gene drives as a way to preserve travel confidence (biosecurity linkage forming)
  - (–) [governance] → transport authorities avoid involvement because ecological accountability sits elsewhere (institutional distance remaining high)
  - (–) [social legitimacy] → public opposition prevents gene-drive deployment near major passenger nodes (authorization barrier dominating)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 — Artificial Wombs & Synthetic Embryos

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

There is no strong direct passenger-transport pathway here beyond long-run demographic effects too broad and uncertain for this GVN. The technology does not address a transport bottleneck or operating-model change in any specific way. It therefore receives a zero.

Weak signals (4):

- (+) [demography] → mobility planners begin modeling significant travel-demand changes from altered fertility or neonatal outcomes tied to these technologies (would create indirect population linkage)
  - (+) [medical transport] → specialized transport services adapt around large-scale use of artificial gestation support systems (would create niche service linkage)
  - (–) [transport relevance] → passenger-transport strategies do not treat the technology as a planning variable (no operational pull)
  - (–) [infrastructure] → no mainstream mobility or transport-infrastructure investment depends on this technology family (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 — Satellite Mega-Constellations & Space Internet

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Mega-constellations matter to passenger transport by extending resilient connectivity, positioning support, and near-real-time situational awareness into rural, maritime, disrupted, and weak-infrastructure areas where current services are patchy. First-order effects include better passenger information, fleet coordination, remote supervision, and service continuity; second-order effects include dependency on a small number of global operators and new cross-border data and security



issues; third-order effects include a more even geography of digitally coordinated mobility services. In a 5.5M-person society that can be significant for accessibility and resilience, especially outside major cities, but it is still one component of the broader connectivity stack rather than the principal transport regime shift. The score is therefore 5.

Weak signals (9):

- (+) [rural accessibility] → on-demand transit, ferries, and remote bus services begin guaranteeing live dispatch and passenger information via satellite links (coverage gap closing)
- (+) [autonomous operations] → remote or low-density driverless services require satellite fallback communications in service permits (resilience becoming mandatory)
- (+) [maritime and island mobility] → passenger vessels and island connectors use space-based connectivity as routine operational infrastructure (remote continuity improving)
- (+) [positioning resilience] → mobility operators adopt satellite-based augmentation where GNSS spoofing or poor terrestrial coverage is a concern (navigation assurance strengthening)
- (+) [disruption response] → flood, storm, or wildfire transport operations rely on constellation-based links after terrestrial outages (mobility resilience becoming visible)
- (–) [market power] → a few constellation providers become critical infrastructure for rural mobility and emergency transport coordination (dependency concentrating)
- (–) [cost] → smaller public operators struggle with terminal and subscription costs for full-time use (access inequality persisting)
- (–) [security] → authorities classify satellite-link jamming or spoofing as passenger-transport continuity threats (space-infrastructure dependence acknowledged)
- (–) [governance] → cross-border data and service disputes arise when mobility operations rely on non-domestic orbital networks (jurisdictional complexity increasing)

## ART 10.080 — Space Resource Utilization (SRU)

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The plausible passenger-transport link is long-run materials supply: platinum-group metals, specialty alloys, or other strategic inputs that could matter for batteries, catalysts, electronics, or power systems. Even if that pathway emerges, it remains far upstream and highly uncertain relative to nearer material-substitution and recycling routes. The impact on this GVN is therefore limited.

Weak signals (4):

- (+) [strategic materials] → transport supply-chain scenarios begin including off-Earth sources for critical metals used in batteries, catalysts, or electronics (upstream hedge being considered)
  - (+) [procurement] → OEMs or infrastructure suppliers signal willingness to certify extraterrestrial-origin materials for transport components (supply pathway becoming imaginable)
  - (–) [economics] → recycled and terrestrial materials continue to dominate transport inputs on cost and certainty (linkage staying remote)
  - (–) [planning] → passenger-transport strategies never treat SRU as an operational assumption (relevance remaining speculative)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 — Closed-Loop Life Support System

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Closed-loop life support is highly relevant in space habitats but has no strong direct mapping to passenger transport beyond very indirect spillovers in air handling or water recycling. Those spillovers are too weak to shape the GVN's operating model. The technology therefore scores zero here.

Weak signals (4):

- (+) [hub sustainability] → transport hubs begin reusing life-support-derived closed-loop air and water systems as core infrastructure (would create sustainability linkage)
  - (+) [remote services] → extreme-environment passenger nodes adapt habitat-style closed loops for autonomous or isolated operations (would create niche resilience linkage)
  - (–) [procurement] → mainstream transport assets do not specify life-support-derived systems as essential capabilities (demand absent)
  - (–) [policy] → mobility planning treats this technology only as a space-sector issue (linkage not internalized)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 — High-Altitude Platforms & Balloons

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

High-altitude platforms can materially help passenger transport by providing temporary or persistent communications, positioning augmentation, and wide-area observation during disruptions or in sparse regions. They are especially relevant where building terrestrial infrastructure is slow or where disaster resilience matters, but they remain an enabling layer rather than a core transport mode. The overall effect is material but bounded.

Weak signals (6):

- (+) [disruption resilience] → transport emergency plans include stratospheric platforms for restoring communications over flooded, storm-hit, or wildfire-affected corridors (rapid coverage becoming credible)
  - (+) [remote accessibility] → rural or maritime passenger services use HAP-supported connectivity instead of waiting for full terrestrial build-out (infrastructure lead time shrinking)
  - (+) [situational awareness] → control centers buy high-altitude observation feeds for corridor monitoring during major events or seasonal risks (wide-area visibility improving)
  - (–) [airspace governance] → aviation and security rules constrain where platforms can loiter near major passenger corridors (operating envelope staying narrow)
  - (–) [cost] → continuous HAP service proves viable only for premium or emergency uses, not routine public transport coverage (benefit staying selective)
  - (–) [vendor dependence] → transport agencies rely on a small number of service providers for crisis communications and observation (capability concentration rising)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

The strongest passenger-transport pathways are verifiable ticketing, asset provenance, shared-vehicle access, and cross-operator settlement without a single central intermediary. Those uses can create concrete efficiencies or new ownership experiments, but they are not obviously superior to non-blockchain alternatives in most core transport functions. The likely impact is therefore limited.

Weak signals (4):

- (+) [ticketing and settlement] → mobility services begin settling fares, subscriptions, or inter-operator revenue shares on shared ledgers (trust automation entering narrow workflows)
  - (+) [shared assets] → community or cooperative vehicle fleets use tokenized ownership or access rights in production services (alternative governance form appearing)
  - (–) [user friction] → key management and recovery problems keep ordinary passengers on conventional accounts and payment rails (consumer fit remaining weak)
  - (–) [regulation] → transport authorities reject ledger-based systems unless they map cleanly to liability and consumer-protection rules (institutional acceptance staying limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 11.084 — Platform Cooperatives & Fair Work

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport is highly exposed to platform power in ride-hailing, delivery-adjacent mobility, and increasingly MaaS intermediation, so cooperative platform models can materially change the ownership and bargaining structure around mobility services. First-order effects include different pricing, working conditions, and service-area choices; second-order effects include alternative governance over algorithms, data, and surplus allocation; third-order effects include competition between shareholder-maximizing and member-governed mobility ecosystems. In a 5.5M-person society that can significantly affect access, labor conditions, and the viability of shared mobility in underserved areas, even if it does not transform the physics of transport. The score is therefore 5.

Weak signals (9):

- (+) [market structure] → ride-hailing, taxi, or neighborhood mobility platforms launch with worker or user ownership rights embedded in governance (ownership model changing)
- (+) [service access] → cooperative mobility services remain active in low-margin areas that investor-owned platforms had exited (coverage incentives diverging)
- (+) [labor conditions] → members gain visibility into dispatch, ranking, and fee logic rather than receiving opaque algorithmic decisions (algorithmic bargaining improving)
- (+) [public procurement] → municipalities explicitly reserve or favor contracts for platform-cooperative transport services (institutional support materializing)

- (+) [data rights] → drivers or users collectively decide how trip data is shared with MaaS aggregators and cities (data governance socialized)
- (–) [capital access] → cooperative platforms struggle to finance fleet upgrades, insurance, or software maintenance at scale (growth constraint surfacing)
- (–) [coordination] → internal voting and dispute processes slow operational changes compared with centrally controlled rivals (governance friction becoming visible)
- (–) [market competition] → incumbent platforms respond with price wars or exclusive data partnerships that squeeze co-op viability (power asymmetry sharpening)
- (–) [equity] → better labor governance does not automatically ensure service to disabled, rural, or low-income users without public support (social goals still contested)

## ART 11.085 — Open Data Sharing Marketplaces

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport suffers from fragmented data across operators, cities, maps, tickets, accessibility services, and private platforms, and open data marketplaces can significantly reduce that fragmentation. First-order effects are better multimodal planning, asset visibility, forecasting, and service coordination; second-order effects include new bargaining over who can monetize mobility data and under what terms; third-order effects include a shift from vertically integrated mobility platforms toward more modular ecosystems—or, conversely, toward new data gatekeepers. In a 5.5M-person society that is large enough to shift hundreds of millions in cost and travel time if integration really improves. The technology is significant, though not a keystone by itself.

Weak signals (9):

- (+) [MaaS integration] → operators begin purchasing and selling standardized live data on occupancy, disruptions, curb availability, and accessibility status (data liquidity increasing)
- (+) [public transport planning] → agencies access private platform data through market-like exchanges instead of long bilateral negotiations (planning visibility broadening)
- (+) [inclusion] → accessibility, elevator, ramp, and curb-condition datasets become tradeable and machine-readable across providers (trip-chain legibility improving)
- (+) [service innovation] → smaller mobility firms launch products by buying curated data bundles instead of building giant proprietary datasets (entry barriers lowering)
- (+) [governance] → contracts move from bespoke data-sharing MoUs to programmable permissions and usage accounting (coordination standardizing)
- (–) [market power] → a few exchange operators dominate access to critical mobility datasets (data infrastructure centralizing)
- (–) [privacy] → public resistance grows if mobility data markets seem to commercialize passenger traces without meaningful control (trust conflict surfacing)
- (–) [quality] → disputes over provenance, update speed, and hidden bias undermine interoperability promises (shared data trust under strain)
- (–) [equity] → wealthy operators buy richer data layers and outperform smaller public or community services (analytic advantage concentrating)

## ART 11.086 — Secure & Resilient Social Platforms

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Secure social platforms matter to passenger transport mainly as a coordination layer during disruptions, protests, disasters, or community-run mobility efforts. They can improve continuity of communication and mutual aid, but they do not strongly alter the normal operating model of passenger transport services. The impact is therefore limited.

Weak signals (4):

- (+) [disruption response] → operators and communities rely on resilient social channels to coordinate detours, pickups, and outage information when mainstream platforms fail (communication resilience gaining value)
  - (+) [community mobility] → neighborhood ride-sharing or volunteer transport groups organize through privacy-preserving interoperable networks (local coordination widening)
  - (–) [official adoption] → most transport agencies still prefer one-way alerts on conventional platforms rather than resilient social infrastructures (institutional pull staying weak)
  - (–) [misinformation] → even secure channels amplify unverified transport disruptions if moderation and verification remain weak (reliability not guaranteed)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.087 — Collective Open Innovation Networks

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Open innovation networks can help passenger transport agencies and firms source ideas, simulations, and problem-solving capacity more widely. That may accelerate some mobility innovation, but it is an upstream coordination tool rather than a direct transport-system lever. The likely impact on this GVN is therefore limited.

Weak signals (4):

- (+) [innovation capacity] → transport agencies post recurring operational and accessibility challenges to open innovation networks instead of relying only on incumbent consultants (problem-solving base broadening)
  - (+) [validation] → mobility pilots increasingly require machine-readable evidence trails and shared benchmarks from external contributors (innovation workflow standardizing)
  - (–) [adoption gap] → many promising external solutions fail to survive procurement, safety, or union constraints (innovation-to-operations gap persisting)
  - (–) [capability concentration] → a few platform operators mediate who gets visibility and credit in mobility innovation ecosystems (coordination power centralizing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.088 — Scalable Decentralized Governance

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Decentralized governance could affect passenger transport in niche settings such as community-run mobility services, shared curb governance, or pooled infrastructure resources. Those are real possibilities, but they are not yet clearly central to the mainstream operation of passenger transport networks. The impact is therefore limited.

Weak signals (4):

- (+) [shared mobility governance] → member-run transport services start using formal digital voting and budget execution for fleet and pricing decisions (collective control becoming operational)
  - (+) [curb and street allocation] → cities pilot machine-auditable participatory governance for pickup zones, parking, or local service priorities (street-rule experimentation rising)
  - (–) [legal fit] → automated governance outputs struggle to map onto public accountability and liability in transport decisions (institutional mismatch persisting)
  - (–) [participation] → low engagement and governance fatigue limit impact beyond small communities (scale staying narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 — Digital Learning Networks and Skill Credentialing

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Passenger transport faces large skill transitions around electrification, software-defined operations, autonomous systems, accessibility, and cyber-physical maintenance. Digital learning networks and portable credentials can materially reduce those retraining bottlenecks and make new competencies easier to verify across operators and regions. That is a material labor and transition effect, though not a direct mobility-model transformation.

Weak signals (6):

- (+) [workforce transition] → large numbers of drivers, mechanics, dispatchers, and station staff retrain through modular digital programs tied to new mobility roles (reskilling pipeline scaling)
  - (+) [credential portability] → operators accept machine-verifiable credentials for EV maintenance, autonomy supervision, accessibility support, or cyber safety across employers (skills becoming legible)
  - (+) [smaller operators] → regional providers use shared credential networks instead of building bespoke academies (training access widening)
  - (–) [quality control] → regulators question whether remote credentials reflect real-world competence in safety-critical transport roles (assessment trust contested)
  - (–) [labor stratification] → workers without digital access or self-paced learning capacity fall behind in transition pathways (reskilling inequality emerging)
  - (–) [vendor dependence] → a few platform providers control the credential standards that gate entry into new transport jobs (training power centralizing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.090 — Prediction-Market Forecasting Platforms

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

Prediction markets can improve transport planning and disruption anticipation by aggregating distributed knowledge about demand, delays, adoption, or policy outcomes. That is potentially useful, but it remains a decision-support overlay rather than a core transport technology. The impact



on the GVN is therefore limited.

Weak signals (4):

- (+) [planning quality] → agencies or large operators begin using structured forecast markets for ridership, disruption, or project-delivery risks (collective forecasting entering governance)
  - (+) [capital allocation] → investment committees request market-based probabilities alongside consultant forecasts for major mobility projects (decision discipline changing)
  - (–) [verification] → transport questions prove too ambiguous or politically contested for reliable settlement (forecast-market utility bounded)
  - (–) [participation] → low liquidity and insider concentration limit forecast quality in mobility-specific markets (signal quality staying weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

**Score:** 10 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport is becoming a dense ecology of vehicles, chargers, signals, stops, ticketing systems, accessibility devices, sensors, and control points, and interoperability standards directly affect whether that ecology can function as a coherent system. First-order effects are lower integration cost, faster maintenance, clearer device behavior, and easier multimodal orchestration; second-order effects include a redistribution of power away from bespoke integrators toward standards-setters and certified stack providers; third-order effects include faster scaling of connected mobility and less vendor lock-in—if the standards remain open and adopted. In a 5.5M-person society, universal interoperability can clearly change how mobility services are assembled and governed at transformative scale. It is not the only keystone, but it is a major infrastructure condition for the challenger regime.

Weak signals (9):

- (+) [integration cost] → public procurements stop accepting proprietary-only interfaces for chargers, stops, signals, and fleet telemetry (interoperability becoming baseline)
- (+) [MaaS orchestration] → new mobility services plug into mixed fleets and public infrastructure with much shorter integration timelines (friction of coordination falling)
- (+) [accessibility] → assistive devices, wayfinding systems, and passenger profiles begin working across operators without custom connectors (inclusive interoperability improving)
- (+) [maintenance] → field technicians use common tools and diagnostics across heterogeneous transport assets (repair complexity decreasing)
- (+) [market entry] → smaller vendors and local operators can join connected mobility ecosystems without bespoke gateway deals (entry barriers lowering)
- (–) [standards politics] → fights intensify over who controls certification profiles and mandatory feature sets (governance power centralizing)
- (–) [security] → shared standards spread vulnerabilities quickly when flaws are found in common implementations (common-mode risk rising)

- (–) [transition cost] → legacy assets become a major budget and schedule burden because they cannot meet new interoperability requirements (retrofit gap surfacing)
- (–) [data control] → some incumbents comply formally while preserving practical lock-in through optional extensions and certification tactics (open-standard capture emerging)

## ART 12.092 — Interoperable Digital Twin Ecosystems

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport increasingly depends on shared representations of vehicles, infrastructure, energy systems, and passenger flows, but today those models are fragmented across vendors and organizations. Interoperable digital twins can significantly improve planning, maintenance, incident response, and cross-operator coordination by making state, history, and assumptions portable. Second-order effects include new questions about model liability, access control, and which actors define “the” twin of a public asset; third-order effects include stronger remote oversight and more simulation-led decision-making before physical changes are made. That is significant for this GVN, though not a standalone regime shift.

**Weak signals (9):**

- (+) [asset coordination] → cities, operators, and OEMs begin exchanging live twin data for vehicles, stations, chargers, and corridors through common interfaces (shared operational picture forming)
- (+) [maintenance] → service teams use portable twins with history and sensor state instead of vendor-locked dashboards (knowledge mobility increasing)
- (+) [disruption response] → control centers rehearse reroutes, closures, and passenger-flow changes on shared twins before acting (decision latency shrinking)
- (+) [energy integration] → transport-energy twins connect depots, chargers, storage, and grid assets in routine operations (cross-system planning deepening)
- (+) [public legitimacy] → redesigns of stops, streets, or timetables are justified with portable twin evidence visible across agencies (assumptions becoming contestable)
- (–) [accountability] → disputes emerge over which twin state is authoritative after incidents or service failures (model authority contested)
- (–) [market power] → a few cloud vendors dominate interoperability layers and compute costs for large mobility twins (digital infrastructure concentrating)
- (–) [surveillance] → richer twins normalize persistent tracking of assets and passenger flows beyond maintenance needs (observability expanding)
- (–) [legacy gap] → older vehicles and stations remain poorly represented, creating a two-speed system of governable and opaque assets (digital inequality persisting)

## ART 12.093 — Global Supply Chain Traceability Networks

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Passenger transport increasingly depends on traceable batteries, electronics, structural materials, safety parts, and service contractors, especially under environmental and security scrutiny. Traceability networks can materially improve recalls, procurement integrity, strategic-material visibility, and low-carbon claims, but they operate mainly upstream of the passenger experience. That makes the impact material but not transformative.

#### Weak signals (6):

- (+) [fleet procurement] → tenders require traceable battery, motor, and electronics provenance rather than simple supplier declarations (sourcing visibility deepening)
  - (+) [safety] → recall management accelerates because vehicles and parts carry portable chain-of-custody and transformation records (root-cause response speeding up)
  - (+) [environmental responsibility] → operators differentiate services or procurement on verified carbon, labor, or recycled-content claims for transport inputs (sustainability becoming auditable)
  - (–) [supplier access] → smaller vendors struggle to satisfy traceability-data demands for public transport contracts (compliance burden raising barriers)
  - (–) [market power] → traceability platform operators gain leverage over supplier participation and certification (infrastructure of trust concentrating)
  - (–) [cost pass-through] → added verification costs show up in vehicles and spare parts without immediate passenger-visible gains (political salience staying low)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.094 — Personal Data Portability & Trust Frameworks

### Score: 5 (Impact in GVN 1)

#### Justification (4 sentences):

Passenger transport becomes more seamless when identity, payment preferences, accessibility needs, subscriptions, and travel entitlements can move with the person across operators and apps. Personal data portability and trust frameworks can significantly reduce switching costs and form-filling while also redistributing control away from single-provider account silos. Second-order effects include new competition dynamics in MaaS and greater user control over mobility data, but also new risks around digital exclusion and credential dependence; third-order effects include transport systems becoming more personalized and easier to optimize around individual consented profiles. That is significant for this GVN.

#### Weak signals (9):

- (+) [multimodal convenience] → passengers carry portable mobility profiles that work across ticketing, booking, accessibility, and payment systems (account silos weakening)
- (+) [accessibility] → verified assistance needs, elevator preferences, or entitlement data travel between operators with user consent (inclusive travel chain smoothing)
- (+) [market competition] → switching between MaaS providers no longer means losing travel history, stored entitlements, or reputation signals (platform lock-in reducing)
- (+) [public services] → concessionary fares and mobility rights are issued as portable credentials rather than operator-specific cards (benefit administration simplifying)
- (+) [cross-border travel] → regional or international trips become easier because identity and payment permissions can be reused safely (friction at boundaries falling)
- (–) [digital exclusion] → users without strong devices, recovery options, or digital literacy struggle as portability frameworks become the norm (inclusion risk surfacing)
- (–) [surveillance] → unified mobility identities make it easier to consolidate personal movement records across providers (privacy stakes rising)
- (–) [market power] → wallet and trust-framework providers become critical gatekeepers between passengers and services (intermediation deepening)

- (–) [policy] → disputes intensify over mandatory vs optional sharing of user data for service optimization (consent boundaries politicizing)

## ART 12.095 — Interoperable Digital Currency Payment Networks

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport depends on low-friction payments across buses, trains, shared vehicles, tolls, subscriptions, and cross-border trips, and payment fragmentation is a real usability and inclusion bottleneck. Interoperable digital-currency networks can significantly reduce settlement friction between operators and make multimodal journeys easier to price and pay for, while also changing who controls payment data and compliance. Third-order effects include easier bundling of mobility services and more dynamic or conditional pricing, but also stronger dependence on identity and rule-enforcement layers. That is a significant but not regime-defining effect.

Weak signals (9):

- (+) [multimodal usability] → one wallet or payment credential starts working across public transport, shared mobility, tolls, and ancillary services without manual top-ups (payment friction collapsing)
- (+) [cross-border mobility] → regional passenger journeys settle instantly across different currency and payment systems (boundary friction easing)
- (+) [small-operator access] → local or cooperative services join larger mobility bundles because settlement integration becomes cheaper (market entry widening)
- (+) [pricing innovation] → operators deploy conditional, usage-based, or capped mobility products that settle automatically across providers (service bundling deepening)
- (+) [public administration] → subsidies, mobility credits, or social benefits are routed directly into interoperable travel wallets (policy delivery becoming programmable)
- (–) [privacy] → transport payments become more linkable to identity and travel history unless selective-disclosure designs are robust (traceability stakes increasing)
- (–) [resilience] → outages or policy freezes in core payment networks immediately affect access to transport services (financial infrastructure coupling visible)
- (–) [compliance burden] → smaller operators struggle with the identity and rule hooks required to join high-assurance payment networks (entry cost rising)
- (–) [market power] → wallet providers and liquidity intermediaries become new gatekeepers over passenger access and operator cash flow (payment control concentrating)

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

**Score:** 10 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport is heavily regulated, and the rules increasingly need to be interpreted in software across autonomous vehicles, curb management, accessibility, emissions, safety zones, insurance, and dynamic service conditions. Machine-readable regulation can transform the speed and consistency with which new mobility services are approved, monitored, and updated, with first-order effects in compliance cost and service adaptability; second-order effects in who controls rule implementation and audit trails; third-order effects in much more dynamically governed transport systems. In a 5.5M-person society this can clearly change how the GVN is operated and contested, especially in the challenger-regime shift toward software-defined transport. The score is 10 because

the magnitude is transformative, though the technology is still an institutional enabler rather than the direct mobility service itself.

Weak signals (9):

- (+) [autonomous deployment] → permits, operating envelopes, and reporting obligations for new mobility services are published in machine-executable form (compliance becoming software-native)
- (+) [curb and street governance] → dynamic pickup, parking, delivery, and priority rules are distributed as code that vehicles and platforms must consume (rules entering operations directly)
- (+) [accessibility] → compliance checking for ramps, service obligations, and passenger rights becomes automated against machine-readable requirements (rights enforcement tightening)
- (+) [operator agility] → service providers update offerings quickly after rule changes because software can test and implement them automatically (policy-to-operations lag shrinking)
- (+) [auditability] → disputes over fares, road use, or permits increasingly rely on clause-level machine traces rather than only human interpretation (enforcement becoming traceable)
- (–) [power] → actors who encode and maintain rule models gain outsized influence over how transport law is actually applied (translation layer becoming political)
- (–) [rigidity] → systems handle edge cases poorly when human discretion is replaced too aggressively by executable rules (justice trade-offs surfacing)
- (–) [small operators] → compliance software requirements create new barriers for informal or low-tech mobility providers (participation narrowing)
- (–) [security] → tampering with rule feeds or policy packages is treated as a critical transport governance risk (regulation becoming attack surface)

## ART 12.097 — Open Metaverse Interoperability Protocols

**Score:** 0 (Impact in GVN 1)

Justification (3 sentences):

Open metaverse protocols do not have a strong direct pathway into passenger transport beyond niche planning, training, or customer-experience layers. Those applications are too peripheral to the core GVN goal of moving people safely, affordably, and efficiently. The direct impact is therefore negligible.

Weak signals (4):

- (+) [planning and training] → transport agencies begin depending on interoperable immersive environments for everyday operations, wayfinding, or customer service (would create workflow linkage)
  - (+) [journey design] → passengers routinely use persistent shared virtual layers to coordinate physical travel and service access (would create hybrid mobility linkage)
  - (–) [operational relevance] → most mobility functions continue to rely on conventional apps, maps, and control systems (metaverse layer not needed)
  - (–) [investment] → transport budgets treat open-metaverse compatibility as optional marketing or design tooling (core demand absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 — Content Authenticity Infrastructure

**Score:** 3 (Impact in GVN 1)

Justification (3 sentences):

Passenger transport increasingly depends on trusted media: incident video, sensor evidence, maintenance records, public alerts, and synthetic guidance content. Content authenticity infrastructure can materially improve liability handling, misinformation resistance, and evidentiary trust around safety-critical or politically sensitive events. That is a meaningful governance and trust effect, though not a core mobility redesign.

Weak signals (6):

- (+) [incident accountability] → transport operators and regulators require signed provenance for camera, sensor, and maintenance media used in investigations (evidence trust tightening)
  - (+) [public safety communication] → passenger alerts and disruption notices carry verifiable authenticity markers across apps and displays (false-alert risk reducing)
  - (+) [autonomous systems] → synthetic training, simulation, and annotated media used in safety cases include provenance trails (AI evidence becoming auditable)
  - (–) [public trust] → uncredentialed but viral transport footage still shapes opinion faster than authenticated records (authenticity not equal reach)
  - (–) [power] → large platforms and certified hardware vendors dominate whose media counts as “trusted” in transport disputes (verification power concentrating)
  - (–) [privacy] → provenance-rich media creates new concerns when location, device, or operator identity becomes too visible (traceability trade-offs surfacing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 — Privacy-Preserving Collaboration Protocols

**Score:** 5 (Impact in GVN 1)

Justification (4 sentences):

Passenger transport is hampered by the inability of operators, cities, fleet providers, payment systems, and infrastructure managers to jointly analyze sensitive data. Privacy-preserving collaboration protocols can significantly improve joint planning, safety analysis, fraud detection, accessibility optimization, and demand management without requiring raw-data pooling. Second-order effects include new neutral compute layers and governance arrangements; third-order effects include stronger whole-system optimization—along with stronger dependence on shared cryptographic and policy infrastructure. That is a significant GVN effect.

Weak signals (9):

- (+) [cross-operator planning] → cities and private mobility providers begin running shared analytics on demand, congestion, and accessibility data without centralizing raw records (coordination friction falling)
- (+) [safety] → insurers, regulators, and operators compute joint risk or incident patterns without exchanging full event histories (shared oversight becoming feasible)
- (+) [fraud and fare integrity] → payment and ticketing actors use privacy-preserving joins to detect abuse across systems (trust without full exposure)



- (+) [accessibility] → agencies and operators coordinate around sensitive disability and assistance data using safe-compute protocols (service design improving without raw sharing)
- (+) [small-actor participation] → smaller providers gain access to shared insights without surrendering commercially sensitive data (collaboration base widening)
- (–) [infrastructure dependence] → a few neutral-compute providers become essential intermediaries for system-wide mobility analytics (control layer consolidating)
- (–) [performance] → slow or costly secure computation limits use in real-time operational settings (value staying uneven across tasks)
- (–) [governance] → disputes arise over acceptable outputs and whether “privacy-safe” results still disadvantage some users or providers (output politics emerging)
- (–) [security] → protocol or key-management failures are treated as system-wide trust incidents affecting transport governance (cryptographic fragility becoming material)

## ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

**Score:** 1 (Impact in GVN 1)

Justification (3 sentences):

This ART matters to passenger transport through safer and faster qualification of vehicles, chargers, autonomy hardware, and other advanced equipment. That can improve procurement confidence and reduce some adoption delays, but it remains an upstream industrial-enabling layer rather than a direct transport-service change. The impact is therefore limited.

Weak signals (4):

- (+) [equipment rollout] → transport buyers begin requiring machine-readable conformance certificates for autonomy hardware, chargers, and advanced components (qualification becoming standardized)
  - (+) [procurement speed] → new vehicle and infrastructure technologies move faster from pilot to routine tender because certification evidence is more portable (adoption friction easing)
  - (–) [supplier access] → smaller manufacturers struggle to afford the testing and certification stack needed for transport-grade approval (market entry tightening)
  - (–) [standard lock-in] → certification regimes favor incumbent designs and slow more radical alternatives (innovation pathway narrowing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## GVN 2: Logistics ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 – Global Broadband Connectivity

**Score:** 10 (Impact in GVN 2)

**Justification:**

Reliable, low-cost connectivity makes vehicles, depots, lockers, and remote corridors continuously addressable, which directly improves routing, tracking, exception handling, and delivery coverage in sparse areas. Institutionally, it supports platformized freight matching, remote operations centers, and direct manufacturer-to-consumer distribution, while also concentrating cyber risk and bargaining power in a smaller number of network/platform providers. Third-order effects include more home-centric logistics, lower inventory buffers, and easier integration of decentralized delivery assets. In a 5.5M-person society, the avoided delays, reduced failed deliveries, and expanded service reach can plausibly exceed the >€1B / hundreds-of-thousands-of-users threshold, so this is transformative but not uniquely the single linchpin.

- [Remote-area accessibility] → carriers add always-connected lockers in sparsely populated districts (coverage becomes serviceable)
- [Accuracy] → fleet contracts specify telemetry uptime SLAs (coordination becomes dependable)
- [Ease] → dispatch software reroutes loads continuously during disruptions (live control normalizes)
- [Crowdsourced participation] → small carriers join real-time freight apps outside cities (capacity pool widens)
- [Cloud services] → depots outsource support to remote control rooms (expertise centralizes)
- [Standardization and prevalence] → municipalities permit curbside smart delivery zones with backhaul (infrastructure follows platforms)
- [Systemic vulnerability] → cyber incidents hit multiple logistics operators through shared links (connectivity concentrates risk)
- [Bargaining power] → connectivity vendors bundle routing and telematics into exclusive contracts (platform dependency grows)
- [Accessibility] → remote merchants offer next-day delivery via connected line-haul hubs (market reach expands)

**ART 01.002 – Ultra-Low Latency Networks**

**Score: 5 (Impact in GVN 2)**

**Justification:**

Ultra-low latency matters where logistics becomes tightly choreographed: teleoperation, robotic hubs, platooning, automated gates, and fast safety loops in mixed human-machine spaces. Its main value is not generic bandwidth but the ability to make distributed control stable enough to replace local human reaction in critical sub-processes. Second-order effects include more centralized operations and new dependence on premium network layers that smaller operators may struggle to afford. That plausibly lands in the €100M–€1B / 50–500M person-hour range; a 10 would need this capability to become the default operating substrate across most depots and public corridors.

- [Autonomous hubs] → ports and depots deploy time-critical private networks (robot swarms stabilize)

- [Ease] → teleoperated exception handling replaces on-site specialists (remote intervention feasible)
- [Accuracy] → freight platooning pilots move from tests to scheduled service (coordination precision rises)
- [Shared infrastructure] → road authorities reserve low-latency roadside compute zones (corridor control emerges)
- [Cost-effectiveness] → contracts price premium for millisecond-grade service windows (latency becomes monetized)
- [Market structure] → only large depots can afford deterministic networking layers (scale advantage deepens)
- [Security] → regulators require fail-safe reporting after latency spikes halt robots (timing becomes safety issue)
- [Flexibility] → mixed fleets share dynamic priority rules at busy gates (throughput improves sharply)
- [Labor] → dispatcher roles shift toward supervising exception queues (human work recenters)

## ART 01.003 – Edge AI for Sensor Data

**Score: 10 (Impact in GVN 2)**

### **Justification:**

Edge AI lets vehicles, lockers, cameras, scanners, and warehouse devices interpret events locally rather than waiting for cloud processing, which is highly aligned with logistics needs for speed, resilience, and distributed operations. It directly enables anomaly detection, automated receiving, predictive maintenance, safer autonomous motion, and viable operation even with patchy connectivity. Institutionally it shifts evidence, control, and performance measurement toward machine judgments near the point of action, including more continuous worker surveillance and new disputes over machine-generated evidence. In magnitude, that can credibly exceed the >€1B / hundreds-of-thousands threshold because it changes how large portions of last-mile, depot, and fleet operations are actually run.

### **Weak signals (9):**

- [Accuracy] → depots deploy vision systems that flag damage at receipt (claims become immediate)
- [Ease] → lockers and vehicles locally verify parcel identity during handoff (latency disappears)
- [Security] → suspicious delivery patterns are blocked before cloud confirmation (threat response localizes)
- [Cost-effectiveness] → predictive maintenance on vans and conveyors reduces unplanned outages (downtime drops)
- [Flexibility] → mixed goods are sorted by AI vision without strict packaging uniformity (heterogeneity becomes manageable)

- [Remote areas] → fleets keep operating safely during network outages (autonomy survives disconnection)
- [Labor] → worker productivity scoring shifts from sample audits to continuous AI monitoring (surveillance intensifies)
- [Governance] → disputes rise over machine-generated evidence in damage and compliance cases (audit standards tighten)
- [Urban logistics] → micro-hubs run with minimal on-site staffing (small sites become viable)

## ART 01.004 – Quantum & High-Precision Sensing

**Score: 3 (Impact in GVN 2)**

### **Justification:**

This ART matters in logistics mainly in critical niches: GNSS-denied navigation, high-assurance timing, cargo inspection, and early detection of infrastructure faults that affect freight corridors. Those are real operational gains, especially for ports, tunnels, hazardous goods, and anti-spoofing, but they do not by themselves remake the overall operating model. The main second-order effect is improved security and resilience for high-value or high-risk logistics rather than sector-wide reorganization. That places it in the €10M–€100M / 5–50M person-hour band; a 5 would require broad rollout beyond critical corridors and premium segments.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → autonomous freight pilots advertise GNSS-denied positioning in tunnels and ports (spoofing risk falls)
- [Security of supply] → critical-freight operators buy ultra-stable timing modules for route control (timing integrity matters)
- [Infrastructure maintenance] → bridge and rail freight owners trial high-precision gravimetric monitoring (hidden failure detection)
- [Cost-effectiveness] → adoption concentrates in hazardous or high-value corridors only (general use stays narrow)
- [Customs/security] → non-invasive sensing units detect concealed materials in sealed loads (inspection quality rises)
  - [Standardization] → insurers treat quantum-sensing certification as a premium add-on (niche remains premium)

## ART 01.005 – Micro/Nano Sensor Networks

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Dense cheap sensor networks turn packages, containers, equipment, loading zones, and warehouse structures into continuously monitored assets. Directly, they reduce manual inspection and make damage, congestion, and degradation visible earlier; institutionally, they shift liability, maintenance

contracts, and inventory control toward real-time data-rich management. Third-order effects include tighter replenishment loops and more viable small-batch or distributed logistics because visibility is no longer expensive. That is significant enough for a 5; a 10 would need sensor networks to become near-universal across most freight and logistics infrastructure.

#### **Weak signals (9):**

- [Accuracy] → trailers, pallets, and shelves expose continuous strain and vibration data (damage seen earlier)
- [Ease] → inbound receiving shifts from spot checks to ambient sensing (manual inspection shrinks)
- [Security of supply] → cold-chain lanes use dense sensor patches on containers (excursions become traceable)
- [Cost-effectiveness] → maintenance is triggered by wear signals from yard equipment (service becomes predictive)
- [Flexibility] → mixed, small-batch flows stay visible without bespoke instrumentation (heterogeneity becomes manageable)
- [Accessibility] → low-cost sensor meshes appear in SME warehouse packages (capability diffuses)
- [Data governance] → platform operators require raw sensor feeds from subcontractors (information asymmetry widens)
- [Cybersecurity] → interference and spoofing reports target dense sensor meshes in depots (trust needs hardening)
- [Urban planning] → municipalities monitor curb usage and loading zones continuously (delivery rules get dynamic)

## **ART 01.006 – Privacy-Preserving Pervasive Sensing**

### **Score: 3 (Impact in GVN 2)**

#### **Justification:**

The main logistics value here is that it lowers social and regulatory resistance to camera-heavy, locker-heavy, home-adjacent, and worker-adjacent sensing. Directly, that enables more acceptable monitoring in last-mile delivery, shared lockers, curb management, and mixed human-robot depots; second-order effects include more subtle forms of surveillance because sensing becomes easier to legitimate. The impact is real but mostly enabling rather than standalone. I therefore score it 3; a 5 would require privacy-preserving sensing to clearly unlock large-scale deployment that was otherwise blocked.

#### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Home-centric delivery] → last-mile cameras shift to on-device recognition with no raw upload (trust barrier drops)
- [Labor relations] → union deals permit local-only analytics but ban raw video retention (adoption becomes negotiable)
- [Shared smart lockers] → occupancy and misuse alerts are sold with privacy proofs (locker networks scale)

- [Governance] → regulators fine operators for non-compliant “privacy-washed” sensing claims (credibility becomes testable)
- [Cross-border logistics] → firms deploy shared analytics where raw data export was blocked (coordination unlocks)
- [Power] → proprietary privacy chips become a new vendor lock-in point (control recentralizes)

## ART 01.007 – Quantum-Resilient and Secure Communication Networks

**Score: 3 (Impact in GVN 2)**

### **Justification:**

This ART matters because logistics is increasingly a critical infrastructure stack with long-lived manifests, routing histories, control links, and cross-border data exchanges. Direct impact is mostly defensive: safer remote operations, lower risk of future decryption of sensitive flows, and stronger trust in multi-party coordination. Institutionally, it raises the bar for critical-freight operators and can widen the gap between large and small firms that can afford managed secure-network upgrades. The likely magnitude is material but bounded, so 3 is appropriate; a 5 would need security demands to become pervasive across routine logistics, not mainly critical or regulated segments.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → logistics tenders require post-quantum protection for control links (long-lived data hardened)
- [Ports and customs] → upgrade cycles begin around secure routers for freight control systems (critical status rises)
- [Cross-firm coordination] → multi-operator data exchanges advertise quantum-resilient trust guarantees (shared planning safer)
- [Cost structure] → small carriers buy managed secure-network services instead of owning stacks (dependency shifts upward)
- [Cyber incidents] → regulators cite weak crypto transitions after fleet-control breaches (migration becomes urgent)
- [Insurance] → cyber policies differentiate secure-by-design fleets and depots (risk pricing changes)

## ART 01.008 – Integrated Sensing and Communication (ISAC)

**Score: 5 (Impact in GVN 2)**

### **Justification:**

ISAC is attractive for logistics because it turns the communications layer itself into a situational-awareness layer for roads, depots, yards, and loading zones. Directly, that cuts the need for separate tracking/safety infrastructure; institutionally, it gives telecom and site-infrastructure owners more control over visibility and operating conditions. Third-order effects include dynamic curb management, denser autonomous traffic, and more software-defined flow control in physical logistics spaces. That reaches the 5 band; a 10 would require widespread deployment across public freight corridors and most urban logistics zones.



**Weak signals (9):**

- [Shared infrastructure] → private 6G and warehouse networks sell location and safety layers together (comms and sensing merge)
- [Accuracy] → depots track forklifts, robots, and parcels without separate sensor grids (visibility becomes infrastructure)
- [Ease] → urban delivery zones use network sensing to manage curb occupancy (curb orchestration sharpens)
- [Cost-effectiveness] → carriers drop standalone tracking hardware where radio infrastructure already senses motion (capex consolidates)
- [Flexibility] → mixed fleets coordinate in cluttered yards with fewer blind spots (dense traffic becomes manageable)
- [Privacy] → cities face complaints about passive sensing of workers and residents (acceptance becomes contested)
- [Market power] → telecom and infrastructure owners control operational visibility layers (coordination power centralizes)
- [Security] → anomalies near high-value cargo are flagged by network reflections (perimeter awareness improves)
- [Regulation] → safety cases for autonomous depots reference network-based situational sensing (infrastructure becomes certified)

**2. Computing Hardware & Non-Von-Neumann Paradigms****ART 02.009 – Compute-in-Memory & Neuromorphic Chips****Score: 3 (Impact in GVN 2)****Justification:**

For logistics, the main value is cheaper, lower-power embedded intelligence in scanners, cameras, robots, vehicles, and dense sensor environments. That can materially reduce latency, power draw, and device cost in distributed logistics systems, but the operating-model change is mostly captured by the downstream AI and autonomy ARTs rather than this chip layer itself. Second-order effects include wider AI adoption by SMEs and less dependence on cloud inference. I therefore score it 3; a 5 would require this hardware to become the decisive enabler of mass edge autonomy across most logistics nodes.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → sensor and robot vendors advertise always-on local inference at lower power (embedded AI gets cheaper)
- [Remote areas] → autonomous nodes operate longer off-grid or on small batteries (distributed deployment broadens)
- [Ease] → handheld scanners and wearables add richer local decision support (field work accelerates)
- [Market structure] → a few chip-toolchain vendors dominate logistics AI devices (hardware dependence grows)

- [Accessibility] → SME warehouse packages include advanced edge analytics by default (capability diffuses downward)
- [Standards] → procurement starts specifying supported low-power AI runtimes (ecosystem lock-in hardens)

## ART 02.010 – Novel transistor technologies and materials beyond silicon CMOS

**Score: 1 (Impact in GVN 2)**

### **Justification:**

This is an upstream general-purpose hardware improvement rather than a distinct logistics operating technology. In mature form it would lower the cost, heat, and power burden of electronics across fleets, depots, and sensing systems, but most logistics value would still be mediated through downstream robotics, AI, and connectivity applications. That makes it worth watching, yet the logistics-specific linkage is too indirect for a higher score. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → logistics device vendors market longer-lived always-on electronics (hardware overhead shrinks)
- [Ease] → more compute appears in low-maintenance field devices and smart labels (capability spreads quietly)
- [Supply chains] → freight OEMs shift procurement toward new semiconductor ecosystems (upstream dependence changes)
- [Autonomy] → entry-level robots gain features previously limited to premium hardware (capability threshold falls)

## ART 02.011 – Quantum Computing Platforms

**Score: 3 (Impact in GVN 2)**

### **Justification:**

Quantum platforms could matter where logistics faces very large combinatorial planning problems: route design, network reconfiguration, fleet scheduling, and some cryptographic tasks. The direct operational upside is mostly in planning and scenario analysis rather than daily mechanical movement of goods. Second-order effects include advantage concentrating in carriers, platforms, and 3PLs with access to premium compute services. That is material enough for a 3; a 5 would require routine operational use that clearly outperforms advanced classical optimization across a broad share of logistics planning.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → route-optimization vendors publish hybrid quantum freight solvers (planning stack changes)

- [Flexibility] → disruption-planning tools benchmark quantum-assisted scenario runs (reconfiguration gets faster)
- [Market structure] → large shippers sign premium compute deals unavailable to smaller carriers (planning power concentrates)
- [Governance] → users demand auditable reasons when quantum recommendations override standard plans (trust becomes issue)
- [Security] → logistics cryptography roadmaps explicitly reference future quantum compute threats (planning and security couple)
- [Operational uptake] → usage remains concentrated in network design, not dispatch (impact stays bounded)

## ART 02.012 – Photonic and Optical Computing

**Score: 1 (Impact in GVN 2)**

### **Justification:**

For logistics this mainly lowers the back-end compute burden of AI, digital twins, and network optimization. That is useful, especially for large platforms and cloud providers serving logistics, but it does not create a distinct logistics pathway of its own. The value is therefore indirect and mostly captured by other ARTs. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Digital platforms] → logistics SaaS vendors advertise lower-cost high-volume optimization at scale (backend efficiency rises)
- [Interoperability] → large twin and planning providers move workloads to optical accelerators (compute bottlenecks ease)
- [Market structure] → only hyperscale providers capture most benefits (advantage centralizes)
- [Simulation] → real-time scenario planning becomes cheaper in large logistics control towers (planning refresh quickens)

## ART 02.013 – Next-Gen Memory & Storage

**Score: 1 (Impact in GVN 2)**

### **Justification:**

The logistics relevance here is primarily better local state retention and larger histories for edge devices, vehicles, and digital twins. That can improve audit trails and offline resilience, but it is still an enabling hardware layer rather than a direct shaper of logistics structure. Most of the value would be realized through other sensing, AI, and twin systems. I therefore assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → vehicles and lockers store longer local event histories without cloud sync (audit resilience improves)
- [Security of supply] → depots retain richer local state during outages (recovery becomes cleaner)
- [Market structure] → fleet software starts depending on proprietary storage formats and persistence layers (lock-in deepens)
- [Digital twins] → high-frequency asset histories remain live instead of being aggressively compressed (model fidelity rises)

## ART 02.014 – Molecular Computing

**Score: 0 (Impact in GVN 2)**

### Justification:

I do not see a clear, defensible pathway by which molecular computing materially changes how this logistics GVN moves goods. Any effect would be highly indirect through unrelated sectors or very specialized sensing niches that are too speculative to count as meaningful logistics impact. So I assign 0 and treat the signals below as watchpoints that would create a linkage.

### Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Smart packaging] → vendors pilot chemical-compute labels that make local spoilage or handling decisions (would create pathway)
- [Hazmat logistics] → microfluidic cartridges start taking onboard classification decisions inside shipments (would embed computation)
- [Regulation] → transport authorities publish handling rules for reactive computation media (would permit deployment)
- [Cold chains] → package-level biochemical controllers connect to standard logistics APIs (would make linkage real)

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 – Causal Learning & Reasoning

**Score: 5 (Impact in GVN 2)**

### Justification:

Causal AI fits logistics because operators constantly need to ask intervention questions: what happens if a route changes, a depot closes, a tariff appears, or a delivery promise tightens. Directly it improves disruption response, inventory policy, network design, and the ability to explain operational changes; institutionally it can shift accountability from intuition and trial-and-error toward auditable modeled assumptions. Third-order effects include less bullwhip amplification and better balancing of efficiency versus resilience. That places it solidly in the 5 band; a 10 would require causal models to become the dominant control logic for most logistics decisions, not mainly decision support.

**Weak signals (9):**

- [Accuracy] → TMS and WMS vendors add “what if” intervention engines (decisions become counterfactual)
- [Cost-effectiveness] → carriers test causal models before changing service levels or routes (bad experiments shrink)
- [Security of supply] → disruption playbooks reference modeled knock-on effects across suppliers (resilience planning deepens)
- [Flexibility] → operators simulate heterogeneous flow rules before seasonal peaks (policy tuning improves)
- [Governance] → disputes arise over whose causal assumptions are embedded in planning tools (model power matters)
- [Labor] → planner roles shift from crafting plans to auditing model assumptions (skill profile changes)
- [Market structure] → large platforms expose causal simulation as a premium planning service (advantage monetizes)
- [Urban planning] → municipalities test delivery-zone policies in logistics models before rollout (policy gets datafied)
- [Accessibility] → smaller shippers buy causal planning as software rather than consultancy (capability diffuses)

**ART 03.016 – Federated & Privacy-Preserving Learning****Score: 5 (Impact in GVN 2)****Justification:**

Fragmented logistics systems often sit on valuable but siloed data across carriers, depots, retailers, and public infrastructure. Federated learning directly unlocks shared forecasting, routing, anomaly detection, and safety models without centralizing raw operational data, which is especially relevant in a vertically fragmented sector. Institutionally it can reduce some data monopolies, but it can also create new governance layers and consortium gatekeepers. The plausible impact is significant enough for a 5; a 10 would require federated learning to become the standard learning layer across most logistics ecosystems.

**Weak signals (9):**

- [Accuracy] → competing carriers join shared forecasting or ETA-learning consortia (sector learning becomes pooled)
- [Security of supply] → critical corridors use cross-operator incident models without raw data sharing (resilience collaboration deepens)
- [Accessibility] → SMEs receive improved shared models while keeping local data in place (small firms benefit)
- [Cost-effectiveness] → insurers accept federated risk models for pricing and prevention (coordination gains monetize)
- [Governance] → disputes emerge over who controls aggregation servers and update rules (consortium power hardens)
- [Market structure] → major platforms demand participation in federated ecosystems as a service condition (entry becomes conditional)

- [Privacy] → regulators approve logistics analytics that were previously blocked by data-sharing concerns (compliance unlocks adoption)
- [Urban logistics] → public and private actors co-train curb-demand or congestion models (city coordination improves)
- [Security] → poisoning or update-manipulation events trigger monitoring standards (shared learning becomes attack surface)

## ART 03.017 – Trustworthy AI Systems

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Logistics only adopts high-autonomy AI at scale if failures, biases, and unsafe behavior can be monitored, audited, and bounded. Directly, trustworthy AI lowers deployment friction in routing, warehouse control, inspection, and customer-facing automation; institutionally, it affects insurance, regulation, and labor acceptance because accountability becomes more legible. Third-order effects include more automated operations but also tighter algorithmic governance over workers and subcontractors. This is a strong 5; a 10 would require trustworthy AI to become the decisive bottleneck whose resolution releases sector-wide autonomous logistics.

### **Weak signals (9):**

- [Accuracy] → logistics AI procurement requires confidence estimates and audit logs (opaque systems lose ground)
- [Security of supply] → fallback-mode reporting becomes mandatory in autonomous depots (safe degradation matters)
- [Cost-effectiveness] → insurers offer better terms to operators with verified AI monitoring stacks (trust gets priced)
- [Labor relations] → unions negotiate review rights over algorithmic assignment and scoring systems (oversight institutionalizes)
- [Governance] → litigation cites absent provenance and auditability after AI-caused losses (trust tools become compulsory)
- [Market structure] → certified trustworthy-AI platforms command premium access to regulated logistics work (compliance favors incumbents)
- [Regulation] → authorities publish sector-specific AI assurance templates for freight and warehousing (deployment path clarifies)
- [Accessibility] → SMEs buy managed AI assurance services instead of building internal audit teams (capability spreads)
- [Security] → adversarial-input incidents in sorting or routing trigger tighter validation regimes (robustness becomes visible)

## ART 03.018 – Automated Machine Learning (AutoML)

**Score: 5 (Impact in GVN 2)**

### **Justification:**

AutoML matters because logistics has many local modeling problems but limited data science talent across smaller carriers, depots, and municipalities. Directly it reduces the cost of building



forecasting, routing, anomaly detection, and scheduling models; institutionally it broadens adoption while also increasing dependence on software vendors and reward-design choices. Third-order effects include faster local experimentation and quicker adaptation to volatile flows. That is enough for a 5; a 10 would require AutoML to become the main route by which most logistics intelligence is built and maintained.

#### **Weak signals (9):**

- [Accessibility] → SME carriers launch route and demand models without dedicated data-science teams (capability broadens)
- [Flexibility] → depots retrain local prediction models around seasonal shifts in days not months (adaptation speeds up)
- [Cost-effectiveness] → operations software markets “self-optimizing” planning modules as standard features (modeling commoditizes)
- [Accuracy] → automated feature and policy search improves parcel ETA quality on local data (performance lifts quickly)
- [Governance] → bad reward settings create unsafe or unfair dispatch behavior (automation mis-specifies goals)
- [Market structure] → large software suites lock customers into proprietary AutoML pipelines (vendor dependence deepens)
- [Security of supply] → maintenance and exception models update continuously from fresh fleet data (resilience improves)
- [Labor] → analyst roles shift toward data stewardship and guardrail design (skill mix changes)
- [Compliance] → regulators ask for model lineage when AutoML-generated rules affect service access (documentation burden rises)

## **ART 03.019 – Collaborative Multi-Agent AI**

**Score: 20 (Impact in GVN 2)**

#### **Justification:**

This ART sits at the center of the challenger regime because flexible logistics increasingly depends on many distributed actors—vehicles, robots, depots, lockers, and digital agents—coordinating in real time. Directly it enables dynamic load pooling, shared maps, automated handoffs, and decentralized response to disruptions; institutionally it shifts power toward orchestration platforms while shrinking classic dispatch and coordination roles. Third-order effects include dense urban choreography, viable low-density service through pooled capacity, and a software-defined logistics layer that changes how goods movement is organized. The autonomous, highly responsive logistics model described in the GVN is much harder to realize without this, so 20 is justified.

#### **Weak signals (9):**

- [Flexibility] → carriers pool loads through AI brokers that reassign vehicles mid-route (capacity gets fluid)
- [Accuracy] → depots coordinate robots, doors, and vehicles from one shared task graph (handoffs tighten)

- [Cost-effectiveness] → empty-return kilometers fall in regions using cross-fleet agent coordination (network waste shrinks)
- [Accessibility] → SMEs join shared dispatch layers instead of building standalone control stacks (small actors plug in)
- [Remote areas] → agent networks bundle low-density demand into viable schedules (coverage improves)
- [Labor] → dispatch offices shrink as humans move to exception handling (coordination jobs erode)
- [Power] → orchestration platforms demand privileged access to fleet and customer data (platform leverage grows)
- [Security] → cascading failures are reported when shared agents misallocate capacity (systemic risk appears)
- [Urban planning] → curb, locker, and depot slots are negotiated automatically across actors (physical flow gets software-defined)

## ART 03.020 – Quantum-Accelerated AI Systems

**Score: 1 (Impact in GVN 2)**

### **Justification:**

This is a second-order optimization layer on top of already advanced AI rather than a distinct logistics operating technology. It could improve some hard planning or training problems, but the logistics linkage remains narrow and concentrated in premium use cases. Most firms would experience its benefits, if any, through outsourced platform services rather than direct operational redesign. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → elite planning vendors market quantum-assisted scheduling or search (niche premium appears)
- [Market structure] → large carriers sign exclusive access deals for premium hybrid AI compute (advantage concentrates)
- [Accessibility] → benefits remain bundled inside black-box platforms rather than diffusing broadly (spillover stays limited)
- [Disruption planning] → rare-event scenario search is marketed as a quantum-AI feature (would enlarge planning linkage)

## ART 03.021 – AI-Driven Autonomous Scientific Discovery

**Score: 1 (Impact in GVN 2)**

### **Justification:**

This could accelerate the R&D pipeline for better batteries, materials, packaging, and logistics software, but that is an indirect technology-development effect rather than a direct logistics operating shift. The sector may benefit from faster innovation cycles, yet the causal chain is long and diffuse. So it is worth monitoring but not scoring high for this GVN itself. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Innovation capacity] → logistics OEMs adopt AI-run materials and component discovery partnerships (upstream R&D speeds up)
- [Cost-effectiveness] → packaging and battery suppliers credit autonomous discovery for faster product cycles (spillover reaches logistics)
- [Market structure] → discoveries remain concentrated in a few large suppliers (benefits diffuse unevenly)
- [Supply chains] → time from lab concept to logistics component trial shortens markedly (would strengthen linkage)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 – Immersive Augmented & Virtual Reality

**Score: 5 (Impact in GVN 2)**

**Justification:**

AR/VR can materially change logistics work by compressing training, remote support, teleoperation, and spatial problem-solving in warehouses, ports, and delivery operations. Directly it reduces travel and setup errors; institutionally it centralizes scarce expertise and can intensify worker monitoring through persistent guided workflows. Third-order effects include faster scaling of new sites and more viable remote exception handling. That places it in the 5 band; a 10 would require immersive interfaces to become the dominant mode of operating logistics environments.

**Weak signals (9):**

- [Ease] → pickers and maintenance staff use AR guidance as a default workflow (procedural work spatializes)
- [Accuracy] → remote experts resolve warehouse exceptions through first-person immersive views (travel need falls)
- [Cost-effectiveness] → onboarding time for seasonal labor falls after VR simulation training (ramp-up compresses)
- [Security of supply] → ports and depots rehearse disruption playbooks in shared twins (preparedness improves)
- [Labor] → worker acceptance debates focus on continuous gaze and gesture tracking (monitoring intensifies)
- [Market structure] → headset/software vendors bundle logistics workflows into closed ecosystems (tool dependence grows)
- [Accessibility] → scarce specialists support many small sites from centralized control rooms (expertise stretches)
- [Flexibility] → temporary micro-hubs open faster with immersive remote commissioning (site setup accelerates)
- [Safety] → incident reporting standards emerge around mixed-reality use in active yards (human factors matter)

## ART 04.023 – Brain-Computer Interfaces (BCI)

**Score: 1 (Impact in GVN 2)**

**Justification:**

BCI has possible niche logistics uses in hands-free teleoperation, accessibility, and specialized control roles, but the linkage to the overall logistics operating model is weak. Even in a mature state, ordinary voice, gesture, AR, and automation are likely to capture most of the same value more cheaply. The most plausible impact is inclusion of a limited set of workers and niche control improvements. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accessibility] → logistics teleoperation centers trial BCI for workers with limited motor control (niche inclusion appears)
- [Ease] → hands-free control pilots emerge in sterile, noisy, or gloved environments (special-case interface value)
- [Governance] → employers and unions negotiate neural-data boundaries for work use (privacy barrier visible)
- [Safety] → BCI is paired with robotic handling in tasks where manual input is constrained (would create clearer path)

## ART 04.024 – Advanced Prosthetics & Exoskeletons

**Score: 5 (Impact in GVN 2)**

**Justification:**

This ART maps directly to a major logistics bottleneck: repetitive lifting, carrying, walking, and awkward handling in depots, stores, and last-mile operations. Directly it can reduce injuries, fatigue, and absenteeism; institutionally it reshapes labor standards, extends participation, and may also intensify work expectations because physical limits shift. Third-order effects include slower full automation in some roles because human physical capability improves. The scale of injury avoidance and labor-force effects plausibly supports a 5.

**Weak signals (9):**

- [Cost-effectiveness] → warehouse operators procure exoskeleton fleets for picking and loading (ergonomic capex normalizes)
- [Accuracy] → workers handle heavy or awkward items with lower drop and damage rates (manual quality improves)
- [Accessibility] → recruitment expands to older or mobility-limited workers (labor pool widens)
- [Ease] → delivery routes include wearable assistance for stairs and dense urban hand-carry tasks (last-mile burden drops)
- [Labor relations] → contracts address whether aided workers may be assigned heavier quotas (work intensification risk)

- [Insurance] → claims handling begins distinguishing aided and unaided manual roles (risk models change)
- [Security of supply] → peak-season operations sustain output despite labor shortages (capacity becomes steadier)
- [Training] → exosuit certification appears in warehouse and delivery onboarding (new skill layer forms)
- [Market power] → wearable vendors tie service contracts to proprietary analytics and maintenance (dependency deepens)

## ART 04.025 – Haptic and Multi-Sensory Feedback Systems

**Score: 3 (Impact in GVN 2)**

### **Justification:**

The clearest logistics pathway is better teleoperation and finer control in remote handling, delicate picking, and hazardous or inaccessible environments. That is meaningful for ports, cold stores, high-value cargo, and exception handling, but it does not change most logistics flows.

Institutionally it centralizes scarce manual expertise into remote control setups. I assign 3; a 5 would need remote handling to become routine across broad swathes of warehousing and delivery operations.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Ease] → teleoperators gain force feedback for remote loading and exception handling (precision improves)
- [Accuracy] → damage rates fall in fragile-goods handling when tactile cues are added (remote manipulation matures)
- [Safety] → hazardous or cold environments shift toward haptic teleoperation (human exposure drops)
- [Market structure] → remote-control platforms bundle proprietary haptic devices with service contracts (tool lock-in grows)
- [Accessibility] → central experts supervise more sites through rich feedback consoles (skills stretch farther)
- [Training] → certification regimes appear for remote tactile operation in ports and depots (use remains specialized)

## ART 04.026 – AI Understanding of Human Intent & Context

**Score: 3 (Impact in GVN 2)**

### **Justification:**

This ART mainly reduces interface friction between workers, dispatch systems, robots, and customers. Directly it helps interpret spoken requests, gestures, customer constraints, and contextual cues in busy logistics settings; second-order it also deepens behavioral surveillance and subtle algorithmic nudging. The impact is real but mostly incremental compared with more structural autonomy and traceability technologies. I therefore score it 3; a 5 would require intent-aware systems to become standard control interfaces across last-mile and warehouse operations.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Ease] → dispatch tools infer exceptions from voice, posture, and context instead of fixed forms (interaction friction drops)
- [Accessibility] → multilingual or low-literacy workers use more natural interfaces in depots (participation widens)
- [Customer delivery] → systems infer preferred handoff windows and modalities from behavior (failed deliveries fall)
- [Labor] → worker acceptance debates focus on emotion or intent inference at work (surveillance concerns rise)
- [Governance] → complaints target opaque behavioral scoring used in assignment systems (context models gain power)
- [Human-robot collaboration] → shared workcells adapt speed and prompts to operator state (would raise linkage)

**ART 04.027 – Brain-to-Brain Interfaces**

**Score: 0 (Impact in GVN 2)**

**Justification:**

I do not see a defensible mature-state pathway by which brain-to-brain interfaces materially change logistics operations for moving goods and materials. Any possible use is too speculative and too far from the stated logistics bottlenecks relative to more conventional coordination tools. So I assign 0 and treat the signals below as watchpoints only.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Remote coordination] → emergency-response logistics trials experiment with direct shared-state interfaces (would create first pathway)
- [Teleoperation] → specialized handling teams test BBI-assisted joint manipulation (would define niche use)
- [Governance] → workplace policies begin addressing inter-person neural data exchange (would signal real deployment)
- [Accessibility] → disability-focused logistics pilots adopt BBI for collaborative control (would create concrete linkage)

**ART 04.028 – Memory Prostheses**

**Score: 1 (Impact in GVN 2)**

**Justification:**

The logistics linkage is limited to supporting some workers in high-procedure or interruption-heavy roles. That could matter at the margin for safety-critical handling, maintenance, and complex exception management, but it does not reshape the logistics operating model. The main value would be inclusion and reduced cognitive lapses in a narrow set of tasks. I assign 1.



**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Safety] → pilots target workers in high-procedure maintenance or hazardous-goods roles (niche reliability value)
- [Accessibility] → supported-return-to-work programs include implanted or wearable memory aids (inclusion pathway appears)
- [Governance] → employers are restricted from mandating cognitive implants for performance (boundary setting matters)
- [Training] → procedural recall aids are linked into logistics certification systems (would tighten sector linkage)

## 5. Robotics & Physical Autonomy

### ART 05.029 – Self-Driving Vehicles

**Score: 20 (Impact in GVN 2)**

**Justification:**

This is the clearest keystone technology in the challenger logistics regime because it directly changes who or what performs freight movement on shared road infrastructure. Directly it transforms line-haul, last-mile, scheduling, utilization, and delivery coverage; institutionally it resets labor relations, liability, insurance, urban planning, and the competitive position of fleet operators. Third-order effects include more home-centric delivery, less dependence on consumer self-transport, changed retail geography, and more software-defined logistics. The autonomous, smart-robotized logistics model in the GVN is much harder to realize without self-driving freight, so 20 is warranted.

**Weak signals (9):**

- [Ease] → driverless freight routes move from pilot windows to routine schedules (autonomy normalizes)
- [Cost-effectiveness] → carriers report lower asset downtime through near-24/7 autonomous utilization (utilization jumps)
- [Remote areas] → low-density routes regain service via autonomous vans and trucks (coverage improves)
- [Urban planning] → municipalities redesign curbspace and micro-hubs for unmanned transfer (streets adapt)
- [Shared smart lockers] → unmanned delivery vehicles increasingly hand off to lockers rather than people (last-mile model shifts)
- [Employment] → commercial driver training demand falls and retraining programs expand (labor transition starts)
- [Security] → cargo theft and spoofed-sensor incidents target unattended vehicles (new attack surface)
- [Regulation] → minimum remote-supervisor and incident-reporting rules are formalized (governance hardens)

- [Market structure] → large fleets consolidate share by spreading autonomy capex and data advantage (scale power rises)

## ART 05.030 – Drone Swarms & Aerial Robots

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Drone swarms are not the core of everyday logistics, but they can materially change remote-area delivery, urgent shipments, yard inspection, inventory checks, and post-disruption response. Directly they improve speed and access where ground routes are costly or slow; institutionally they create new airspace, noise, privacy, and security questions. Third-order effects include new illicit-delivery risks and a sharper split between dense urban/no-fly environments and regions where aerial logistics becomes normal. That supports a 5; a 10 would require drone delivery to become a mainstream last-mile layer rather than a targeted complement.

### **Weak signals (9):**

- [Remote-area accessibility] → operators schedule regular aerial delivery rounds to sparse settlements (coverage expands)
- [Accuracy] → inventory and yard inspections shift from periodic manual checks to routine swarm scans (visibility quickens)
- [Cost-effectiveness] → urgent medical and high-value parcels use standardized drone lanes (premium service routinizes)
- [Flexibility] → temporary swarms are deployed after storms or road closures (disruption response accelerates)
- [Security] → ports and depots report spoofing, theft, or contraband-delivery incidents by drone (dual-use risk rises)
- [Governance] → municipalities codify noise, privacy, and corridor restrictions for delivery drones (public acceptance contested)
- [Shared infrastructure] → rooftops and depots add drone docks and automated battery handling (support network forms)
- [Labor] → inspector and courier roles partially shift toward remote supervision (job mix changes)
- [Market structure] → large platforms reserve prime corridors and vertiports before smaller entrants (airspace access concentrates)

## ART 05.031 – Humanoid and General-Purpose Robots

**Score: 10 (Impact in GVN 2)**

### **Justification:**

General-purpose robots directly attack a core logistics bottleneck: large volumes of repetitive but irregular physical work in spaces built for humans. In mature form they can load, unload, sort, relabel, move returns, replenish local nodes, and perform off-hours tasks without major rebuilding of every facility. Institutionally they reshape labor demand, safety regimes, facility design, and vendor dependence on robot platforms and update ecosystems. That is transformative for how

logistics is realized, but still less keystone than self-driving road vehicles and traceability networks, so I assign 10.

### **Weak signals (9):**

- [Ease] → depots run night shifts with robot unloading and shelf replenishment (24/7 operations emerge)
- [Flexibility] → robots handle mixed parcel shapes without custom line redesign (heterogeneity automates)
- [Accessibility] → small urban micro-hubs open with minimal staffing (micro-fulfillment scales)
- [Accuracy] → returns, relabeling, and exception handling move from manual tables to robot cells (error-prone work drops)
- [Cost-effectiveness] → peak-season labor shortages are offset with rented robot fleets (capacity becomes leasable)
- [Employment] → wage pressure and redeployment disputes rise in warehousing and store backrooms (manual roles shrink)
- [Safety] → regulators require incident disclosure for human-robot contact in mixed zones (safety case matures)
- [Power] → robot vendors bundle software, spare parts, and financing into long lock-in contracts (vendor dependence deepens)
- [Urban structure] → retailers shift space from parking and stockrooms to automated pick-up nodes (land use changes)

## **ART 05.032 – Soft Robotics & Bio-Inspired Machines**

### **Score: 5 (Impact in GVN 2)**

#### **Justification:**

Soft robotics matters in logistics where goods are variable, fragile, slippery, or awkward for rigid automation. Directly it enables gentler handling of food, pharma, irregular parcels, and returns; institutionally it can lower packaging requirements and ergonomic strain while shifting labor from manual dexterity to supervision. Third-order effects include more automation in categories previously left manual because item variability was too high. That is a meaningful 5; a 10 would require soft-robotic handling to become a dominant default across mainstream logistics nodes.

### **Weak signals (9):**

- [Flexibility] → mixed-goods picking lines adopt soft grippers instead of manual exception tables (heterogeneity automates)
- [Accuracy] → damage rates fall for fragile food, pharma, and consumer goods (gentle handling pays)
- [Cost-effectiveness] → packaging specs loosen because handling no longer needs rigid standard shapes (secondary savings appear)
- [Ease] → returns centers automate sorting of deformable or awkward goods (manual burden shrinks)
- [Labor] → manual dexterity roles are reclassified into robot oversight and maintenance (job content shifts)

- [Standards] → hygiene and durability certification expands for soft end-effectors in food logistics (adoption gated)
- [Accessibility] → smaller facilities lease soft-robot cells for variable inventory mixes (automation diffuses)
- [Market structure] → integrators bundle proprietary end-effectors with service ecosystems (tool lock-in grows)
- [Waste reduction] → gentler automation reduces over-packaging and handling spoilage (waste falls upstream)

## ART 05.033 – Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 5 (Impact in GVN 2)**

### Justification:

This bundle matters most at the edges of logistics: ports, yards, tunnels, remote sites, infrastructure inspection, disaster response, and hazardous environments. Directly it reduces human travel and exposure while increasing persistence of monitoring and servicing; institutionally it centralizes expert control and changes how remote or risky logistics nodes are staffed. Third-order effects include more resilient critical logistics infrastructure and more dependence on remote supervisory control. That supports a 5 rather than a 10 because the main impact is strong but concentrated in specific subdomains.

### Weak signals (9):

- [Security of supply] → ports and yards shift routine inspection rounds to autonomous surface or aerial robots (presence becomes persistent)
- [Ease] → remote operators supervise multiple sites instead of traveling to each one (expertise centralizes)
- [Accuracy] → digital maps from autonomous inspection feed directly into maintenance and routing (asset state becomes live)
- [Hazard reduction] → hazardous, underwater, or confined-space logistics tasks are delegated to autonomous machines (human exposure falls)
- [Security] → communication loss or spoofing incidents trigger new supervision requirements (autonomy boundaries harden)
- [Labor] → on-site inspection and support roles decline at remote logistics assets (staffing pattern changes)
- [Flexibility] → disaster logistics uses autonomous robots to reopen routes faster (recovery speeds up)
- [Market structure] → rugged autonomous-service providers win long-term critical-infrastructure contracts (service market concentrates)
- [Governance] → regulators set certified operating envelopes for unsupervised robotic activity near freight assets (liability formalizes)

## ART 05.034 – Supportive Infrastructure for Autonomy

**Score: 10 (Impact in GVN 2)**

**Justification:**

Autonomy-supporting infrastructure translates messy physical logistics space into an environment that robots and autonomous vehicles can reliably use. Directly it includes markers, docking nodes, handoff points, charging, coordination posts, and robot-readable layouts; institutionally it shifts planning, procurement, and municipal power toward autonomy-ready corridors and sites. Third-order effects are large because simpler machines become economically viable once the environment is prepared for them. This is transformative, though still slightly less keystone than self-driving vehicles themselves and traceability, so I assign 10.

**Weak signals (9):**

- [Standardization and prevalence] → new depots specify robot-readable floors, markers, and docking nodes (autonomy-ready design spreads)
- [Urban planning] → cities create dedicated automated loading corridors and locker clusters (public realm adapts)
- [Cost-effectiveness] → simpler robots win procurement where environments are instrumented for them (infrastructure substitutes for complexity)
- [Accuracy] → autonomous fleets reserve lanes, doors, and work zones through shared traffic posts (conflicts drop)
- [Ease] → charging, transfer, and maintenance happen at standardized unmanned nodes (friction falls)
- [Access/equality] → smaller operators struggle to afford certified autonomy-ready sites (infrastructure becomes barrier)
- [Governance] → municipalities and site owners gain leverage over who can use autonomy lanes (gatekeeping hardens)
- [Security] → attacks on coordination posts or markers cause multi-robot disruption events (infrastructure becomes target)
- [Shared smart lockers] → locker networks are integrated as standard machine-to-machine handoff points (last-mile scales)

## **ART 05.035 – Optical/Microwave Power Beaming for Persistent Robotics**

**Score: 3 (Impact in GVN 2)****Justification:**

The logistics relevance is mainly in persistent robots or drones at depots, yards, ports, and fixed corridors where line-of-sight power delivery is manageable. Directly it reduces charging downtime and human battery servicing; institutionally it creates new safety zones and gives infrastructure owners more control over persistent robotic activity. The impact is meaningful but geographically concentrated. I therefore score it 3; a 5 would require this to become a standard power layer for large classes of logistics robots.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → fixed yards deploy beam-powered patrol or inventory drones (downtime constraint weakens)
- [Ease] → battery-swap labor falls in sites with persistent robotic coverage (maintenance burden drops)
- [Safety] → logistics sites add exclusion zones and beam-interruption protocols (new hazard regime appears)
- [Market structure] → infrastructure operators control access to powered robot lanes (site power concentrates)
- [Security of supply] → round-the-clock monitoring becomes routine in weather-protected freight zones (presence persists)
- [Remote areas] → isolated assets test beam-powered robotic inspection where servicing is costly (would expand use)

## ART 05.036 – Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1 (Impact in GVN 2)**

### **Justification:**

This is a niche logistics technology for inspection and manipulation on smooth vertical or overhead surfaces such as containers, vehicle exteriors, racks, and building facades. It can reduce scaffolding or manual climbing in some maintenance tasks, but it does not materially change the broader logistics operating model. The main effect is targeted productivity and safety in special environments. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Safety] → climbing-inspection robots appear for container stacks and warehouse facades (niche access improves)
- [Cost-effectiveness] → maintenance tenders replace temporary access equipment with adhesive robots (inspection method changes)
- [Standards] → cleaning and contamination certification emerges for dry-adhesion pads in industrial sites (use stays specialized)
- [Precision] → overhead surface work shifts from manual rope access to robotic attachment (would deepen linkage)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 – Multi-Material & Hybrid 3D Printing

**Score: 3 (Impact in GVN 2)**

### **Justification:**

For logistics, the main pathway is local production of complex spare parts, fixtures, repair kits, and integrated components that reduce multi-step sourcing. That changes some flows from finished parts toward feedstocks and digital files, but it does not directly remake most freight movement. Institutionally it favors firms that can manage digital rights, quality control, and distributed



production nodes. I score it 3; a 5 would require broad migration of spare-parts and custom-component logistics to localized print networks.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → depots or maintenance hubs print replacement fixtures and repair parts locally (spare-part transport shrinks)
- [Flexibility] → operators stock feedstock and design files instead of many low-volume SKUs (inventory logic changes)
- [Governance] → OEMs restrict printable part libraries through licensing terms (file control becomes bottleneck)
- [Security of supply] → critical assets maintain local print capacity for hard-to-source parts (resilience rises)
- [Certification] → insurers require traceable print-process data for field-installed parts (quality gate forms)
- [Accessibility] → regional service hubs offer print-on-demand logistics support to SMEs (would widen impact)

## ART 06.038 – Digital Twin & Simulation-Driven Production

**Score: 3 (Impact in GVN 2)**

**Justification:**

This ART affects logistics mainly through tighter synchronization between production and replenishment. Directly it reduces surprises, scrap-related disruptions, and bad production-to-distribution handoffs; institutionally it increases dependence on shared data models between manufacturers and logistics providers. Third-order effects include lower safety stocks and faster response to product or process changes. That is material but not dominant for logistics itself, so I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → manufacturers share live production-twin outputs with logistics planners (handoff visibility improves)
- [Cost-effectiveness] → transport bookings are adjusted from simulated line output rather than static schedules (buffers shrink)
- [Security of supply] → disruption effects are tested virtually before changing outbound plans (resilience planning tightens)
- [Power] → firms with access to factory twins gain bargaining leverage over transport providers (data asymmetry grows)
- [Interoperability] → disputes arise over whose twin is authoritative when forecasts diverge (coordination friction visible)
- [Flexibility] → small-batch changeovers trigger faster logistics replanning (reconfiguration loops close)

## ART 06.039 – Reconfigurable & Agile Factories

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Agile factories can materially reshape logistics by shortening production runs, enabling more local manufacturing, and making output mixes more volatile but geographically closer to demand. Directly this changes shipment frequency, inventory strategy, and dependence on long upstream supply chains; institutionally it redistributes power toward firms that can orchestrate smaller, faster loops. Third-order effects include less transport of some finished goods but more frequent movement of modules, feedstocks, and replenishment flows. That reaches a 5; a 10 would require widespread relocalization of production across major sectors.

### **Weak signals (9):**

- [Flexibility] → manufacturers move to shorter, more frequent replenishment cycles with logistics partners (batch logic changes)
- [Cost-effectiveness] → regional plants replace some long-distance finished-goods flows (distance compresses)
- [Accessibility] → smaller markets gain viable localized production runs (demand gets served closer)
- [Accuracy] → transport orders are triggered from real-time cell reconfiguration states (planning becomes tighter)
- [Market structure] → firms that own modular factory stacks gain leverage over slower suppliers (competitive pressure rises)
- [Labor] → logistics and production roles blur around local, fast-turn facilities (skill boundaries shift)
- [Urban planning] → light industrial nodes reappear nearer consumption centers (land-use pattern changes)
- [Security of supply] → firms reduce exposure to fragile global chains with regional modular capacity (resilience improves)
- [Reverse logistics] → more local customization increases complexity of returns and service flows (aftermarket burden grows)

## ART 06.040 – Circular & Sustainable Manufacturing

**Score: 5 (Impact in GVN 2)**

### **Justification:**

This ART is strongly linked to logistics because circularity creates large reverse flows of used products, materials, and certified recovered inputs. Directly it raises demand for collection, sorting, take-back, and condition-aware transport; institutionally it shifts compliance burdens, product-passport expectations, and bargaining power toward actors that control material histories. Third-order effects include less virgin-material freight but more local circular loops and more visible material-value recovery. That is a clear 5.

### **Weak signals (9):**

- [Reverse logistics] → producers launch take-back contracts tied to recovery-value pricing (returns become feedstock)
- [Accuracy] → recovered materials are routed based on measured condition and passport data (sorting gets granular)
- [Cost-effectiveness] → logistics tenders include avoided disposal and recovered-value metrics (economics broaden)
- [Accessibility] → regional sorting and refabrication hubs appear outside major industrial centers (local loops form)
- [Governance] → compliance failures around waste classification trigger transport delays or penalties (rules become harder)
- [Power] → actors controlling passport and recovery data gain leverage over carriers and recyclers (information power rises)
- [Flexibility] → carriers add mixed reverse-flow capabilities to standard service offers (circular services normalize)
- [Urban planning] → municipalities site reuse and repair hubs near dense consumption areas (city logistics changes)
- [Security] → illicit dumping and false “recovered” labeling prompt stronger verification layers (fraud risk surfaces)

## ART 06.041 – Bio-fabrication technologies

**Score: 1 (Impact in GVN 2)**

### **Justification:**

Bio-fabrication mainly affects a specialized biomedical logistics segment rather than the logistics GVN as a whole. It can create local delivery of sensitive biological constructs and different cold-chain requirements, but that remains a narrow, high-regulation domain. The linkage is therefore concrete but limited. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cold chains] → specialized local delivery networks appear for bioprinted products (niche temperature logistics grows)
- [Accuracy] → chain-of-custody and viability telemetry become standard in biofabricated shipments (handling becomes stricter)
- [Governance] → transport regulations distinguish living manufactured products from standard medical goods (sector boundary appears)
- [Localization] → hospital-adjacent production reduces long-haul movement of fragile constructs (would strengthen linkage)

## ART 06.042 – 4D Printed & Programmable Materials

**Score: 1 (Impact in GVN 2)**

### **Justification:**

The most plausible logistics pathway is smarter packaging or deployable components that change shape or function during transport or installation. That could reduce some assembly and handling

costs, but it is too narrow and indirect to materially change the logistics operating model on its own. It is worth watching in packaging-intensive niches. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Packaging] → shippers test self-forming inserts or protective elements for variable goods (handling logic changes slightly)
- [Ease] → containers or fixtures that self-deploy on arrival appear in field logistics (manual setup shrinks)
- [Certification] → transport standards start covering state-changing materials in transit (regime begins forming)
- [Cold chains] → adaptive thermal packaging responds to temperature excursions autonomously (would deepen logistics relevance)

## **ART 06.043 – Volumetric Additive Manufacturing**

**Score: 3 (Impact in GVN 2)**

**Justification:**

Fast layerless printing matters for logistics mainly by compressing spare-part and custom-component lead times. Directly it can reduce storage of slow-moving parts and support local maintenance nodes; institutionally it pushes more value into design files, certification, and local production quality control. The impact is real but narrower than a broad production shift. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → service depots print urgent replacement parts within operational windows (downtime shrinks)
- [Security of supply] → critical assets rely less on long-tail spare-part inventories (inventory logic changes)
- [Certification] → field use depends on machine-readable quality records for printed parts (qualification becomes central)
- [Accessibility] → regional repair hubs offer rapid local print services to multiple operators (capacity diffuses)
- [Power] → OEMs control digital part libraries and authorized print networks (file ownership matters)
- [Flexibility] → temporary or mobile logistics nodes print custom fixtures on site (would deepen linkage)

## **7. Advanced Materials & Nano-engineering**

### **ART 07.044 – Metamaterials for Novel Optics & Connectivity**

**Score: 3 (Impact in GVN 2)**

**Justification:**

The strongest logistics pathway is better wireless coverage, smarter sensing, and lighter wave-handling hardware in depots, vehicles, and corridors. That can materially improve connectivity and positioning in cluttered sites, but the effect is still mainly enabling rather than operating-model defining. Institutionally it strengthens the role of infrastructure and equipment vendors. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Connectivity] → depots retrofit wave-steering surfaces to remove blind spots (coverage becomes engineered)
- [Accuracy] → low-profile high-gain antennas appear on trucks, lockers, and drones (link reliability rises)
- [Security] → controlled signal leakage is marketed for high-value cargo sites (RF exposure becomes manageable)
- [Market structure] → connectivity gains depend on proprietary surface-control ecosystems (vendor leverage grows)
- [Ease] → smart warehouses use thin sensing and communications skins instead of bulky hardware (fit-out changes)
- [Durability] → exposed logistics deployments publish weathering and maintenance results (would determine broader uptake)

## ART 07.045 – Room-Temperature Superconductors

**Score: 3 (Impact in GVN 2)****Justification:**

If genuinely mature, this could materially improve high-current charging, refrigeration, motors, and some transport infrastructure relevant to logistics. But the effect is still indirect through energy and propulsion systems rather than a direct logistics-control technology. The upside is large enough to matter, yet a higher score would require specific freight propulsion or charging architectures to change at scale. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → freight depots pilot compact ultra-high-current power paths (charging bottlenecks ease)
- [Cold chains] → superconducting refrigeration or magnetic systems appear in premium logistics equipment (niche operational gains)
- [Heavy transport] → freight OEM roadmaps reference compact high-power drivetrain changes (would tighten linkage)
- [Infrastructure] → early benefits are captured mostly in the grid, not logistics assets (impact stays indirect)
- [Market structure] → specialty conductor supply becomes concentrated among few industrial suppliers (dependency risk rises)
- [Ports] → high-throughput electrified cargo equipment cites superconducting components (would raise sector relevance)

## ART 07.046 – Self-Healing & Smart Polymers

**Score: 3 (Impact in GVN 2)**

**Justification:**

The logistics value is straightforward: longer-lived packaging, seals, tires, liners, protective coatings, and light structural components. Directly this reduces downtime, replacement cycles, and some damage propagation; institutionally it shifts maintenance expectations and lifecycle contracting. The upside is meaningful but mostly incremental. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → fleet and packaging vendors market longer-life self-healing components (replacement cycles stretch)
- [Accuracy] → condition indicators show when polymer repairs have activated in service (maintenance becomes observable)
- [Security of supply] → difficult-access assets use self-healing seals and coatings by default (service burden drops)
- [Recycling] → operators report trouble separating or reprocessing advanced repair polymers (end-of-life friction rises)
- [Market structure] → warranty terms lock buyers into proprietary repair chemistries (supplier power grows)
- [Packaging] → reusable transport packaging survives more cycles before retirement (asset economics improve)

## ART 07.047 – Nano-Catalysts & Advanced Coatings

**Score: 3 (Impact in GVN 2)**

**Justification:**

This ART matters through lower friction, anti-corrosion, anti-fouling, cleaner fuel processing, easier cleaning, and more durable surfaces on logistics assets. Those improvements are broad but mostly incremental across fleets, containers, cold chains, and depots. Institutionally, maintenance and warranty regimes shift toward coating performance data and certified surface treatments. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → carriers specify low-friction or anti-corrosion coatings in fleet renewals (lifecycle economics improve)
- [Accuracy] → sensorized coatings report wear before surface failure (maintenance timing sharpens)
- [Cold chains] → antimicrobial or anti-fouling finishes become standard in food logistics (cleanability improves)



- [Supply chains] → coating performance depends on scarce catalyst elements or specialty applicators (upstream vulnerability appears)
- [Certification] → insurers and regulators require proof of coating durability in harsh logistics environments (quality gate tightens)
- [Ease] → faster-cleaning surfaces reduce turnaround times for reusable assets (throughput improves)

## ART 07.048 – High-Entropy Alloys & Advanced Metals

**Score: 3 (Impact in GVN 2)**

### **Justification:**

Stronger, more wear-resistant, and more temperature-stable metals can materially improve trailers, containers, cranes, bearings, and other long-lived logistics assets. The direct effect is lower failure risk and potentially lower weight; the second-order effect is changed certification, repair, and material sourcing. It is significant but still an incremental materials pathway rather than a logistics operating-model shift. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → asset operators buy advanced-metal components for high-wear logistics machinery (lifetime value improves)
- [Accuracy] → condition histories show lower fatigue or heat-related drift in freight equipment (performance stabilizes)
- [Security of supply] → hard-to-service assets adopt advanced metals to stretch maintenance intervals (access burden drops)
- [Supply chains] → material qualification depends on scarce alloying inputs or long certification cycles (scaling stays slow)
- [Repairability] → welding and replacement workflows become more specialized (service complexity rises)
- [Payload] → lighter high-strength structures appear in trailers and drones (would deepen impact)

## ART 07.049 – Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

**Score: 1 (Impact in GVN 2)**

### **Justification:**

The logistics linkage is mostly indirect through carbon-management infrastructure, captured-CO<sub>2</sub> movement, and low-carbon fuel systems. That may create some new material flows and compliance pressures, but it does not materially alter the logistics GVN by itself. The main effect is adjacent rather than core. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Compliance] → logistics hubs add capture units to meet emissions or fuel-production targets (adjacent flow appears)
- [Energy logistics] → captured CO<sub>2</sub> begins moving through new short-haul industrial routes (new commodity flow emerges)
- [Cost-effectiveness] → logistics firms buy offsets instead of capture-linked transport changes (keeps impact indirect)
- [Fuel hubs] → power-to-X sites near ports specify MOF-based capture cartridges (would tighten linkage)

## ART 07.050 – Graphene and Nanotube Composites for Lightweight Strength

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Lighter, stronger composites directly matter for drones, electric vehicles, containers, and condition-sensing structures. Directly they improve payload, range, fatigue life, and embedded monitoring; institutionally they alter maintenance, material sourcing, and safety certification. Third-order effects include making electrified and aerial logistics more viable at lower operating cost. That supports a 5.

### **Weak signals (9):**

- [Cost-effectiveness] → vehicle and drone OEMs advertise payload gains from nano-composite structures (energy per delivery falls)
- [Accuracy] → trailers and containers self-report strain and crack growth through conductive composites (damage becomes visible)
- [Flexibility] → lighter bodies make electric and aerial fleets viable on more routes (service envelope widens)
- [Security of supply] → lower fatigue reduces downtime for hard-used logistics assets (availability improves)
- [Supply chains] → health and handling rules tighten around nano-material processing (manufacturing overhead rises)
- [Market structure] → a few composite suppliers dominate premium lightweight logistics platforms (upstream leverage grows)
- [Accessibility] → smaller drone-service providers adopt stronger, longer-life airframes (entry expands)
- [Urban logistics] → lighter vehicles and drones fit tighter emissions and noise constraints (policy compatibility improves)
- [Repairability] → insurers and fleets demand new repair standards for nano-composite damage (service model changes)

## ART 07.051 – Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 5 (Impact in GVN 2)**

**Justification:**

This ART fits logistics unusually well because cold chains, temperature-sensitive parcels, warehouses, and depots all face thermal-control costs and spoilage risk. Directly it improves passive cooling, temperature stability, and depot energy efficiency; institutionally it shifts packaging norms, insurance expectations, and site design. Third-order effects include more decentralized handling of food, pharma, and other sensitive goods because thermal precision becomes easier. That is a clear 5.

**Weak signals (9):**

- [Accuracy] → passive thermal packaging keeps narrow-temperature goods within spec longer (spoilage risk falls)
- [Cost-effectiveness] → refrigerated depots and vehicles reduce peak loads with phase-change materials (energy burden drops)
- [Flexibility] → smaller micro-hubs handle temperature-sensitive goods reliably (distribution decentralizes)
- [Ease] → trailers and containers use adaptive thermal skins instead of active-only control (operations simplify)
- [Certification] → regulators require cycle-life proof for smart thermal materials in pharma and food lanes (quality gate rises)
- [Market structure] → premium packaging vendors lock in customers via proprietary thermal materials and telemetry (vendor power grows)
- [Urban planning] → dense areas tolerate more local cold-chain nodes with lower noise and energy demand (city fit improves)
- [Security of supply] → outage tolerance increases for critical temperature-sensitive flows (resilience improves)
- [Recycling] → advanced thermal laminates create separation and disposal challenges (end-of-life friction appears)

**ART 07.052 – Rare-Earth-Free Magnets for Sustainable Motors**

**Score: 3 (Impact in GVN 2)**

**Justification:**

The logistics relevance is strong but mostly indirect: motors matter for EVs, conveyors, robots, forklifts, and warehouse equipment. Rare-earth-free magnets improve supply resilience and potentially cost stability for electrified logistics assets, but they do not themselves reshape logistics organization. The main second-order effect is lower geopolitical exposure in motor-intensive systems. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → fleet and robot OEMs market rare-earth-light motor options (upstream risk shrinks)
- [Cost-effectiveness] → long-term procurement contracts shift away from neodymium exposure (price volatility matters)
- [Electrification] → forklift, conveyor, and delivery-vehicle platforms validate alternative magnet grades (motor supply broadens)

- [Performance] → adoption remains limited in the highest-power duty cycles (impact stays partial)
- [Market structure] → new magnet supply chains concentrate in different specialist producers (dependency reappears)
- [Policy] → public procurement scores supply-resilient motor components in logistics equipment (would strengthen impact)

## ART 07.053 – Nano-Engineered Membranes for Low-Energy Desalination

**Score: 0 (Impact in GVN 2)**

### Justification:

This has no meaningful direct pathway to change logistics operations for moving goods. Any effect would be indirect through regional water availability or adjacent industrial systems, which is too diffuse to count for this GVN. I therefore assign 0.

### Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Ports and hubs] → desalination becomes a direct constraint for logistics-energy sites in arid regions (would create pathway)
- [Hydrogen hubs] → freight fuel infrastructure becomes co-dependent on desalination performance (would tighten linkage)
- [Operations] → no logistics procurement categories explicitly reference desalination membranes (keeps linkage absent)
- [Remote logistics] → isolated ports or depots bundle water and freight infrastructure procurement (would create niche relevance)

## ART 07.054 – Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 5 (Impact in GVN 2)**

### Justification:

This ART directly improves power electronics for chargers, drivetrains, refrigeration, automation, and energy management in depots and vehicles. The operational gains are lower losses, higher power density, faster charging, and smaller cooling requirements; institutionally that shifts infrastructure design, vendor competition, and maintenance practices. Third-order effects include making electrified logistics more practical in space-constrained urban and high-throughput settings. That is strong enough for a 5.

### Weak signals (9):

- [Cost-effectiveness] → ultra-fast freight chargers and depot converters adopt new high-temperature modules (losses fall)
- [Ease] → refrigerated vehicles and warehouses use smaller, quieter power electronics (system footprint shrinks)

- [Flexibility] → mobile or temporary charging assets become more practical for peak logistics demand (infrastructure becomes portable)
- [Urban logistics] → denser charging is permitted in space-constrained sites because hardware is smaller (site viability rises)
- [Supply chains] → module procurement depends on specialized wafers and packaging ecosystems (new bottlenecks emerge)
- [Maintenance] → field technicians need new diagnostics for different failure modes (skill profile changes)
- [Security of supply] → depots integrate higher-power backup and conversion systems more economically (resilience improves)
- [Automation] → robots and conveyors operate with more compact, efficient drive systems (electrified motion scales)
- [Market structure] → early gains accrue to large OEMs and site operators who can redesign power architectures (scale advantage grows)

## ART 07.055 – Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score: 3 (Impact in GVN 2)**

### **Justification:**

This matters if hydrogen wins meaningful niches in long-range freight, forklifts, ports, or drone operations. Directly it improves safety and density relative to high-pressure handling; institutionally it creates new cartridge, refueling, and certification models. The impact is real but contingent on hydrogen adoption staying meaningful in logistics. I assign 3; a 5 would need broad freight use rather than corridor or equipment-specific niches.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Safety] → hydrogen forklifts or yard vehicles adopt solid-storage modules in place of high-pressure tanks (handling risk falls)
- [Ease] → refueling shifts toward swappable or easier-to-certify storage cartridges (site operations simplify)
- [Remote areas] → hard-to-service logistics assets use safer hydrogen storage for backup or range extension (niche fit improves)
- [Infrastructure] → uptake remains tied to hydrogen corridors rather than mainstream depots (impact stays bounded)
- [Governance] → new storage standards and inspection routines delay deployment (certification becomes gate)
- [Ports] → port equipment tenders explicitly mention safer hydrogen storage materials (would expand relevance)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 – Fusion Energy Reactors

**Score: 1 (Impact in GVN 2)**

**Justification:**

Fusion could eventually lower energy costs and support electrified logistics or synthetic fuel production, but the linkage to logistics operations is indirect. Most logistics effects would be mediated through the broader energy system rather than through a distinct logistics bottleneck. That keeps it worth watching but not highly scoreable for this GVN. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Energy cost] → logistics firms sign future power or heat MOUs tied to fusion sites (would create direct tie)
- [Fuel production] → port-adjacent synthetic-fuel plans explicitly depend on fusion-grade electricity (would tighten linkage)
- [Operations] → logistics capex roadmaps remain unchanged because energy impact stays system-level (keeps effect indirect)
- [Critical hubs] → cold-chain or mega-depot developers begin treating fusion as reliable baseload input (would raise relevance)

**ART 08.057 – Small Modular Fission Reactors (SMRs)**

**Score: 1 (Impact in GVN 2)**

**Justification:**

SMRs could support ports, large depots, synthetic-fuel production, and resilient power for critical freight nodes, but the impact is still largely via the energy system. That is meaningful adjacent value, not a direct change in how logistics itself is organized. So I score it 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → major ports or freight hubs evaluate SMR-backed power supply (site resilience gains relevance)
- [Fuel hubs] → power-to-X logistics clusters are co-sited with SMR proposals (energy and freight couple)
- [Governance] → public acceptance and security concerns keep logistics operators at arm's length (direct linkage stays weak)
- [Remote assets] → isolated heavy logistics nodes consider SMR power where grid access is poor (would deepen impact)

**ART 08.058 – Thin-film solar cells**

**Score: 3 (Impact in GVN 2)**

**Justification:**

Thin-film solar can materially help distributed logistics by adding generation to warehouses, containers, lockers, refrigerated units, and some vehicle surfaces where rigid panels are awkward.



Direct effects are modest but broad: more local power for sensing, refrigeration support, and energy resilience. Institutionally it spreads energy ownership across logistics assets and sites. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → lockers, trailers, or containers ship with integrated thin-film power skins (small loads self-power)
- [Cold chains] → refrigerated assets use local solar to support monitoring and thermal buffering (operational resilience rises)
- [Accessibility] → remote depots adopt thin-film generation without heavy roof retrofits (energy access broadens)
- [Durability] → contracts and warranties center on abrasion, flexing, and weathering performance (reliability becomes decisive)

## ART 08.059 – Bionic Leaf Technology

**Score: 1 (Impact in GVN 2)**

**Justification:**

The logistics pathway here is indirect through local production of storable energy molecules. That could eventually reshape fuel supply patterns for some freight modes, but it is too contingent and upstream to score highly for logistics itself. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Fuel logistics] → depots pilot direct sunlight-to-fuel systems for on-site molecule production (would create visible pathway)
- [Remote assets] → isolated logistics sites use bionic-leaf outputs instead of delivered fuels (would strengthen relevance)
- [Cost-effectiveness] → most freight decarbonization still favors grid power or conventional power-to-X (keeps impact indirect)
- [Ports] → chemical-fuel bunkering plans begin referencing panel-based synthesis modules (would tighten linkage)

## ART 08.060 — Grid-Scale Energy Storage

**Score: 5 (Impact in GVN 2)**

**Justification:**

Grid-scale storage materially matters for logistics because fleet electrification, depot charging, cold chains, and automated hubs all create timing mismatches between energy demand and supply. Directly it reduces peak constraints and outage risk; institutionally it changes relationships with utilities, aggregators, and site developers. Third-order effects include more viable electrified freight networks and less need to overbuild grid connections at every logistics site. That supports a 5.

**Weak signals (9):**

- [Depot charging bottleneck] → carriers co-locate storage with fast chargers at major hubs (grid peaks are shaved)
- [Cold-chain resilience] → refrigerated depots keep service during outages using on-site storage (spoilage risk drops)
- [Cost-effectiveness] → time-of-use arbitrage becomes a visible line item in fleet operating models (energy planning matters)
- [Accessibility] → smaller depots buy storage-as-a-service instead of grid upgrades (entry barriers fall)
- [Urban planning] → municipalities approve logistics hubs with storage-backed grid connections (site viability increases)
- [Safety] → fire and gas-handling rules tighten around storage at warehouses (new compliance burden)
- [Market power] → utilities and storage aggregators control dispatch windows for charging fleets (energy dependence shifts)
- [Security of supply] → cyber incidents target depot energy management systems (energy and logistics couple)
- [Fleet operations] → overnight charging schedules align to storage optimization rather than static tariffs (operations become energy-aware)

**ART 08.061 — Solid-State Batteries****Score: 10 (Impact in GVN 2)****Justification:**

Solid-state batteries directly affect a core logistics transition: safer, denser electrification of vans, trucks, drones, robots, and warehouse vehicles. Directly they improve range, charging practicality, payload economics, and insuranceability; institutionally they accelerate zero-emission policy adoption and shift dependence toward new cell supply chains. Third-order effects include more viable autonomous electric delivery, quieter urban logistics, and reduced resistance to battery-heavy operations in dense areas. That is transformative for how large parts of logistics are realized, though not as singularly keystone as self-driving vehicles or traceability.

**Weak signals (9):**

- [Cost-effectiveness] → medium-haul electric trucks cross key routes without mid-day charging (range constraint weakens)
- [Safety] → insurers price electric fleets differently once thermal-runaway incidents drop (risk premium falls)
- [Ease] → delivery vans fast-charge within normal loading windows (operations simplify)
- [Drone logistics] → heavier or longer-range drone services become commercially routine (air logistics widens)
- [Warehouse automation] → robots and forklifts run denser packs with less cooling overhead (indoor autonomy scales)

- [Supply chain power] → cell manufacturers and mineral refiners lock in carriers through long contracts (upstream leverage grows)
- [Infrastructure] → depots delay hydrogen or liquid-fuel investments after better batteries arrive (path dependence shifts)
- [Workforce] → maintenance and rescue protocols are rewritten around new battery chemistries (skills change)
- [Urban logistics] → zero-emission delivery zones expand because vehicle performance is adequate (policy tightens)

## ART 08.062 — Green Hydrogen & Power-to-X

**Score: 5 (Impact in GVN 2)**

### **Justification:**

This ART matters most for heavy freight, shipping, aviation-adjacent logistics, and resilient backup energy at major nodes. Directly it creates new fuel supply chains, bunker systems, and long-duration energy buffers; institutionally it shifts bargaining power toward sites with cheap power, water, and synthesis capacity. Third-order effects include rerouting energy logistics and changing the geography of port and corridor investment. That is significant enough for a 5.

### **Weak signals (9):**

- [Long-haul freight] → hydrogen or e-fuel corridors appear on major freight routes (new fueling geography forms)
- [Ports] → bunkering and storage projects tie logistics nodes to power-to-X production (energy and freight co-locate)
- [Security of supply] → operators use stored molecules to buffer electricity volatility for critical logistics sites (resilience broadens)
- [Cost-effectiveness] → shippers sign low-carbon freight contracts linked to fuel-origin certification (market demand forms)
- [Water and siting] → permit conflicts emerge around water use and safety zones near hubs (local friction rises)
- [Market structure] → access concentrates in sites with cheap renewable power and capital (regional advantage grows)
- [Accessibility] → off-grid or hard-to-electrify operations adopt molecule-based decarbonization pathways (transition options widen)
- [Governance] → fuel-origin, carbon-intensity, and handling rules become part of logistics compliance stacks (administrative burden grows)
- [Infrastructure] → depots and ports add automated compression, storage, and leak-monitoring layers (handling gets industrialized)

## ART 08.063 — High-Efficiency Wind Turbines

**Score: 1 (Impact in GVN 2)**

### **Justification:**

Wind affects logistics mainly through cheaper clean electricity and, in some cases, direct supply to

ports, depots, and fuel-production sites. That can matter to operating costs, but it does not directly reshape logistics organization. The effect is therefore adjacent and indirect. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Energy cost] → freight hubs sign direct supply contracts with high-output wind projects (energy linkage strengthens)
- [Fuel hubs] → green-fuel logistics corridors explicitly depend on wind-powered synthesis plants (would tighten connection)
- [Operations] → logistics firms mostly treat wind as a general grid input rather than a site strategy (impact stays indirect)
- [Ports] → port electrification plans are bundled with nearby offshore wind integration (site relevance grows)

## ART 08.064 — Wireless & Space-Based Power Transfer

**Score: 1 (Impact in GVN 2)**

**Justification:**

The direct logistics pathway is niche: remote sites, temporary operations, or mobile assets where cabling or fuel delivery is awkward. That could matter in edge cases, but it does not plausibly change mainstream logistics organization on its own. The main value is contingency and remote-access support. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Remote assets] → isolated depots or emergency logistics sites test beamed power reception (niche pathway appears)
- [Temporary operations] → disaster-response logistics uses beam-fed power instead of generators (would strengthen linkage)
- [Governance] → safety and spectrum restrictions keep logistics uptake highly constrained (mainstream use blocked)
- [Mobile robotics] → autonomous assets are marketed with beam-compatible receiver packages (would create practical tie)

## ART 08.065 — Advanced geothermal technology

**Score: 1 (Impact in GVN 2)**

**Justification:**

Advanced geothermal can support energy-intensive logistics nodes, refrigeration, and fuel production, but again the channel is largely indirect through site energy supply. It is more important to the energy system than to the logistics operating model itself. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → cold chains and freight hubs seek geothermal-backed power or heat contracts (site resilience gains relevance)
- [Fuel hubs] → port-adjacent power-to-X projects reference geothermal input (would tighten logistics link)
- [Operations] → logistics strategies remain unchanged where geothermal sits only behind the grid (keeps impact indirect)
- [Remote regions] → inland logistics clusters use geothermal to stabilize energy-intensive operations (would broaden relevance)

**ART 08.066 — Resilient microgrids**

**Score: 5 (Impact in GVN 2)**

**Justification:**

Microgrids directly target a real logistics weakness: outages that disrupt depots, cold chains, charging, automated lockers, and local delivery networks. Directly they improve continuity and black-start recovery; institutionally they shift control toward site operators, aggregators, and local energy-governance arrangements. Third-order effects include more viable neighborhood-scale logistics infrastructure and less dependence on centralized reliability alone. That supports a 5.

**Weak signals (9):**

- [Security of supply] → depots and cold stores install islandable local power systems (continuity becomes site-managed)
- [Cost-effectiveness] → fleets combine charging, storage, and local generation under one microgrid controller (energy coordination deepens)
- [Ease] → lockers and neighborhood pickup nodes stay operational through wider outages (service continuity improves)
- [Accessibility] → remote or congested areas gain viable logistics sites without major grid reinforcements (site options broaden)
- [Governance] → disputes emerge over who may island, reconnect, or sell excess power (local power politics rise)
- [Cybersecurity] → attacks on microgrid controllers become logistics-operational incidents (energy-control risk couples)
- [Urban planning] → municipalities approve logistics hubs partly on resilience-service grounds (microgrids alter siting)
- [Cold chains] → spoilage losses fall after microgrid adoption at food and pharma sites (risk reduction monetizes)
- [Market structure] → energy-service providers gain leverage over logistics sites through integrated contracts (dependency grows)

**9. Bio-engineering & Life-Science Technologies**

## ART 09.067 — Next-Generation Gene Editing

**Score: 1 (Impact in GVN 2)**

**Justification:**

The logistics relevance is indirect through agriculture, biomaterials, and industrial biotech supply chains. Those could eventually change some freight composition, but not the logistics operating model in a direct, near-systemic way. So this is worth watching but not highly scoreable for logistics itself. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Agri supply chains] → edited crops or inputs materially alter cold-chain or bulk transport patterns (would create clearer pathway)
- [Bio-based materials] → logistics packaging begins using gene-edited feedstocks at scale (would tighten connection)
- [Operations] → freight contracts rarely reference gene editing outside product category labels (keeps effect indirect)
- [Pest resistance] → transport-loss reductions are explicitly attributed to edited source materials (would strengthen linkage)

## ART 09.068 — mRNA Therapies & Vaccines

**Score: 3 (Impact in GVN 2)**

**Justification:**

This ART affects logistics through cold chains, authenticated temperature monitoring, last-mile health distribution, and surge-response delivery systems. Directly it makes certain logistics segments more demanding and data-intensive; institutionally it increases the value of secure, temperature-assured, high-visibility transport networks. The broader logistics GVN is not transformed, but some medically critical segments are materially affected. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → authenticated temperature telemetry becomes mandatory for more biologic shipments (cold-chain precision rises)
- [Ease] → pharmacies and clinics receive smaller, more frequent controlled deliveries (distribution pattern changes)
- [Security of supply] → public-health stockpiles rely on dynamic distribution contracts rather than static warehousing (surge logistics matures)
- [Governance] → counterfeit and diversion controls tighten around high-value mRNA products (security burden grows)
- [Cost structure] → specialized cold-chain providers capture premium margins (market concentration deepens)



- [Accessibility] → rural health logistics upgrades around assured-temperature last-mile delivery (coverage quality improves)

## ART 09.069 — Cellular Agriculture & Cultured Meat

**Score: 5 (Impact in GVN 2)**

### **Justification:**

This could materially reshape food logistics by moving some value creation from farms, feed chains, and animal transport toward urban or regional bioprocessing and controlled ingredient flows. Directly it changes what moves, where it moves from, and how temperature and sterility matter; institutionally it redistributes power across food production, retail, and cold-chain infrastructure. Third-order effects include shorter final-product chains, different waste flows, and new dependencies on energy and bioreactor inputs. That is large enough for a 5.

### **Weak signals (9):**

- [Food logistics] → urban or regional production sites replace part of long livestock or carcass flows (route geography changes)
- [Cold chains] → ingredient and finished-product handling specs shift toward sterility and process consistency (requirements change)
- [Cost-effectiveness] → retailers contract directly with regional cultured-protein plants (intermediaries thin out)
- [Accessibility] → dense regions gain local food-production nodes closer to demand (distance compresses)
- [Market structure] → a few platform-like producers control recipe, process, and distribution standards (food power recentralizes)
- [Energy dependence] → logistics costs become more tied to electricity and bioreactor uptime than farm seasonality (new bottleneck appears)
- [Waste flows] → feed, by-product, and packaging flows change around controlled production systems (material mix shifts)
- [Urban planning] → industrial-zoned food bioprocess sites appear nearer consumption centers (land use changes)
- [Governance] → regulators create new transport and labeling rules for cultured outputs (compliance stack thickens)

## ART 09.070 — Organoids & Tissue Engineering

**Score: 1 (Impact in GVN 2)**

### **Justification:**

This ART affects only a specialized biomedical logistics layer involving fragile, high-value biological materials. It can increase demand for controlled transport and chain-of-custody, but the impact on the overall logistics GVN is limited. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cold chains] → live tissue shipments require tighter viability telemetry and handling windows (niche logistics complexity rises)
- [Accuracy] → chain-of-custody tools expand for lab-grown tissue movements (integrity gets operationalized)
- [Scale] → logistics uptake remains confined to clinical and research channels (effect stays narrow)
- [Localization] → production near hospitals reduces long-distance movement of fragile tissues (would increase relevance)

## ART 09.071 — Synthetic Biology & Designer Microbes

**Score: 3 (Impact in GVN 2)**

### **Justification:**

Synthetic biology can shift logistics by localizing production of chemicals, materials, and some ingredients, especially from low-value or waste feedstocks. Directly that changes commodity mix and some route structures; institutionally it introduces biosafety, traceability, and containment requirements into certain supply chains. The impact is material but more about freight composition than logistics control. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → local microbial production replaces part of imported specialty chemicals or additives (commodity flows change)
- [Circularity] → waste-to-feedstock routes expand around bio-manufacturing nodes (reverse flows gain value)
- [Security of supply] → firms reduce reliance on long upstream chains for selected materials (regional resilience improves)
- [Governance] → biosafety and containment transport rules tighten around engineered strains (compliance thickens)
- [Market structure] → process-IP holders control recipe and strain access across distributed plants (platform power grows)
- [Packaging/materials] → bio-based logistics consumables move from niche to standard procurement (would deepen linkage)

## ART 09.072 — Microbiome Engineering

**Score: 1 (Impact in GVN 2)**

### **Justification:**

The clearest logistics pathway is narrower control of spoilage, contamination, soil or water conditions, and warehouse hygiene. Those are real but peripheral to the overall logistics operating model. The main impact would be niche efficiency and maintenance benefits rather than structural change. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Food logistics] → microbial control products cut spoilage losses in storage and transport (niche operational gain)
- [Waste handling] → microbiome-managed decay or remediation appears in logistics-adjacent waste systems (peripheral pathway forms)
- [Governance] → containment and environmental-use rules limit routine deployment in logistics assets (linkage stays narrow)
- [Warehouse hygiene] → microbial monitoring becomes part of standard site telemetry (would raise relevance)

## ART 09.073 — Precision Medicine & Genomic Diagnostics

**Score: 1 (Impact in GVN 2)**

**Justification:**

This ART mainly enlarges specialized sample, diagnostic, and personalized-treatment logistics rather than the logistics GVN broadly. It increases requirements for secure, time-sensitive, traceable transport in healthcare supply chains, but the overall effect remains segment-specific. I therefore assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Healthcare logistics] → more routine genomic sample flows demand rapid specialized transport (niche volume grows)
- [Accuracy] → chain-of-custody standards tighten for personalized diagnostic shipments (traceability strengthens)
- [Scale] → impact remains concentrated in health logistics, not general freight (keeps score low)
- [Localization] → decentralized testing reduces long sample routes while increasing short controlled moves (would sharpen linkage)

## ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids

**Score: 0 (Impact in GVN 2)**

**Justification:**

I do not see a meaningful direct pathway from this ART to the broader logistics operating model. Any effect would sit inside specialized biomedical R&D logistics rather than the value network for moving goods and materials in general. I therefore assign 0.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Biomed logistics] → specialized consumable and chip transport grows around distributed testing labs (would create niche relevance)
- [Cold chains] → organ-on-chip cartridges gain distinct transport requirements (would define a limited pathway)
- [Scale] → no broader freight categories are materially affected (keeps linkage absent)
- [Automation] → logistics platforms add handling classes specifically for living-chip systems (would raise relevance)

## ART 09.075 — Biological Aging & Longevity Barriers

**Score: 1 (Impact in GVN 2)**

### **Justification:**

The logistics effect is mainly through workforce availability, injury recovery, and long-duration performance, not through direct freight technology. That matters at the margin in a labor-intensive sector, but it is too indirect to score highly. The most plausible impact is slower labor scarcity and longer experienced worker participation. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Labor supply] → logistics employers track biological-age or recovery interventions in retention programs (workforce pathway appears)
- [Safety] → faster recovery reduces lost-time injuries in physically demanding roles (marginal operational gain)
- [Governance] → anti-discrimination and coercion rules emerge around workplace longevity interventions (employment boundary matters)
- [Training] → longer careers keep experienced technicians in automation-heavy logistics roles (would strengthen linkage)

## ART 09.076 — Engineered Living Materials

**Score: 3 (Impact in GVN 2)**

### **Justification:**

Engineered living materials can matter for logistics through self-repairing surfaces, crack-sealing infrastructure, adaptive packaging, and lower-maintenance facilities. Directly they reduce maintenance visits and can extend asset life; institutionally they create new certification and performance-monitoring requirements. The effect is real but still mostly on the durability layer of logistics assets. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → warehouse floors, facades, or barriers adopt self-repairing materials (maintenance burden drops)

- [Security of supply] → difficult-access logistics assets use living materials to delay repairs (service intervals lengthen)
- [Packaging] → condition-responsive living composites appear in reusable transport packaging (new niche forms)
- [Governance] → biosecurity and shelf-life rules slow adoption in mainstream freight assets (certification becomes hurdle)
- [Monitoring] → performance tracking focuses on activation cycles and survivability, not just structural metrics (maintenance model changes)
- [Carbon footprint] → logistics-site materials are marketed as long-lived carbon sinks (would strengthen procurement linkage)

## ART 09.077 — Gene Drive Pest Control

**Score: 3 (Impact in GVN 2)**

### Justification:

Pest pressure is a genuine logistics issue in ports, warehouses, grain storage, and biosecurity-sensitive trade flows. Directly, gene-drive pest control could reduce spoilage, contamination, and invasive-species risks; institutionally it creates major governance, liability, and cross-border accountability issues. The upside is material in specific logistics-adjacent domains, but the political and ecological risks keep it from being a broader operating-model technology. I assign 3.

### Weak signals (6):

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Stored-goods losses] → pest-prone logistics nodes are discussed in gene-drive deployment scenarios (warehouse linkage becomes explicit)
- [Biosecurity] → ports and border agencies assess gene-drive tools for invasive-species control (trade protection angle rises)
- [Governance] → cross-border disputes focus on unintended ecological spread from logistics-adjacent releases (accountability becomes central)
- [Cost-effectiveness] → grain and food operators quantify avoided storage losses from persistent pest suppression (economics clarify)
- [Public acceptance] → opposition targets logistics hubs as unjust release sites (deployment friction grows)
- [Security of supply] → reduced infestation changes reserve-storage strategies for food logistics (would deepen impact)

## ART 09.078 — Artificial Wombs & Synthetic Embryos

**Score: 0 (Impact in GVN 2)**

### Justification:

I do not see a meaningful direct pathway from this ART to the logistics operating model, aside from very indirect agricultural or medical spillovers. Those spillovers are too speculative and too far from the GVN's central bottlenecks to count as meaningful impact. I therefore assign 0.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Livestock supply chains] → artificial gestation materially changes animal-breeding transport demand (would create pathway)
- [Conservation logistics] → specialized reproductive bioprocess shipments become a recurring transport category (would tighten niche relevance)
- [Scale] → no broader freight classes are visibly altered (keeps linkage absent)
- [Agri inputs] → synthetic-embryo systems reshape breeding-center siting and distribution patterns (would increase relevance)

## 10. Space & Aeronautical Engineering

### ART 10.079 — Satellite Mega-Constellations & Space Internet

**Score: 5 (Impact in GVN 2)**

**Justification:**

This ART directly improves remote connectivity, tracking, and observation for logistics corridors, maritime links, sparse regions, and disruption monitoring. It does not matter equally everywhere, but where terrestrial infrastructure is weak it materially changes coordination and service viability. Institutionally it increases dependence on a few constellation operators while improving resilience against terrestrial outages. That is significant enough for a 5.

**Weak signals (9):**

- [Remote-area accessibility] → carriers market nationwide service guarantees based on satellite backhaul (coverage gap narrows)
- [Security of supply] → fleets use satellite fallbacks for telemetry and dispatch continuity (outage resilience rises)
- [Accuracy] → earth-observation feeds are integrated into route disruption and capacity planning (situational awareness improves)
- [Ease] → small carriers adopt satellite-linked terminals without bespoke infrastructure projects (entry barriers fall)
- [Market structure] → constellation operators bundle connectivity with logistics analytics or terminals (platform leverage grows)
- [Security] → jamming, spoofing, or terminal theft incidents become a logistics concern (space link becomes attack surface)
- [Maritime and remote freight] → asset tracking becomes continuous on routes previously offline (visibility widens)
- [Disaster logistics] → response networks standardize satellite-connected field depots and lockers (contingency becomes routine)
- [Governance] → critical-freight rules begin treating satellite reliance as infrastructure concentration risk (regulation hardens)



## ART 10.080 — Space Resource Utilization (SRU)

**Score: 1 (Impact in GVN 2)**

**Justification:**

The only logistics linkage is indirect through future critical-material supply for vehicles, batteries, and electronics. That is too upstream and too uncertain to materially score as logistics impact today, even under a mature-state assumption. It is worth watching as a supply-side wildcard, not as a direct logistics technology. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Critical materials] → logistics OEMs start mentioning off-Earth sourcing in long-term materials scenarios (would create tie)
- [Supply chains] → insurers or traders treat SRU outputs as strategic inputs for transport hardware (would tighten linkage)
- [Operations] → no direct freight or depot technologies depend on SRU outputs (keeps effect indirect)
- [Market structure] → battery or motor supply strategies explicitly price potential SRU material access (would strengthen relevance)

## ART 10.081 — Closed-Loop Life Support Systems

**Score: 0 (Impact in GVN 2)**

**Justification:**

This ART has no meaningful direct pathway to terrestrial logistics operations for moving goods and materials. Any spillover would be through remote habitat engineering or extreme-environment support systems, which is too indirect for this GVN. I therefore assign 0.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Remote bases] → terrestrial isolated logistics sites adopt closed-loop habitat utilities (would create niche pathway)
- [Disaster logistics] → long-duration field camps use closed-loop water and waste systems (would tighten relevance)
- [Scale] → no mainstream freight sites treat life-support loops as core logistics infrastructure (keeps linkage absent)
- [Maintenance] → remote depots market “closed-loop” utility pods derived from space systems (would increase relevance)

## ART 10.082 — High-Altitude Platforms & Balloons

**Score: 3 (Impact in GVN 2)**

**Justification:**

High-altitude platforms can materially support regional logistics via temporary or persistent connectivity, navigation augmentation, and wide-area sensing. The strongest use is in remote areas, disaster response, and places where terrestrial infrastructure is weak or disrupted. Institutionally they create new airspace and telecom governance questions. I assign 3; a 5 would require routine, region-wide logistics dependence on HAP layers rather than targeted use.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Remote-area accessibility] → freight corridors and rural delivery regions use HAP links during terrestrial outages (coverage resilience rises)
- [Disaster logistics] → emergency supply chains pre-contract HAP services for rapid restoration (contingency becomes planned)
- [Accuracy] → regional observation from HAPs feeds road, flood, or queue management for freight (situational awareness improves)
- [Governance] → spectrum and airspace approvals limit operating windows and service areas (uptake stays bounded)
- [Market structure] → a few HAP operators capture regional emergency-connectivity contracts (dependency forms)
- [Temporary infrastructure] → seasonal or event-based logistics sites use HAP-backed comms instead of permanent build-out (would widen relevance)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5 (Impact in GVN 2)**

**Justification:**

This ART matters where logistics suffers from reconciliation, provenance disputes, multi-party distrust, and slow settlement. Directly it can automate custody records, payments, and some contractual triggers; institutionally it redistributes trust from bilateral arrangements to protocol and node governance, while also risking new concentration around dominant chains, wallets, or bridge operators. Third-order effects include tokenized capacity markets and more automated cross-border coordination. That supports a 5.

**Weak signals (9):**

- [Accuracy] → shared manifests and custody events are recorded on tamper-evident ledgers (reconciliation burden falls)
- [Cost-effectiveness] → payment release is triggered automatically by verified delivery milestones (working capital tightens)
- [Direct-to-consumer competition] → smaller sellers use shared trust rails instead of large marketplace mediation (entry friction drops)
- [Security of supply] → critical-freight audits rely on immutable multi-party records (trust gets operationalized)

- [Market structure] → logistics ecosystems converge on a few dominant chains, wallet stacks, or bridges (decentralization recentralizes)
- [Security] → bridge exploits or key losses become operational logistics incidents (new technical risk appears)
- [Flexibility] → shared-capacity and subcontracting markets settle faster across firms (coordination speeds up)
- [Governance] → disputes shift from paperwork to protocol rule interpretation (new power centers form)
- [Accessibility] → SMEs join traceable payment and custody networks without bespoke integrations (capability diffuses)

## ART 11.084 — Platform Cooperatives & Fair Work

**Score: 3 (Impact in GVN 2)**

### Justification:

The strongest logistics pathway is crowd logistics and last-mile delivery, where ownership and rule-setting shape service quality, labor stability, and local trust. Directly this can change worker retention, platform fees, and local service coverage; institutionally it shifts bargaining power and makes algorithmic rules more contestable. The impact is meaningful but concentrated in platform-mediated segments rather than the full logistics GVN. I assign 3.

### Weak signals (6):

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Crowdsourced participation] → worker- or courier-owned delivery platforms win municipal or regional contracts (ownership model shifts)
- [Cost-effectiveness] → payout transparency and lower fees are marketed against incumbent delivery apps (value capture becomes visible)
- [Accessibility] → underserved areas are served by locally governed courier networks (coverage logic changes)
- [Governance] → voting blocs or participation fatigue slow operational decisions (co-op coordination limits surface)
- [Market structure] → co-ops struggle to access capital against venture-backed rivals (scaling constraint appears)
- [Labor relations] → union and cooperative hybrids emerge for last-mile work (would deepen GVN relevance)

## ART 11.085 — Open Data Sharing Marketplaces

**Score: 5 (Impact in GVN 2)**

### Justification:

Data fragmentation is a real logistics bottleneck across demand, capacity, traffic, emissions, and asset status. Open data marketplaces directly reduce that barrier by making data access programmable and auditable; institutionally they create new markets for data rents, access rules, and quality certification. Third-order effects include faster coordination across firms and better use

of spare capacity, but also more pressure on smaller actors to reveal operational data. That is significant enough for a 5.

### **Weak signals (9):**

- [Flexibility] → carriers and shippers buy and sell live capacity, delay, and route datasets (coordination becomes tradable)
- [Accuracy] → marketplace-grade quality scores appear for logistics datasets (data becomes contractable)
- [Cost-effectiveness] → SMEs buy external demand or congestion data instead of building their own pipelines (entry barriers fall)
- [Security of supply] → public and private disruption data is shared through standard controlled environments (resilience intelligence improves)
- [Power] → large actors monetize indispensable network data and set access terms (information asymmetry hardens)
- [Governance] → disputes over provenance, usage rights, and re-identification reach courts or regulators (trust rules stiffen)
- [Urban logistics] → municipal curb, traffic, and emissions data is sold or licensed into freight optimization tools (city coordination deepens)
- [Accessibility] → smaller regions gain logistics analytics through shared exchanges rather than bespoke projects (capability diffuses)
- [Security] → false or manipulated data feeds trigger verification and reputation layers (data trust becomes operational)

## **ART 11.086 — Secure & Resilient Social Platforms**

### **Score: 1 (Impact in GVN 2)**

#### **Justification:**

These platforms matter mostly for crisis communication, workforce coordination, and cross-organization messaging when mainstream platforms are fragile or blocked. That is useful but peripheral to the main logistics operating model. The core logistics technologies carry most of the weight. I assign 1.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → logistics organizations shift crisis coordination onto resilient encrypted group platforms (communications harden)
- [Crowdsourced participation] → trusted community courier groups organize through resilient social nodes (niche coordination grows)
- [Operations] → routine logistics remains on conventional enterprise systems, not these platforms (keeps impact limited)
- [Disruption response] → regulators or public agencies publish logistics coordination channels on resilient networks (would deepen relevance)

## ART 11.087 — Collective Open Innovation Networks

**Score: 1 (Impact in GVN 2)**

**Justification:**

The benefit is faster logistics innovation and more distributed problem-solving, not a direct operational change in moving goods. That can matter strategically, but it is too indirect for a higher score in this GVN. I assign 1.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Innovation capacity] → logistics operators post open challenges on routing, packaging, and yard automation (problem-solving diffuses)
- [Accessibility] → SMEs access shared testbeds and benchmarks rather than internal R&D only (capability broadens)
- [Scale] → operational teams remain separated from innovation networks (keeps impact indirect)
- [Standards] → challenge outputs feed directly into logistics procurement or certification criteria (would strengthen linkage)

## ART 11.088 — Scalable Decentralized Governance

**Score: 3 (Impact in GVN 2)**

**Justification:**

This ART matters where logistics requires shared rule-setting across many actors: curb access, locker networks, multi-party platforms, ports, and data consortia. Directly it can lower coordination friction and make rules more inspectable; institutionally it also risks manipulation, voter fatigue, and software-mediated governance capture. The impact is material but mainly in coordination-heavy segments rather than the physical core of goods movement. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Governance] → multi-actor logistics platforms encode voting and budget rules directly into software (shared rule-making operationalizes)
- [Urban logistics] → shared curb or locker schemes use transparent participation and audit trails (coordination becomes inspectable)
- [Power] → disputes emerge over identity quality, delegation, and rule manipulation (software governance gets contested)
- [Accessibility] → smaller operators gain formal say in shared platform rules (participation broadens)
- [Compliance] → legal recognition of software-enforced decisions becomes a bottleneck (adoption stays partial)
- [Ports and hubs] → consortium-managed infrastructure pilots decentralized budget and access rules (would deepen impact)

## ART 11.089 — Digital Learning Networks and Skill Credentialing

**Score: 3 (Impact in GVN 2)**

### **Justification:**

The logistics linkage is strongest through reskilling: autonomous-vehicle supervision, robot maintenance, data-rich warehouse work, and safety/compliance retraining. Directly it reduces training bottlenecks and speeds workforce transition; institutionally it can also stratify labor through continuous credentialing and platform-controlled access to work. The impact is material because labor transition is a stated inhibitor in the GVN, but it remains a support layer rather than a direct operational technology. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Labor transition] → logistics employers replace long classroom training with modular online credentials (reskilling accelerates)
- [Accessibility] → workers in rural or smaller firms gain access to automation-relevant training remotely (skill diffusion widens)
- [Safety] → verified digital credentials become mandatory for robot, drone, or autonomous-fleet supervision (capability gets standardized)
- [Power] → platform-controlled credential wallets determine access to high-value tasks (gatekeeping risk grows)
- [Labor relations] → workers contest opaque scoring and recertification requirements (continuous evaluation intensifies)
- [Cost-effectiveness] → onboarding time for new tech-heavy logistics roles visibly falls (training bottleneck eases)

## ART 11.090 — Prediction-Market Forecasting Platforms

**Score: 3 (Impact in GVN 2)**

### **Justification:**

Prediction markets can improve logistics where fragmented expectations matter: demand swings, disruption risk, launch timing, and policy changes. Directly they can sharpen decision quality and make assumptions more explicit; institutionally they shift some planning authority toward continuously updated market-like signals. The impact is material but secondary compared with data, autonomy, and physical infrastructure. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → supply-chain control towers use internal markets for disruption and volume forecasts (beliefs get measurable)
- [Cost-effectiveness] → forecast-calibration metrics are tied to logistics planning incentives (assumption quality matters)



- [Security of supply] → procurement and routing decisions reference market-based probability bands (risk management formalizes)
- [Governance] → disputes emerge over settlement criteria and who may trade on operational information (fairness becomes issue)
- [Market structure] → better-informed large actors dominate forecast quality in shared platforms (information power concentrates)
- [Accessibility] → smaller operators subscribe to pooled forecast markets instead of bespoke consulting (would broaden uptake)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

**Score: 10 (Impact in GVN 2)**

#### **Justification:**

This is a foundational logistics enabler because the challenger regime depends on heterogeneous devices—tags, lockers, vehicles, robots, sensors, and depots—working together without endless custom integration. Directly it lowers deployment friction and makes goods, vehicles, and infrastructure legible across organizational boundaries; institutionally it shifts power from closed ecosystems toward standard setters, certification bodies, and compliant platform providers. Third-order effects include faster scaling of smart packaging, smart infrastructure, and MaaS-like goods logistics. That is transformative for how the GVN is realized, even if it is not the single most central linchpin.

#### **Weak signals (9):**

- [Standardization and prevalence] → depots procure only tags, lockers, sensors, and vehicles with open profiles (integration costs collapse)
- [Ease] → new devices join carrier systems through QR or NFC onboarding instead of bespoke setup (deployment accelerates)
- [Accuracy] → package, pallet, and vehicle events flow through common schemas across firms (handoffs become legible)
- [Flexibility] → mixed-vendor robot, locker, and cold-chain fleets share data without custom middleware (heterogeneity scales)
- [Accessibility] → SMEs access off-the-shelf interoperable tracking stacks (capability diffuses)
- [Governance] → standard-setting battles emerge over who controls certification profiles (power shifts to standard owners)
- [Security] → mass patch campaigns follow vulnerabilities in widely shared protocol stacks (common-mode risk rises)
- [Shared infrastructure] → municipal curb, depot, and locker systems expose common APIs to operators (public-private coordination improves)
- [Digital platforms] → freight marketplaces plug directly into device events from many carriers (real-time orchestration broadens)

## ART 12.092 — Interoperable Digital Twin Ecosystems

**Score: 5 (Impact in GVN 2)**

### **Justification:**

Interoperable twins matter when fleets, depots, ports, and public infrastructure must be coordinated across many owners and software stacks. Directly they reduce duplicate modeling, improve remote diagnosis, and tighten planning; institutionally they make liability, access rights, and model governance more explicit. Third-order effects include lower buffers and faster reconfiguration because shared state becomes easier to compare and act on. That supports a 5.

### **Weak signals (9):**

- [Accuracy] → ports, warehouses, and fleets exchange twin states across vendor boundaries (shared asset visibility improves)
- [Ease] → maintenance and intervention rehearsals move into reusable twin environments (remote action becomes easier)
- [Cost-effectiveness] → duplicate model-building effort falls in multi-party projects (coordination waste shrinks)
- [Security of supply] → disruption decisions use cross-organization simulation rather than isolated spreadsheets (resilience planning strengthens)
- [Governance] → disputes emerge over whose twin state is authoritative after incidents (model power becomes legal)
- [Market structure] → dominant cloud/twin vendors control ecosystem interfaces despite nominal openness (interoperability recentralizes)
- [Urban planning] → municipalities and operators test curb, depot, and corridor changes in shared twins (policy coordination improves)
- [Flexibility] → temporary sites and seasonal changes are commissioned faster through portable twin packages (reconfiguration speeds up)
- [Security] → high-fidelity twin access becomes a target because it reveals vulnerabilities and capacity (digital exposure grows)

## ART 12.093 — Global Supply Chain Traceability Networks

**Score: 20 (Impact in GVN 2)**

### **Justification:**

This ART is a direct match to the GVN's challenger regime because unique identification, packaging, cloud-linked control, and direct producer-consumer access all depend on portable, trusted histories of goods and materials. Directly it turns items, batches, and returns into machine-readable units that can be routed, audited, priced, and automated differently; institutionally it redistributes power toward actors controlling identifiers, compliance rails, and data visibility while also making illicit or unsafe flows easier to detect. Third-order effects include circular logistics, more direct distribution, tighter competition, and lower need for manual paperwork and prediction buffers. This is a keystone impact: the transformed, data-rich logistics model is drastically easier with it and much harder without it.

**Weak signals (9):**

- [Accuracy] → item-level IDs become mandatory in major retail and industrial contracts (unique identification normalizes)
- [Cost-effectiveness] → recall, damage, and customs disputes are resolved from shared custody data (paperwork collapses)
- [Flexibility] → mixed and small-batch flows stay automatable because each unit is machine-readable (heterogeneity scales)
- [Direct-to-consumer competition] → manufacturers ship directly with authenticated provenance and condition records (wholesaler dependence falls)
- [Circular logistics] → take-back pricing and reuse routing use product history at item level (reverse loops monetize)
- [Power] → dominant platforms and large buyers force suppliers onto proprietary traceability rails (data control concentrates)
- [Security] → cloned identifiers and credential-theft incidents trigger new anti-spoof layers (authenticity becomes contested)
- [Regulation] → automated holds increase when trace data is missing or inconsistent (compliance becomes hard gate)
- [Accessibility] → consumers compare verified delivery, origin, and sustainability attributes at checkout (logistics becomes visible)

**ART 12.094 — Personal Data Portability & Trust Frameworks****Score: 3 (Impact in GVN 2)****Justification:**

The main logistics pathway is portable delivery preferences, identity, permissions, access credentials, and selective sharing across carriers and platforms. Directly that can reduce failed deliveries and onboarding friction; institutionally it weakens some platform lock-in while creating new trust-framework intermediaries. The impact is material but limited to the customer and identity layer of logistics. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accessibility] → customers move delivery preferences and verified addresses between carriers (handoff friction drops)
- [Ease] → pickup, locker, and building-access permissions are granted through reusable consent profiles (last-mile smooths)
- [Cost-effectiveness] → repeated identity checks and failed-delivery contacts decline with portable trusted data (service cost falls)
- [Market structure] → a few wallet or trust-framework providers become required intermediaries (new dependency forms)
- [Governance] → revocation and liability disputes emerge after wrongly shared delivery data (consent governance matters)
- [Customer-centric logistics] → checkout systems begin offering carrier-agnostic data-wallet handoff (would deepen impact)

## ART 12.095 — Interoperable Digital Currency Payment Networks

**Score: 3 (Impact in GVN 2)**

**Justification:**

This ART affects logistics through faster settlement, lower reconciliation burden, better cross-border payments, and more automated release of funds in multi-party delivery chains. Directly that can improve working capital and reduce paperwork; institutionally it shifts some power toward payment-network protocols, compliance gateways, and liquidity providers. The impact is material but still on the financial plumbing around logistics rather than the physical flow layer. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Cost-effectiveness] → cross-border freight settlements clear faster with lower reconciliation effort (working capital improves)
- [Crowdsourced participation] → gig and on-demand carriers are paid instantly across platforms and jurisdictions (capacity becomes easier to mobilize)
- [Accuracy] → delivery milestones trigger atomic release of funds and deposits (dispute handling tightens)
- [Governance] → compliance and identity gateways become choke points for smaller operators (payment power recentralizes)
- [Security] → fraud or smart-payment failures drive stricter operational controls (financial rails become operational risk)
- [Flexibility] → spot-capacity markets become easier to run when settlement is near-real-time (would broaden impact)

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

**Score: 10 (Impact in GVN 2)**

**Justification:**

Logistics is heavily constrained by rules: customs, labor hours, dangerous goods, emissions zones, drone corridors, parking, and local delivery restrictions. Making these rules machine-readable directly reduces paperwork and compliance ambiguity while enabling routing, permitting, and operational checks to happen in software rather than through manual interpretation. Institutionally it shifts power toward software vendors, digital compliance infrastructure, and authorities capable of automated enforcement. Because this changes how logistics is actually executed across many layers, it is transformative and merits 10.

**Weak signals (9):**

- [Regulation] → cities publish delivery-window, curb, and emissions rules via APIs (routing becomes machine-executable)
- [Customs] → import and transit checks are pre-validated by software before border arrival (border friction falls)

- [Hazardous goods] → loading systems reject non-compliant manifests automatically (safety becomes real-time)
- [Drone and autonomy permits] → corridor permissions are granted through programmable compliance checks (new modes scale)
- [Labor protection] → scheduling tools enforce hours and rest rules before dispatch (human oversight shrinks)
- [Enforcement] → instant digital fines rise when telematics show rule breaches (automation hardens control)
- [Market power] → compliance-software vendors become indispensable gatekeepers for smaller carriers (dependency deepens)
- [Governance] → disputes grow over whose coded interpretation of a rule is authoritative (legal power shifts)
- [Ease] → SMEs buy “compliance by default” routing and documentation tools (entry barriers drop)

## ART 12.097 — Open Metaverse Interoperability Protocols

**Score: 0 (Impact in GVN 2)**

### **Justification:**

Any logistics relevance here would be limited to training or remote collaboration, and even those benefits are indirect compared with the more concrete AR/VR and digital-twin ARTs already scored. I do not see a meaningful standalone pathway to change logistics operations themselves. So I assign 0.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Training] → logistics firms demand portable assets and identities across immersive training tools (would create limited pathway)
- [Remote operations] → vendors market metaverse-interoperable control rooms for distributed logistics staff (would tighten niche relevance)
- [Operations] → day-to-day goods movement remains detached from metaverse protocol choices (keeps linkage absent)
- [Digital twins] → logistics twins are routinely embedded in interoperable virtual environments (would increase indirect relevance)

## ART 12.098 — Content Authenticity Infrastructure

**Score: 3 (Impact in GVN 2)**

### **Justification:**

This ART matters for proof-of-delivery images, inspection footage, damage claims, remote audits, and anti-counterfeit documentation. Directly it can reduce fraud and disputes; institutionally it shifts evidence standards toward credentialed media and away from raw files or trust in a single platform. The impact is material but not foundational across all logistics operations. I assign 3.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Accuracy] → proof-of-delivery photos and videos carry verified provenance by default (claims become easier to adjudicate)
- [Security] → customs, insurers, or buyers prefer credentialed inspection media for high-value loads (trust gets standardized)
- [Cost-effectiveness] → fraud losses fall where authenticated media replaces manual dispute handling (verification saves labor)
- [Governance] → disputes shift to missing or broken provenance chains instead of raw image quality (evidence norms change)
- [Market structure] → large platforms control privileged authenticity pipelines from capture to claim (proof infrastructure centralizes)
- [Counterfeits] → operators link media provenance to item-traceability workflows in sensitive supply chains (would deepen impact)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

**Score: 5 (Impact in GVN 2)**

**Justification:**

This ART fits a fragmented logistics sector where firms need joint insight without exposing raw commercial or personal data. Directly it enables safer shared planning, benchmarking, and optimization; institutionally it lowers some trust barriers while creating new dependence on protocol operators, key management, and shared governance. Third-order effects include more frequent collaboration and less redundant data collection across carriers, depots, and public actors. That is significant enough for a 5.

**Weak signals (9):**

- [Flexibility] → competing carriers run joint planning or utilization analyses without sharing raw data (collaboration barrier drops)
- [Accuracy] → public and private actors compute shared congestion or disruption metrics in protected environments (coordination improves)
- [Cost-effectiveness] → manual data-redaction projects are replaced by secure-computation services (overhead falls)
- [Accessibility] → smaller firms join shared analytics networks without surrendering sensitive records (participation broadens)
- [Governance] → counterparties dispute safe-output rules and who may request which analyses (protocol politics emerge)
- [Security] → key-management or output-leak incidents trigger tighter review layers (trust stack becomes visible)
- [Regulation] → authorities endorse protected collaboration where raw pooling was previously blocked (compliance unlocks value)
- [Market structure] → a few protocol operators or hosted MPC services dominate high-assurance networks (new gatekeepers form)



- [Security of supply] → resilient shared planning emerges for critical corridors without full data centralization (joint resilience deepens)

## **ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure**

**Score: 3 (Impact in GVN 2)**

### **Justification:**

The logistics pathway is indirect but real: faster qualification of equipment, locally produced spare parts, and more auditable performance claims across distributed manufacturing. Directly this reduces some supplier-switching and quality-verification friction; institutionally it strengthens the role of certifiers, metrology providers, and machine-readable quality evidence. The main logistics effect is on reliability and sourcing flexibility rather than the core movement of goods. I assign 3.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- [Security of supply] → certified local additive spare parts are accepted into maintenance workflows (supplier switching speeds up)
- [Accuracy] → machine-readable conformance certificates travel with components into logistics asset servicing (quality gets portable)
- [Cost-effectiveness] → qualification time falls for new suppliers or replacement parts (procurement friction drops)
- [Market structure] → accredited labs and certifiers become bottlenecks for distributed manufacturing networks (authority concentrates)
- [Governance] → disputes focus on test-suite definitions rather than informal vendor assurances (evidence regime hardens)
- [Accessibility] → smaller regional manufacturers enter logistics-equipment supply chains once certification is standardized (entry barrier falls)

## **GVN 3: Manufacturing of Goods ART Impact**

### **Group1. Sensing, Measurement & Connectivity**

#### **ART 01.001 — Global Broadband Connectivity**

**Score: 5 (Impact in GVN 3)**

### **Justification (3–5 sentences):**

Reliable high-capacity connectivity makes it easier to run remote diagnostics, coordinate subcontractors, use distributed digital manufacturing chains, and support local small plants without dense local expertise. It reduces the siting advantage of existing industrial clusters and strengthens platform vendors that control data, service, and network layers. It also increases exposure to cyber disruption if connectivity becomes a production-critical utility. In a 5.5M-person society, the

combined effect on downtime, travel, subcontracting, and resilience can plausibly land in the €100M–€1B band, which fits **5**.

#### **Weak signals (9):**

- (+) [Maintenance and repair] → OEM machine contracts bundle remote-first support and backup links (travel intensity drops)
- (+) [Subcontractors] → tenders start requiring always-on digital trace exchange (networked chains thicken)
- (+) [Local employment] → new microfactories appear outside legacy hubs (siting logic loosens)
- (+) [Ease of purchasing] → spare-part ordering portals connect directly to machine telemetry (ordering friction falls)
- (+) [Reduced vulnerability] → plants add secondary non-terrestrial links to continuity plans (connectivity becomes utility)
- (–) [Security] → industrial cyber-insurance premiums start referencing network-path diversity (attack surface priced)
- (–) [Market structure] → telecom/cloud bundles tie connectivity to MES or data contracts (dependency concentrates)
- (–) [Quality control] → audits flag missing synchronized records from remote suppliers (link reliability matters)
- (–) [Risk aversion] → lenders request communications-resilience evidence in capex reviews (finance gates adoption)

## **ART 01.002 — Ultra-Low Latency Networks**

### **Score: 5 (Impact in GVN 3)**

#### **Justification (3–5 sentences):**

Ultra-low latency links enable tighter coordination of robots, machine vision, teleoperation, and shared control loops across factories, warehouses, and remote experts. They favor plants that can afford edge compute and deterministic networking, while shifting more responsibility to software vendors and network operators. They also amplify both automation gains and cascading failures when timing guarantees break. That is large enough to change throughput, safety, and changeover economics across many sites, plausibly in the €100M–€1B band, so **5**.

#### **Weak signals (9):**

- (+) [Functionality] → robot-cell tenders specify deterministic latency rather than raw bandwidth (timing becomes bottleneck)
- (+) [Maintenance and repair] → OEMs offer remote teleoperation for fault recovery (experts travel less)
- (+) [Flexibility] → mixed-machine cells start sharing real-time coordination buses (distributed control rises)
- (+) [Quality control] → in-line inspection closes the loop on fast process adjustments (response time monetized)
- (+) [Competitive adaptability] → contract manufacturers advertise millisecond-grade orchestration capability (speed becomes differentiator)
- (–) [Safety and compliance] → regulators demand timing-validation evidence for remote control use (liability formalizes)

- (–) [Market structure] → edge-cloud providers lock plants into proprietary control stacks (control centralizes)
- (–) [Security] → incident reports cite packet-delay attacks causing near-misses (timing becomes attack vector)
- (–) [Risk aversion] → CFOs reject retrofits lacking clear uptime payback (capex hurdle visible)

## ART 01.003 — Edge AI for Sensor Data

### Score: 10 (Impact in GVN 3)

#### Justification (3–5 sentences):

Edge AI changes manufacturing from periodic inspection and centralized analysis toward continuous local interpretation and action at the machine, line, and cell level. It enables real-time defect detection, anomaly response, and adaptive control even in noisy plants, while reducing dependence on scarce specialists and favoring firms that own the model stacks, data, and update channels. It can either shrink scrap and downtime or create synchronized failure modes if models drift or are compromised. Because it changes how quality, maintenance, and control are realized across many plants, affecting hundreds of thousands of workers and customers weekly, **10** is justified.

#### Weak signals (9):

- (+) [Quality control] → final release procedures begin accepting edge-model defect calls (AI crosses release boundary)
- (+) [Maintenance and repair] → OEM warranties reference continuous anomaly logs from machines (service becomes predictive)
- (+) [Flexibility] → recipe changes automatically retune inspection thresholds on the edge (changeovers accelerate)
- (+) [Competitive adaptability] → SMEs buy retrofit vision kits instead of custom automation projects (entry barriers fall)
- (+) [Resource efficiency] → scrap reduction claims appear in quarterly plant KPIs (waste becomes measurable)
- (+) [Lack of skills] → operator roles shift toward supervising alerts and exceptions (skill mix changes)
- (–) [Safety and compliance] → regulators demand model version traceability in incident reviews (AI becomes auditable)
- (–) [Market structure] → a few vendors bundle cameras, chips, models, and cloud updates (stack control concentrates)
- (–) [Security] → recalls are traced to corrupted edge-model updates or sensor spoofing (model integrity matters)

## ART 01.004 — Quantum & High-Precision Sensing

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

This mainly affects high-value manufacturing niches that depend on advanced metrology, fine material characterization, timing, or navigation without external references. It can tighten certification and reduce safety margins in sectors like semiconductors, aerospace, advanced materials, and high-end machinery. It may also widen the capability gap between frontier

manufacturers and the rest. That is a clear but narrower pathway, plausibly in the €10M–€100M range in affected subsectors, so **3**.

#### **Weak signals (6):**

- (+) [Perceived quality] → high-end plants add new ultra-sensitive metrology stations (tolerance control deepens)
  - (+) [Quality control] → destructive sampling is replaced by continuous precision measurement (inspection becomes live)
  - (+) [Functionality] → GNSS-denied positioning specs appear in autonomous factory vehicles (reference dependence falls)
  - (–) [Safety and compliance] → certification bodies publish new evidence rules for quantum-grade sensors (trust must formalize)
  - (–) [Market structure] → precision-sensor procurement narrows to a small supplier set (capability concentrates)
  - (–) [Risk aversion] → pilots stay confined to premium product lines (spillover remains narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 01.005 — Micro/Nano Sensor Networks**

### **Score: 5 (Impact in GVN 3)**

#### **Justification (3–5 sentences):**

Dense micro/nano sensor networks make factories, tools, stock, and even products much more observable at low unit cost. They improve early fault detection, traceability, process tuning, and asset utilization, while shifting advantage toward firms with the data infrastructure to filter billions of measurements. They also raise new privacy and disposal questions. This is large enough to plausibly reach the €100M–€1B band, so **5**.

#### **Weak signals (9):**

- (+) [Quality control] → strain, vibration, or humidity specks get embedded in fixtures (more failure precursors seen)
- (+) [Maintenance and repair] → condition maps replace route-based inspections in plants (attention becomes targeted)
- (+) [Customization] → parts with built-in sensor patches enter pilot lots (products become self-reporting)
- (+) [Reduced need for storage/logistics] → warehouse zones gain dense low-cost environment meshes (inventory spoilage drops)
- (+) [Perceived quality] → warranty analytics begin using product-embedded sensor histories (field feedback shortens)
- (–) [Labor] → worker councils contest invisible sensing on shop floors (monitoring norms challenged)
- (–) [Security] → red-team exercises target spoofing of distributed sensor swarms (trust in readings tested)
- (–) [Waste handling] → recyclers request disclosure of embedded microelectronics content (material loops complicate)
- (–) [Market structure] → gateway and analytics providers become choke points (data power concentrates)

## ART 01.006 — Privacy-Preserving Pervasive Sensing

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Its main manufacturing value is not more sensing by itself, but enabling pervasive sensing in plants, warehouses, and supplier networks without immediate legal or trust backlash. It can loosen a real inhibitor to worker-facing automation and cross-site benchmarking, while also normalizing more continuous monitoring under a privacy-compliant label. The impact is therefore material but narrower than core sensing or AI layers. It fits the €10M–€100M range and a 3.

#### Weak signals (6):

- (+) [Risk aversion] → worker-monitoring pilots proceed only with on-device analytics clauses (trust becomes design variable)
- (+) [Quality control] → audits accept aggregated sensor outputs instead of raw video retention (privacy unlocks deployment)
- (+) [Subcontractors] → shared benchmarking uses encrypted or local-only data processing (data sharing broadens)
- (–) [Labor] → disputes shift from “no sensing” to “who sets privacy policy” (monitoring becomes normalized)
- (–) [Safety and compliance] → procurement asks for privacy-by-design certification on industrial cameras (governance formalizes)
- (–) [Market structure] → secure-chip vendors capture sensing stack margins (compliance rents emerge)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.007 — Quantum-Resilient and Secure Communication Networks

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Manufacturing benefits mainly through stronger protection of design files, control traffic, and long-lived IP as remote operations and digital supply chains expand. It can reduce hesitancy around inter-firm data exchange and automated remote service, but it also adds upgrade costs and dependency on security-certified vendors. The likely impact is real but mostly institutional and enabling rather than operating-model-defining. So 3 is appropriate.

#### Weak signals (6):

- (+) [Intellectual property] → equipment and CAD platforms begin advertising post-quantum secure links (future-proofing monetized)
- (+) [Subcontractors] → supplier onboarding requires upgraded cryptographic profiles (secure coordination hardens)
- (+) [Maintenance and repair] → remote service contracts add integrity guarantees for machine control traffic (remote trust rises)
- (–) [Risk aversion] → legacy-machine upgrades stall over crypto retrofit cost (installed base resists)
- (–) [Safety and compliance] → export-control and critical-infrastructure reviews start referencing algorithm migration (security becomes compliance issue)

- (–) [Market structure] → certified secure-network vendors gain oligopoly positions (assurance concentrates)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 — Integrated Sensing and Communication (ISAC)

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

ISAC can turn plant and warehouse network infrastructure into a shared awareness layer for asset tracking, safety zoning, motion detection, and coarse environmental mapping. It lowers the cost of dense situational awareness and supports autonomy, while also creating new privacy, interference, and cybersecurity issues because communication infrastructure becomes part of the sensing stack. Across many industrial sites, the operational and safety effects can plausibly sit in the €100M–€1B band. So 5 fits.

**Weak signals (9):**

- (+) [Safety and compliance] → wireless upgrades are sold with built-in motion or occupancy sensing (networks become sensors)
- (+) [Maintenance and repair] → forklifts, AGVs, and tools are tracked through radio infrastructure alone (separate sensors avoided)
- (+) [Flexibility] → temporary production layouts keep asset visibility without re-cabling (reconfiguration gets cheaper)
- (+) [Reduced need for storage/logistics] → warehouses use network-based object tracking in dense aisles (inventory awareness thickens)
- (+) [Competitive adaptability] → brownfield sites adopt ISAC retrofits instead of full vision stacks (lower adoption barrier)
- (–) [Labor] → worker groups object to passive movement tracking from communications gear (privacy conflict widens)
- (–) [Security] → incident drills include spoofed sensing via compromised network nodes (dual-use risk surfaces)
- (–) [Quality control] → plants discover blind spots when communications tuning overrides sensing quality (trade-off becomes visible)
- (–) [Market structure] → telecom equipment vendors move into industrial safety markets (boundary shifts)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 — Compute-in-Memory & Neuromorphic Chips

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

These chips make it cheaper to run perception, anomaly detection, and adaptive control close to machines and sensors under tight power and thermal limits. That supports wider deployment of local intelligence in tools, products, and industrial infrastructure while increasing dependence on specialized hardware ecosystems. It can also shift advantage toward manufacturers that redesign equipment around always-on embedded intelligence. The effect is significant but mostly enabling, so 5 fits the €100M–€1B band.



**Weak signals (9):**

- (+) [Functionality] → industrial cameras and sensors ship with local AI acceleration as standard (local intelligence normalizes)
- (+) [Maintenance and repair] → condition-monitoring modules shrink to retrofit form factors (brownfield adoption rises)
- (+) [Customization] → smart products add embedded inference without battery or heat penalties (intelligence enters BOM)
- (+) [Resource efficiency] → machine control vendors advertise lower AI power draw per cell (edge economics improve)
- (+) [Quality control] → low-latency pattern recognition moves inside inspection heads (central servers avoided)
- (–) [Market structure] → a small set of chip toolchains dominate industrial deployment (software dependence grows)
- (–) [Risk aversion] → integrators report debugging difficulty for mixed-signal AI hardware (support burden rises)
- (–) [Security] → firmware signing becomes mandatory for smart sensor modules (hardware trust formalizes)
- (–) [Skills] → vacancies shift toward embedded-AI hardware integration roles (capability bottleneck appears)

## ART 02.010 — Novel transistor technologies and materials beyond silicon CMOS

**Score: 3 (Impact in GVN 3)****Justification (3–5 sentences):**

The manufacturing effect comes mostly through better industrial electronics: smaller, cooler, lower-power controllers, sensors, and embedded compute. That matters, but mainly as a broad hardware efficiency improvement rather than a distinct change in manufacturing organization. The main second-order effects come through semiconductor supply concentration and new equipment dependency. The likely total effect is material but not transformative for this GVN, so **3**.

**Weak signals (6):**

- (+) [Functionality] → industrial devices advertise always-on sensing with much lower heat (electronics constraints ease)
- (+) [Competitive adaptability] → more compute is embedded directly in machine tools (control gets denser)
- (+) [Resource efficiency] → OEMs cite lower electronics cooling needs in plant retrofits (supporting costs drop)
- (–) [Market structure] → advanced-process supply agreements become strategic procurement items (component power concentrates)
- (–) [Risk aversion] → industrial buyers demand long-duration reliability proofs before switchovers (qualification slows spread)
- (–) [Standards] → certification labs add new test methods for unfamiliar device physics (validation burden grows)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 — Quantum Computing Platforms

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

The clearest manufacturing pathways are faster optimization, materials and process design, and select high-value scheduling or simulation tasks. Access is likely to be concentrated in large firms or premium service platforms, potentially widening capability gaps. It may accelerate IP races in chemicals, electronics, and advanced materials more than factory-floor operations. That is meaningful but still narrower than the core manufacturing shift, so **3**.

#### Weak signals (6):

- (+) [Variety and innovation] → materials or process teams start using quantum cloud slots in development pipelines (advanced search enters R&D)
- (+) [Subcontractors] → design-service firms market quantum-assisted optimization to manufacturers (specialist layer forms)
- (+) [Functionality] → certain high-value product lines cite quantum-derived material recipes (niche performance edge)
- (–) [Market structure] → only very large firms secure recurring quantum access contracts (capability gap widens)
- (–) [Intellectual property] → patent filings mention quantum-optimized formulations or layouts (IP race intensifies)
- (–) [Risk aversion] → factory teams keep quantum use outside safety-critical decisions (operational impact stays narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 — Photonic and Optical Computing

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Its manufacturing impact is mainly through compute-heavy workloads such as machine vision, simulation, optimization, and dense digital-twin operation under tighter energy constraints. It benefits firms with high data volumes and advanced automation but requires major new hardware ecosystems, so the gain is uneven. That produces a clear but not system-wide manufacturing effect. This fits **3**.

#### Weak signals (6):

- (+) [Quality control] → high-throughput vision vendors begin shipping optical accelerators (inspection density rises)
- (+) [Competitive adaptability] → simulation-heavy process industries add optical compute appliances (design loops shorten)
- (+) [Resource efficiency] → data-center energy per twin or vision workload becomes a procurement KPI (compute efficiency monetized)
- (–) [Market structure] → specialized vendors tie photonic hardware to proprietary compilers (stack lock-in emerges)
- (–) [Risk aversion] → manufacturers limit deployment to non-mission-critical workloads (adoption remains staged)

- (–) [Cost-effectiveness] → optical modules are approved only where power or speed savings are extreme (niche economics dominate)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 — Next-Gen Memory & Storage

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

More persistent and denser memory supports digital twins, traceability, machine logs, and edge systems that need fast local state retention. It strengthens data-rich manufacturing models and lowers some infrastructure costs, while raising retention, governance, and cyber-recovery obligations. The impact is useful and material but mostly an enabler. So **3** is appropriate.

#### Weak signals (6):

- (+) [Quality control] → machine vendors keep much longer local process histories on equipment (state stays near machine)
- (+) [Interoperability] → asset twins retain live operational state across shutdowns (restart friction falls)
- (+) [Maintenance and repair] → service teams rely on high-frequency local logs after faults (root-cause quality improves)
- (–) [Security] → incident response plans emphasize secure wipe and recovery of persistent edge memory (data persistence cuts both ways)
- (–) [Compliance] → retention policies expand to industrial machine data stores (governance burden grows)
- (–) [Market structure] → memory-specific firmware ecosystems become new industrial dependencies (infrastructure power shifts)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 — Molecular Computing

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The clearest pathway is limited to chemical and biological manufacturing contexts where computation inside molecular environments directly adds value. For general manufacturing of goods, that is still a niche enabling layer rather than a broad driver of plant organization, quality, or market structure. It is worth monitoring, but the plausible impact remains below the material band. So **1** fits.

#### Weak signals (4):

- (+) [Variety and innovation] → specialty bioprocess lines test molecular logic in reactors (bio-process coupling starts)
- (+) [Quality control] → in-reactor molecular sensing-and-decision demos move from lab to pilot (chemistry becomes programmable)
- (–) [Cost-effectiveness] → buyers reject systems unless they replace expensive sampling steps (niche payback required)

- (–) [Safety and compliance] → regulators treat molecular-compute components as new process-critical elements (governance stays heavy)  
Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 — Causal Learning & Reasoning

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Causal AI is valuable in manufacturing because it helps plants choose interventions rather than just detect correlations: which parameter to change, which supplier change caused drift, which maintenance action reduces failures. It reduces dependence on a few experts and makes process know-how more portable, while also creating accountability fights when causal claims are embedded in automated decisions. Better intervention logic compounds with faster experimentation and reconfiguration. That is large enough to plausibly sit in the €100M–€1B range, so **5**.

**Weak signals (9):**

- (+) [Quality control] → root-cause tools begin showing “best intervention” rather than only anomaly flags (decision support deepens)
- (+) [Competitive adaptability] → process teams run counterfactual simulations before recipe changes (trial-and-error shrinks)
- (+) [Subcontractors] → supplier quality reviews use causal evidence instead of simple defect correlations (accountability sharpens)
- (+) [Resource efficiency] → plants attribute scrap reduction to specific controllable variables (interventions become investable)
- (+) [Lack of skills] → fewer decisions wait for single expert sign-off (knowledge bottlenecks loosen)
- (–) [Safety and compliance] → incident reviews contest which causal model version was authoritative (model governance matters)
- (–) [Market structure] → platform vendors own the dominant causal templates for sectors (reasoning stack concentrates)
- (–) [Risk aversion] → managers keep manual override on all high-stakes interventions (trust stays conditional)
- (–) [Labor] → engineers report deskilling as systems recommend parameter moves directly (agency shifts)

#### ART 03.016 — Federated & Privacy-Preserving Learning

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This is highly relevant for manufacturing networks where plants, suppliers, and OEMs need shared models but do not want to expose raw process data, trade secrets, or worker data. It can change bargaining power by letting smaller firms benefit from pooled learning without fully surrendering data, while also creating dependence on shared standards and aggregation operators. Better shared models can accelerate quality convergence across whole supplier tiers. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Subcontractors] → supplier consortia pilot shared defect models without centralizing raw data (coordination barrier weakens)
- (+) [Quality control] → OEMs accept locally trained updates from many plants (fleet learning begins)
- (+) [Risk aversion] → data-sharing pilots that had stalled resume under privacy-preserving terms (trust unlocks action)
- (+) [Competitive adaptability] → SMEs gain access to sector models via federation programs (capability diffusion starts)
- (+) [Perceived quality] → cross-site model benchmarks become procurement evidence (learning quality gets standardized)
- (–) [Market structure] → aggregation platforms become new choke points in supply networks (orchestrator power rises)
- (–) [Security] → procurement adds poisoning-resilience tests for federated updates (shared learning gets attacked)
- (–) [Labor] → local teams are pressured to conform to global model templates (local autonomy shrinks)
- (–) [Compliance] → legal reviews focus on whether model updates leak proprietary process traits (privacy claims tested)

**ART 03.017 — Trustworthy AI Systems****Score: 10 (Impact in GVN 3)****Justification (3–5 sentences):**

Manufacturing is explicitly constrained by safety, compliance, risk aversion, and accountability; trustworthy AI directly attacks those inhibitors. It lets firms use AI in quality, planning, control, and maintenance with better auditability and fallback behavior. It also changes procurement, insurance, and regulator expectations, while accelerating adoption of more automated and decentralized production and concentrating power in assurance, monitoring, and certified model platforms. Because it changes how AI becomes acceptable in the GVN rather than just improving one task, **10** is justified.

**Weak signals (9):**

- (+) [Risk aversion] → AI procurement checklists start requiring audit trails and rollback modes (trust becomes purchasable)
- (+) [Safety and compliance] → regulators accept explainability and provenance packs in plant approvals (AI enters compliance path)
- (+) [Quality control] → final release decisions reference confidence thresholds and trace logs (opaque AI becomes governable)
- (+) [Subcontractors] → OEMs require model lineage disclosure from automated suppliers (trust propagates downstream)
- (+) [Insurance] → policies price AI systems differently when verified fallback modes exist (assurance gains monetary value)
- (+) [Lack of skills] → mid-tier manufacturers buy pre-certified AI modules instead of building from scratch (adoption broadens)

- (–) [Market structure] → certification and assurance vendors become mandatory intermediaries (gatekeeper layer grows)
- (–) [Labor] → disputes move toward who defines AI constraints and escalation rules (control shifts upward)
- (–) [Security] → safety incidents are traced to policy bypass or poisoned monitoring layers (trust stack becomes critical)

## ART 03.018 — Automated Machine Learning (AutoML)

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

AutoML matters because lack of AI skills is a stated inhibitor in the GVN. It lowers the effort of building and maintaining inspection, scheduling, maintenance, and forecasting models. It lets more firms participate but can also spread mediocre or unsafe models quickly if objectives are badly set, and it shortens feedback loops from operations to new model deployment. That is significant enough to fall in the €100M–€1B range, so **5**.

#### Weak signals (9):

- (+) [Lack of skills] → plants without in-house data scientists start deploying custom models (skill bottleneck weakens)
- (+) [Competitive adaptability] → model refreshes move from quarterly projects to routine operations (iteration cadence rises)
- (+) [Quality control] → inspection models are rebuilt automatically for new SKUs (variant handling improves)
- (+) [Cost-effectiveness] → AI subscriptions replace custom consulting in SME budgets (capability gets standardized)
- (+) [Functionality] → MES or ERP systems ship with built-in model factories (AI becomes default feature)
- (–) [Safety and compliance] → postmortems reveal reward or metric mis-specification in automated models (governance gap shows)
- (–) [Market structure] → cloud vendors lock AutoML into their own data stacks (platform dependence rises)
- (–) [Labor] → engineers report pressure to accept machine-generated models they cannot inspect (judgment shifts)
- (–) [Security] → model pipelines become a common industrial attack surface (automation expands exposure)

## ART 03.019 — Collaborative Multi-Agent AI

### Score: 10 (Impact in GVN 3)

#### Justification (3–5 sentences):

Collaborative multi-agent AI is a strong fit for the challenger regime because future manufacturing increasingly involves many robots, sensors, software services, suppliers, and logistics assets coordinating in real time. It enables dynamic task allocation and more fluid, decentralized production; changes labor roles, control-room power, and vendor dependency; and can produce powerful scaling effects or fast cascade failures when coordination rules are wrong. Because it changes how production is organized rather than just optimizing one station, **10** is appropriate.



**Weak signals (9):**

- (+) [Flexibility] → orchestration software starts assigning work across many robots and machines dynamically (cells become fluid)
- (+) [Subcontractors] → supplier ecosystems expose machine-readable task and capacity APIs (network coordination deepens)
- (+) [Reduced vulnerability] → plants recover faster from local failures through automatic rerouting (resilience becomes software-defined)
- (+) [Customization] → mixed small-batch orders are split across autonomous cells without manual planning (batch economics change)
- (+) [Ease of purchasing] → customers buy capacity or outcome guarantees instead of fixed runs (production becomes service-like)
- (+) [Lack of skills] → one supervisor manages many agent clusters across sites (attention scales differently)
- (–) [Safety and compliance] → incident reports trace failures to agent-goal conflicts (coordination needs governance)
- (–) [Market structure] → orchestration platforms gain power over equipment from many vendors (control centralizes)
- (–) [Security] → adversarial messages or spoofed agents trigger production disturbances (coordination becomes attack surface)

**ART 03.020 — Quantum-Accelerated AI Systems****Score: 1 (Impact in GVN 3)****Justification (3–5 sentences):**

This has a plausible manufacturing pathway through niche optimization and search problems, but the effect is likely concentrated in a small number of high-value use cases. It does not clearly reshape the broad operating model of manufacturing goods, and much of the benefit is already captured under AI and quantum computing more generally. That keeps it in the “worth watching” category. So 1 fits.

**Weak signals (4):**

- (+) [Variety and innovation] → manufacturers test quantum-enhanced search inside design platforms (niche optimization appears)
- (+) [Subcontractors] → specialist consultancies sell hybrid quantum-AI planning services (premium layer emerges)
- (–) [Cost-effectiveness] → only top-tier firms can justify recurring access fees (benefits stay concentrated)
- (–) [Risk aversion] → production teams confine use to advisory mode (operational trust remains low)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 03.021 — AI-Driven Autonomous Scientific Discovery****Score: 5 (Impact in GVN 3)****Justification (3–5 sentences):**

Manufacturing increasingly competes on faster materials, process recipes, toolpaths, and product

variants; autonomous discovery compresses those loops. It can move advantage toward firms that combine labs, simulation, and automated process development, while also concentrating IP and reducing the role of some human experts. Faster discovery feeds reconfigurable production and customized goods. The plausible impact on innovation throughput and process improvement is large enough for 5.

#### **Weak signals (9):**

- (+) [Variety and innovation] → process-development labs start running autonomous experiment queues (discovery cadence rises)
- (+) [Customization] → new product variants reach pilot manufacture after far fewer human design iterations (design-to-build compresses)
- (+) [Resource efficiency] → materials teams find lower-waste recipes through closed-loop AI experimentation (discovery shifts economics)
- (+) [Functionality] → supplier contracts start offering AI-found process improvements as a service (innovation externalizes)
- (+) [Competitive adaptability] → firms publicize much shorter development-to-ramp timelines (speed becomes market signal)
- (–) [Intellectual property] → patent disputes center on AI-generated formulations and process inventions (ownership norms strain)
- (–) [Labor] → fewer junior R&D roles appear in routine optimization tasks (career ladder changes)
- (–) [Market structure] → platforms combining lab automation and models dominate discovery workflows (capability concentrates)
- (–) [Safety and compliance] → regulators ask how autonomous experiment agents were constrained (governance follows discovery)

## **4. Human-Machine Interaction & Augmentation**

### **ART 04.022 — Immersive Augmented & Virtual Reality**

#### **Score: 5 (Impact in GVN 3)**

#### **Justification (3–5 sentences):**

AR/VR improves training, remote troubleshooting, layout design, and assembly or maintenance guidance, which is especially valuable when skilled staff are scarce or geographically concentrated. It can support more decentralized production and faster onboarding, while also shifting power toward platform vendors and expanding possibilities for worker monitoring. Better spatial guidance also feeds faster changeovers and lower rework. That is significant enough to sit in the €100M–€1B band, so 5.

#### **Weak signals (9):**

- (+) [Lack of skills] → onboarding programs move from manuals to guided immersive work instructions (training burden drops)
- (+) [Maintenance and repair] → remote experts troubleshoot machines through shared first-person views (expert reach scales)
- (+) [Competitive adaptability] → layout or cell changes are rehearsed in digital space before installation (reconfiguration speeds up)

- (+) [Perceived quality] → assembly guidance overlays are used on high-variance tasks (error rates fall)
- (+) [Local employment] → smaller sites run with remote specialist support rather than full in-house teams (decentralization becomes easier)
- (–) [Labor] → headset telemetry is used in performance reviews (monitoring intensifies)
- (–) [Market structure] → equipment vendors tie support content to proprietary XR platforms (service lock-in grows)
- (–) [Safety and compliance] → incident reports cite distraction or overlay errors (interface becomes safety-critical)
- (–) [Cost-effectiveness] → pilots stall where content creation costs stay high (content bottleneck visible)

## ART 04.023 — Brain-Computer Interfaces (BCI)

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

BCI has some niche manufacturing value through hands-free control, accessibility, and possibly fatigue or attention measurement in special settings. But it does not map cleanly onto the dominant or challenger manufacturing regime at broad scale, and the privacy, ergonomics, and acceptance issues are unusually strong. That makes it concrete but limited. So **1** fits.

#### Weak signals (4):

- (+) [Accessibility] → pilot programs use BCIs for operators who cannot use standard controls (participation expands at margins)
  - (+) [Functionality] → clean-room or sterile environments test hands-free BCI interfaces (niche control case forms)
  - (–) [Labor] → unions object to neural-state monitoring in safety roles (privacy resistance surfaces)
  - (–) [Risk aversion] → employers keep BCI use voluntary and non-critical (broad rollout stays unlikely)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 — Advanced Prosthetics & Exoskeletons

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

These technologies can reduce injuries, extend productive participation, and keep some manual tasks economically viable where full automation is not yet sensible. They shift bargaining around ergonomics, disability inclusion, and the pace of automation, and may both relieve labor shortages and delay some automation investments. That is a real manufacturing effect but mostly in labor-intensive or ergonomically harsh settings. So **3** is appropriate.

#### Weak signals (6):

- (+) [Local employment] → plants add exoskeleton-supported roles for older or partially disabled workers (labor pool widens)
- (+) [Cost-effectiveness] → injury-reduction metrics are used to justify wearable support purchases (ergonomics monetized)

- (+) [Functionality] → procurement specs include wearable assistance compatibility for manual tasks (manual work is augmented)
  - (–) [Labor] → negotiations focus on whether wearables raise expected pace or load (assistive tech becomes managerial tool)
  - (–) [Safety and compliance] → insurers add wearable-device requirements to injury investigations (liability formalizes)
  - (–) [Automation] → some firms postpone mechanization after wearable productivity gains (substitution path slows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 — Haptic and Multi-Sensory Feedback Systems

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The strongest path is through teleoperation, precision manipulation, training, and fine manual quality work where feedback matters. It can globalize certain skilled tasks and reduce travel for specialists, but it also creates new dependencies on low-latency networks and new safety liabilities if force or feedback is wrong. The impact is material yet narrower than broad plant automation. So **3** is appropriate.

**Weak signals (6):**

- (+) [Maintenance and repair] → remote service stations adopt force-feedback tools for precision interventions (telework reaches physical tasks)
  - (+) [Perceived quality] → training rigs use realistic tactile replay for assembly skills (tacit skill transfer improves)
  - (+) [Functionality] → delicate handling tasks move from local experts to remote operators (expert reach widens)
  - (–) [Safety and compliance] → incident reports cite haptic calibration errors (feedback becomes liability issue)
  - (–) [Market structure] → remote-manipulation platforms bundle network and haptic hardware (capability centralizes)
  - (–) [Labor] → wage arbitration appears for cross-border remote manipulation work (labor market broadens unevenly)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 — AI Understanding of Human Intent & Context

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This makes complex equipment, robots, and planning systems easier to operate by inferring what workers are trying to do and adapting interfaces accordingly. It lowers training barriers and enables more mixed human-machine teams, while also increasing worker surveillance and managerial asymmetry. Smoother interaction then accelerates uptake of more complex automation and reconfiguration. That is large enough to plausibly reach the €100M–€1B band, so **5**.

**Weak signals (9):**

- (+) [Ease of use] → industrial HMIs begin adapting prompts to operator context or role (interface burden falls)
- (+) [Lack of skills] → novice operators handle more complex equipment with AI guidance (training barrier weakens)
- (+) [Safety and compliance] → cobots adjust behavior to inferred distraction or overload states (context enters control loop)
- (+) [Competitive adaptability] → reconfigured lines are staffed faster because interfaces self-adapt (changeover labor drops)
- (+) [Functionality] → voice, gesture, and behavior cues are combined in standard machine control (interaction gets naturalized)
- (–) [Labor] → worker councils challenge emotion or intent inference in production environments (monitoring boundary contested)
- (–) [Market structure] → machine vendors bundle proprietary intent models into service contracts (control stack thickens)
- (–) [Security] → spoofing or adversarial behavior tests become part of safety validation (human cues become attack vector)
- (–) [Accountability] → incident reviews dispute whether operator intent was correctly inferred (responsibility blurs)

## ART 04.027 — Brain-to-Brain Interfaces

### Score: 0 (Impact in GVN 3)

#### Justification (3–5 sentences):

Even on a mature assumption, there is no clear high-confidence pathway from brain-to-brain interfaces to broad manufacturing-system change. The most plausible uses are highly specialized tacit knowledge transfer or elite coordination scenarios, which remain too narrow and socially constrained to move this GVN materially. Score **0** unless the watchpoints below start creating a clearer manufacturing linkage.

#### Weak signals (4):

- (+) [Lack of skills] → pilots claim direct transfer of setup or repair routines between experts and trainees (linkage would become real)
  - (+) [Maintenance and repair] → hazardous-task teleoperation trials add shared neural cue channels (coordination would deepen)
  - (–) [Labor] → employers explicitly ban neural-sharing tools in production contracts (social ceiling becomes visible)
  - (–) [Safety and compliance] → no industrial insurer offers coverage language for BBI use (institutional pathway absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 — Memory Prostheses

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The most plausible manufacturing effect is preserving specialist recall, reducing error in complex procedures, and extending participation of a small number of expert workers. That can matter in maintenance or highly procedural sectors, but it does not point to a broad change in manufacturing organization or economics. It is worth watching but remains a **1**.

**Weak signals (4):**

- (+) [Lack of skills] → specialist maintenance teams test memory-support implants or adjuncts (expert retention becomes target)
  - (+) [Safety and compliance] → critical-procedure roles explore cognitive-support tools after incident reviews (error reduction sought)
  - (–) [Equality] → employers limit cognitive aids to elite technical roles (benefits stay narrow)
  - (–) [Privacy] → labor agreements prohibit employer access to cognitive-support telemetry (governance blocks scale)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 — Self-Driving Vehicles

**Score: 5 (Impact in GVN 3)****Justification (3–5 sentences):**

Autonomous road vehicles change manufacturing via inbound and outbound logistics, yard operations, internal shuttling, and the feasible geography of plants and suppliers. They reduce dependence on scarce drivers and shift power toward fleet platforms, while also creating labor displacement and cyber-safety exposure. More reliable logistics can support leaner inventories and more distributed production footprints. This is significant enough to fit **5**.

**Weak signals (9):**

- (+) [Reduced need for storage/logistics] → plants cut buffer stock after autonomous freight contracts start (inventory dependence softens)
- (+) [Local manufacturing] → smaller factories appear farther from traditional logistics hubs (siting options widen)
- (+) [Ease of purchasing] → inbound material delivery windows become tighter and more predictable (coordination improves)
- (+) [Cost-effectiveness] → yard tractors and shuttle routes go driverless before road legs do (adoption stair-step appears)
- (+) [Reduced vulnerability] → continuity plans rely on autonomous freight during labor shortages (resilience logic shifts)
- (–) [Labor] → driver and yard-operator unions renegotiate staffing and redeployment terms (job mix changes)
- (–) [Safety and compliance] → supplier contracts allocate liability for autonomous delivery incidents (responsibility formalizes)
- (–) [Security] → logistics cyber drills begin modeling hijack or spoof scenarios (vehicle software becomes critical)
- (–) [Market structure] → major manufacturers sign exclusive capacity deals with autonomy fleet operators (platform dependence grows)



## ART 05.030 — Drone Swarms & Aerial Robots

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

The main manufacturing pathways are site inspection, security, inventory, stockyard mapping, environmental monitoring, and rapid checks at large facilities. This can lower inspection labor and help remote supervision, but it also introduces airspace, privacy, and safety governance burdens. The effect is real and material for large or hazardous sites, yet not broad enough to transform the whole GVN. So 3 fits.

#### Weak signals (6):

- (+) [Maintenance and repair] → large plants shift roof, flare, or tank inspection to drone fleets (hazard exposure falls)
- (+) [Reduced need for storage/logistics] → stockyards and yards use aerial inventory counts routinely (visibility improves)
- (+) [Reduced vulnerability] → incident response drills include autonomous aerial inspection first (speed becomes operational)
- (–) [Safety and compliance] → industrial sites add permanent geofenced drone corridors (airspace governance hardens)
- (–) [Labor] → security and inspection roles shift toward remote fleet supervision (task composition changes)
- (–) [Security] → drone countermeasure systems appear in plant procurement lists (airborne misuse becomes concern)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.031 — Humanoid and General-Purpose Robots

### Score: 20 (Impact in GVN 3)

#### Justification (3–5 sentences):

This ART is almost a direct embodiment of the challenger regime's multi-skilled robotics and movement away from fixed production lines. General-purpose robots let factories automate a far wider share of varied manipulation, maintenance, changeover, and low-volume customized work in spaces built for humans. They reshape labor bargaining, supplier design choices, capex models, and ownership of production know-how, while making decentralized, line-less, locally adaptable manufacturing far more viable. Because this is close to a necessary enabler of the GVN's most important transformative shift, 20 is warranted rather than 10.

#### Weak signals (10):

- (+) [Mass production in large facilities] → capex shifts from dedicated lines to robot-ready flexible cells (line logic weakens)
- (+) [Customization] → contract manufacturers guarantee profitable low-volume variant runs (batch threshold collapses)
- (+) [Maintenance and repair] → robots take over routine machine tending and unscheduled interventions (human presence decouples)
- (+) [Local employment] → municipalities market small automated plants as local anchors (decentralization becomes investable)

- (+) [Ease of purchasing] → customers accept shorter order-to-build cycles for customized goods (production gets closer)
- (+) [Integration of design and manufacturing] → new product introductions rely on software updates more than tooling rebuilds (design loops tighten)
- (–) [Labor] → union bargaining shifts from line staffing to redeployment, pacing, and supervision (employment structure rewrites)
- (–) [Safety and compliance] → insurers require robot-behavior evidence packages for mixed human zones (liability hardens)
- (–) [Intellectual property] → robot skill libraries become proprietary bottlenecks in production contracts (know-how centralizes)
- (–) [Security] → incident drills model remote compromise of embodied robots (cyber-physical risk scales)

## ART 05.032 — Soft Robotics & Bio-Inspired Machines

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

Soft and compliant robots expand automation into handling tasks that are variable, delicate, cluttered, or unsafe for rigid machines, which broadens the sectors that can automate. They make more local and small-batch production feasible while changing labor needs in packaging, food, textiles, electronics, and repair. They also support product variety by reducing the tooling burden for handling variability. That is a significant manufacturing effect, so 5.

#### Weak signals (9):

- (+) [Variety] → automation spreads into mixed-shape or fragile-part handling tasks (rigid-machine ceiling falls)
- (+) [Perceived quality] → delicate assembly or packaging lines show lower damage rates (gentle handling pays)
- (+) [Local employment] → smaller plants automate variable tasks without huge safety cages (SME adoption broadens)
- (+) [Customization] → short runs with many shape variants stay automated (tooling burden shrinks)
- (+) [Safety] → collaborative soft end-effectors replace manual risky handling (injury exposure drops)
- (–) [Cost-effectiveness] → maintenance teams report material fatigue and replacement learning curves (new upkeep costs appear)
- (–) [Standards] → certification bodies add new test protocols for compliant manipulators (validation catches up)
- (–) [Market structure] → a few motion-library vendors dominate niche applications (software layer gains power)
- (–) [Labor] → some manual sorting roles disappear before re-skilling paths are ready (displacement becomes visible)

## ART 05.033 — Fully Autonomous Drones, Robots & Underwater Vehicles

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

For manufacturing, the value is strongest in hazardous plants, remote infrastructure, inspection of

dispersed assets, and autonomous handling where human access is hard or dangerous. This shifts more maintenance and monitoring toward remote control rooms and new vendor ecosystems. It also increases cyber and certification demands because autonomy reaches more physical tasks. The impact is material but narrower than general-purpose robotics, so **3**.

**Weak signals (6):**

- (+) [Maintenance and repair] → remote industrial sites use autonomous inspection fleets routinely (human site visits fall)
  - (+) [Reduced vulnerability] → plants keep autonomous response assets on standby for incidents (continuous presence becomes possible)
  - (+) [Safety] → confined-space and toxic-zone checks become machine-first procedures (hazard transfer happens)
  - (–) [Security] → penetration tests target autonomous service fleets at plants (new physical attack path)
  - (–) [Safety and compliance] → regulators define minimum supervision ratios for autonomous industrial tasks (autonomy gets bounded)
  - (–) [Market structure] → rugged autonomy systems remain dominated by specialized providers (capability stays concentrated)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.034 — Supportive Infrastructure for Autonomy

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Autonomy-supportive infrastructure changes factories themselves: robot-readable surfaces, docking points, shared traffic rules, machine zones, and digital service layers reduce the burden on each robot and make dense automation much more reliable. It shifts capex from single smart machines to autonomy-ready environments and creates new standards, retrofitting races, and interoperability politics. It also lets simpler cheaper robots scale, which can accelerate decentralized and high-mix production. Because it changes how production spaces are designed and governed, **10** is appropriate.

**Weak signals (9):**

- (+) [Mass production in large facilities] → greenfield plants are designed around robot lanes and docking nodes (environment becomes autonomy-native)
- (+) [Competitive adaptability] → brownfield retrofits add markers, charging, and machine-readable zones (retrofitting becomes strategic)
- (+) [Cost-effectiveness] → buyers choose cheaper robots because smart infrastructure carries more burden (system architecture flips)
- (+) [Safety and compliance] → shared traffic rules are baked into plant infrastructure rather than robot-by-robot logic (coordination becomes environmental)
- (+) [Customization] → reconfigurable work areas reserve autonomous access like utilities (flexibility becomes physical layer)
- (+) [Subcontractors] → equipment tenders require compliance with site autonomy interfaces (interoperability gets enforced)
- (–) [Market structure] → infrastructure vendors seek platform control over many robot brands (plant control centralizes)

- (–) [Risk aversion] → retrofit business cases split sharply between high- and low-utilization sites (deployment polarizes)
- (–) [Labor] → workers are re-trained around autonomy zones, exception handling, and access rights (workplace norms shift)

## ART 05.035 — Optical/Microwave Power Beaming for Persistent Robotics

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The manufacturing pathway is mainly niche: persistent aerial or fixed inspection systems and selected mobile robots where battery swaps are a major bottleneck. Even in a mature state, line-of-sight, zoning, and safety constraints keep it from becoming a broad manufacturing operating model. It is therefore concrete but limited. So **1** fits.

**Weak signals (4):**

- (+) [Maintenance and repair] → difficult-to-access sites test beam-powered inspection drones (battery servicing becomes target)
- (+) [Reduced vulnerability] → persistent monitoring pilots appear around hazardous plants (continuous watch becomes feasible)
- (–) [Safety and compliance] → exclusion-zone hardware becomes mandatory in industrial pilots (radiation governance dominates)
- (–) [Cost-effectiveness] → deployments stay confined to high-risk inspection use cases (economics remain narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 — Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The clear path is specialized climbing, fixturing, and delicate handling where suction or magnets are unsuitable. That can matter in some maintenance and electronics or finish-sensitive tasks, but it does not materially shift the general manufacturing model. It is worth tracking as a niche enabler. So **1** fits.

**Weak signals (4):**

- (+) [Maintenance and repair] → vertical surface inspection tools adopt dry-adhesion pads (access method broadens)
- (+) [Perceived quality] → delicate-finish handling tools replace suction on premium goods (surface damage falls)
- (–) [Cost-effectiveness] → adoption stays tied to contamination-sensitive tasks only (niche value visible)
- (–) [Quality control] → cleaning and wear protocols become necessary for adhesion pads (maintenance burden appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

## ART 06.037 — Multi-Material & Hybrid 3D Printing

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This directly supports the challenger regime by collapsing multi-step assembly into digitally driven fabrication of complex, customized, functionally integrated goods. It reduces tooling dependence, inventory, and lead times for complex low-volume products and spare parts. It also shifts value toward design files, feedstocks, and certification layers while intensifying IP and liability disputes, and can pull manufacturing closer to customers and service operations. Because it changes how many goods are made rather than merely improving one process, **10** is justified.

**Weak signals (9):**

- (+) [Customization] → customers begin buying configurable parts that are printed on order (tooling economics change)
- (+) [Maintenance and repair] → local service depots print certified replacement parts routinely (inventory gets displaced)
- (+) [Functionality] → product launches advertise embedded channels, seals, or electronics from single builds (assembly count drops)
- (+) [Reduced need for storage/logistics] → firms replace stocked spares with approved build-file libraries (digital inventory rises)
- (+) [Integration of design and manufacturing] → engineers release geometry and material maps directly to production (design-production boundary thins)
- (+) [Variety] → profitable lot sizes fall sharply for complex assemblies (high-mix production expands)
- (–) [Intellectual property] → lawsuits rise over leaked build files and unauthorized local production (digital copying bites)
- (–) [Safety and compliance] → insurers require batch-level process evidence for printed end-use parts (trust becomes data-driven)
- (–) [Market structure] → printer OEMs seek control over approved material ecosystems (feedstock lock-in strengthens)

## ART 06.038 — Digital Twin & Simulation-Driven Production

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Digital twins close the loop between design, process engineering, operations, maintenance, and ramp-up, which is central to the challenger regime. They reduce downtime, scrap, and changeover risk by making process interactions testable before physical disruption. They also make expertise portable and shift power toward firms that control the model layer, while enabling faster iteration and more fluid capacity allocation across distributed sites. Because they transform how manufacturing decisions are made and validated, **10** is appropriate.

**Weak signals (9):**

- (+) [Integration of design and manufacturing] → engineering changes are simulated before physical release by default (design-production loop tightens)
- (+) [Quality control] → deviations are investigated first in the twin environment (diagnosis becomes model-centric)

- (+) [Competitive adaptability] → new SKUs are ramped using virtual commissioning rather than long physical trials (ramp risk falls)
- (+) [Resource efficiency] → energy and scrap forecasts from twins enter daily production meetings (optimization becomes routine)
- (+) [Subcontractors] → suppliers exchange model states, not just drawings or spreadsheets (shared operational picture forms)
- (+) [Lack of skills] → less tacit local know-how is needed for line restarts and re-tuning (expertise becomes reusable)
- (–) [Safety and compliance] → incident investigations dispute whether the twin was sufficiently faithful (model liability appears)
- (–) [Market structure] → major vendors try to make their twin format the system of record (data gravity increases)
- (–) [Security] → cyber drills include corrupted twin states feeding bad operational advice (model integrity matters)

## ART 06.039 — Reconfigurable & Agile Factories

### Score: 20 (Impact in GVN 3)

#### Justification (3–5 sentences):

This is the clearest operating-model realization of the challenger regime: modular workcells, software-defined changeovers, shorter runs, and closer integration of design with manufacturing. It breaks the economics that force large stable batches and rigid lines, and rewrites capex, workforce roles, supplier relationships, and certification practices. It also enables local, small-batch, highly varied production while potentially concentrating power in module vendors and orchestration platforms. Because it is a keystone technology for the GVN's most important transformation, **20** is justified.

#### Weak signals (10):

- (+) [Mass production in large industrial facilities] → plant capex shifts from fixed lines to modular cells (dominant regime weakens)
- (+) [Customization] → profitable minimum order quantities keep falling across sectors (batch economics flip)
- (+) [Variety] → factories advertise same-day or next-day product-family switching (changeover becomes capability)
- (+) [Integration of design and manufacturing] → product teams release updated recipes without major physical rebuilds (design enters operations faster)
- (+) [Reduced need for storage/logistics] → more output is built against live orders instead of forecasts (inventory burden drops)
- (+) [Local employment] → smaller regional plants win work once reserved for large centralized sites (decentralization becomes investable)
- (+) [Subcontractors] → contract manufacturers market “module libraries” rather than dedicated lines (production becomes composable)
- (–) [Safety and compliance] → insurers demand evidence for every reconfiguration event (liability follows fluidity)
- (–) [Labor] → bargaining shifts from headcount per line to access, redeployment, and software control (shop-floor power reorders)
- (–) [Market structure] → orchestration and module standards become strategic chokepoints (ecosystem control matters)



## ART 06.040 — Circular & Sustainable Manufacturing

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Circular manufacturing shifts manufacturing from virgin-input linear flows toward monitored recirculation, requalification, and bio-based or recyclable feedstocks. It reduces exposure to raw-material volatility, disposal, and long supply chains. It also creates new power around sorting, certification, and product-passport data, and can relocate manufacturing near waste streams and service networks while introducing quality-drift and contamination risks. Because it can transform material sourcing and production logic rather than just improve efficiency, **10** fits.

**Weak signals (9):**

- (+) [Resource efficiency] → plants start treating scrap and returned goods as scheduled feedstock (waste becomes input)
- (+) [Reduced need for storage/logistics] → local recirculation hubs appear near manufacturing clusters (material loops shorten)
- (+) [Cost-effectiveness] → procurement begins specifying recovered-content ranges with real-time quality data (recycled inputs normalize)
- (+) [Ease of purchasing] → digital product passports become mandatory in B2B sourcing (material identity becomes tradable)
- (+) [Maintenance and repair] → designs are revised to improve disassembly and component recovery (repair logic enters design)
- (+) [Competitive adaptability] → firms market resilience against virgin-material shocks through circular feedstock contracts (resilience becomes sales point)
- (–) [Quality control] → auditors flag inconsistent output caused by variable recovered feedstocks (requalification becomes critical)
- (–) [Market structure] → sorting and traceability operators gain leverage over smaller producers (new intermediaries rise)
- (–) [Safety and compliance] → novel bio-based materials face lengthy approval queues (green shift meets regulation)

## ART 06.041 — Bio-fabrication technologies

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Bio-fabrication matters for specific manufacturing domains—medical products, biomaterials, specialized tissues, and biologically derived goods—but not for the whole manufacturing system. It creates new sterile production, QC, and logistics models, while also increasing regulatory burden and facility specialization. That gives it a material yet sector-specific effect. So **3** fits.

**Weak signals (6):**

- (+) [Variety and innovation] → tissue or bio-material production lines move from labs to contract manufacturing facilities (sector industrializes)
- (+) [Quality control] → automated sterility and viability analytics become batch-release gates (bioprocess control formalizes)
- (+) [Local manufacturing] → hospital-adjacent or regional fabrication sites emerge for urgent biological goods (distance matters less)

- (–) [Safety and compliance] → batch failures from contamination gain high public visibility (trust becomes fragile)
  - (–) [Cost-effectiveness] → consumables and sterile infrastructure dominate pilot budgets (economics stay constrained)
  - (–) [Market structure] → a few platform providers own validated cell or scaffold workflows (specialized control grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 — 4D Printed & Programmable Materials

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Programmable materials can reduce assembly, shipping volume, and maintenance by embedding change or self-adjustment into the material itself. The main effects are likely concentrated in selected products and components rather than all factories. They also complicate certification, recycling, and warranty logic. That is material but still narrower than the main manufacturing-system shift, so **3**.

#### Weak signals (6):

- (+) [Functionality] → products start advertising self-deploying or self-adjusting components (assembly complexity moves into material)
  - (+) [Reduced need for storage/logistics] → flat-packed programmable components replace bulkier shipped forms (transport burden falls)
  - (+) [Maintenance and repair] → components self-calibrate after installation in pilot settings (service visits may drop)
  - (–) [Perceived quality] → warranty claims begin hinging on whether transformations triggered correctly (behavior becomes quality issue)
  - (–) [Safety and compliance] → regulators require lifecycle-state testing, not just final-shape testing (certification broadens)
  - (–) [Circularity] → recyclers flag difficulties separating responsive multi-material structures (end-of-life gets harder)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 — Volumetric Additive Manufacturing

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

Layerless volumetric printing can greatly compress prototyping and small-batch production times, which matters for custom parts, tooling, short-run products, and local manufacture. It lowers the coordination burden of outsourced machining and tooling, but also shifts risk toward feedstock qualification and process validation. Faster physical iteration then accelerates design-manufacture integration. That is significant enough for **5**.

#### Weak signals (9):

- (+) [Customization] → customers accept rapid on-demand production for bespoke geometries (lead-time expectations change)

- (+) [Variety] → pilot plants produce many SKU variants without new tooling (variant cost drops)
- (+) [Maintenance and repair] → service centers print short-life fixtures or spares in minutes (response speed monetized)
- (+) [Integration of design and manufacturing] → CAD updates move into production almost immediately (digital-to-physical loop shrinks)
- (+) [Reduced need for storage/logistics] → firms replace stocked niche parts with print-on-demand queues (physical inventory falls)
- (–) [Quality control] → certification focuses heavily on resin chemistry and cure consistency (feedstock trust dominates)
- (–) [Intellectual property] → digital build files become central assets in aftermarket supply (copying risk rises)
- (–) [Market structure] → material vendors seek closed ecosystems for approved resins (lock-in strengthens)
- (–) [Safety and compliance] → environmental and health controls tighten around novel photochemistries (operating burden appears)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 — Metamaterials for Novel Optics & Connectivity

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Metamaterials matter to manufacturing mainly by enabling new product performance and better sensing/connectivity hardware in selected sectors. They can strengthen advanced domestic capability in optics, antennas, and specialized components, while creating precision-manufacturing and IP bottlenecks. That is a real but still sector-specific manufacturing effect. So **3** fits.

**Weak signals (6):**

- (+) [Functionality] → product roadmaps start including flat-optics or wave-shaping surfaces (new component class enters BOM)
  - (+) [Competitive adaptability] → factories retrofit radio-steering surfaces to improve dense wireless reliability (site performance gets tunable)
  - (+) [Perceived quality] → premium products advertise thinner, lighter wave-control components (design constraints ease)
  - (–) [Market structure] → only a few suppliers can meet precise fabrication tolerances (capability concentrates)
  - (–) [Cost-effectiveness] → adoption stays limited to high-margin goods at first (economics remain selective)
  - (–) [Safety and compliance] → new certification test methods appear for wave-shaping materials (validation work grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 07.045 — Room-Temperature Superconductors

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

If mature and manufacturable, room-temperature superconductors could materially alter factory power systems, motors, magnetic equipment, sensing, and selected product architectures. They would shift supply chains, capital priorities, and locational economics for energy-intensive manufacturing, while also creating new safety and reliability standards. Firms with access to the new conductor ecosystem could leap ahead. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Cost-effectiveness] → high-current industrial equipment tenders start naming superconducting options (energy loss becomes design variable)
- (+) [Functionality] → compact high-field magnets appear in mainstream industrial equipment catalogs (new performance envelope opens)
- (+) [Resource efficiency] → energy-intensive plants model power-loss reductions as major capex cases (factory power architecture shifts)
- (+) [Competitive adaptability] → regions market superconducting infrastructure to attract advanced industry (siting logic changes)
- (+) [Variety and innovation] → machine tool and process equipment vendors announce new product families around high-current density (equipment redesign begins)
- (–) [Market structure] → supply contracts for advanced superconducting materials become strategic bottlenecks (upstream concentration rises)
- (–) [Safety and compliance] → insurers demand quench/failure evidence and shielding protocols (new failure modes formalize)
- (–) [Risk aversion] → adoption begins in premium continuous-process sectors only (rollout remains staged)
- (–) [Maintenance and repair] → service teams require new competencies for conductor joints and monitoring (skills shift)

## ART 07.046 — Self-Healing & Smart Polymers

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

These materials can materially change both the manufactured products and the manufacturing system by reducing minor-failure downtime, extending tool and part life, and lowering inspection frequency. They shift warranty, maintenance, and replacement economics, while also creating recycling and certification complications. Longer-lasting components also change purchasing patterns and spare-part demand. That is clearly significant enough for **5**.

**Weak signals (9):**

- (+) [Perceived quality] → products start advertising crack-sealing or self-repair features (durability becomes active)
- (+) [Maintenance and repair] → tooling and seals stay in service longer before replacement (downtime pressure eases)
- (+) [Cost-effectiveness] → warranty models incorporate self-healing performance assumptions (lifecycle economics change)
- (+) [Resource efficiency] → plants cut preventive replacement intervals for polymer-intensive parts (material use falls)
- (+) [Variety] → adaptive polymer parts reduce need for multiple component variants (functional range broadens)

- (–) [Circularity] → recyclers report difficulty processing self-healing formulations (end-of-life friction grows)
- (–) [Safety and compliance] → regulators require proof that healed damage still meets specification (trust threshold rises)
- (–) [Market structure] → formula owners seek licensing control over downstream product categories (chemistry rents emerge)
- (–) [Risk aversion] → buyers limit early use to non-critical applications until long-cycle evidence matures (adoption stages itself)

## ART 07.047 — Nano-Catalysts & Advanced Coatings

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Nano-catalysts and advanced coatings have broad manufacturing relevance because they raise process efficiency, surface performance, corrosion resistance, cleanability, and reaction selectivity across many sectors. They change maintenance cycles, energy use, and product durability, while creating new dependence on scarce materials and specialized providers. Better surfaces and reactions can also make local smaller-scale production more viable. That is a strong **5**.

**Weak signals (9):**

- (+) [Resource efficiency] → plants report measurable energy savings from catalyst or coating retrofits (surface engineering pays back)
- (+) [Perceived quality] → anti-corrosion and anti-fouling coatings become standard in higher-volume goods (lifetime expectations rise)
- (+) [Maintenance and repair] → cleaning intervals are extended after advanced coating adoption (downtime shrinks)
- (+) [Functionality] → process lines switch outputs by swapping catalyst packs rather than major hardware (chemical flexibility rises)
- (+) [Safety] → surfaces are specified for easier decontamination in regulated plants (cleanability becomes strategic)
- (–) [Market structure] → critical coatings rely on a handful of proprietary formulations (upstream leverage grows)
- (–) [Safety and compliance] → worker-exposure and disposal rules tighten around nanoparticle handling (operating burden appears)
- (–) [Cost-effectiveness] → some retrofits are rejected due to scarce catalyst inputs (materials constrain rollout)
- (–) [Quality control] → auditors demand wear-state evidence to prove coated surfaces still perform (performance must be tracked)

## ART 07.048 — High-Entropy Alloys & Advanced Metals

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The value is strongest in harsh or high-performance manufacturing contexts where better heat, corrosion, fatigue, or creep resistance allows longer-lasting tools and products. HEAs can shift supply risk and certification burdens, but the impact is likely concentrated in certain sectors rather than general consumer manufacturing. That supports a material but narrower **3**.

**Weak signals (6):**

- (+) [Perceived quality] → premium equipment lines switch to advanced alloy grades for lifetime claims (durability premium forms)
  - (+) [Maintenance and repair] → plants extend replacement intervals on wear-critical components (harsh-condition life improves)
  - (+) [Functionality] → smaller or hotter-running hardware becomes feasible with new alloys (design envelope expands)
  - (–) [Cost-effectiveness] → only high-value applications justify alloy cost at first (spillover stays narrow)
  - (–) [Safety and compliance] → certification timelines lengthen for unfamiliar alloy recipes (qualification burden rises)
  - (–) [Supply chains] → sourcing concerns emerge around specific multi-element compositions (materials risk shifts)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 07.049 — Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation****Score: 3 (Impact in GVN 3)****Justification (3–5 sentences):**

This affects manufacturing mainly by helping emitting plants keep operating under tighter carbon constraints and by enabling lower-carbon process routes. It changes permitting, energy costs, and industrial siting, while also favoring larger firms that can manage integrated capture infrastructure. The manufacturing impact is meaningful but concentrated in selected sectors such as cement, chemicals, refining, and other high-process-emission industries. That supports **3**.

**Weak signals (6):**

- (+) [Cost-effectiveness] → carbon-intensive plants model capture media swaps as routine operating decisions (capture becomes operationalized)
  - (+) [Risk aversion] → expansion plans proceed only with integrated carbon-capture provisions (permit pathway changes)
  - (+) [Local employment] → existing industrial sites stay open under tighter carbon policy (transition slows closure)
  - (–) [Resource efficiency] → capture energy penalties become a key line-item in plant economics (trade-off becomes explicit)
  - (–) [Market structure] → carbon-service providers gain leverage over emitters' operating flexibility (intermediary power rises)
  - (–) [Safety and compliance] → sorbent degradation and handling standards appear in inspections (new process risk formalizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 07.050 — Graphene and Nanotube Composites for Lightweight Strength****Score: 3 (Impact in GVN 3)****Justification (3–5 sentences):**



These composites matter by enabling lighter, stronger, and sometimes self-sensing manufactured goods, along with more durable tooling or structural parts. They can alter inspection practice and product-performance competition, but dispersion, handling, and joining constraints likely keep the impact concentrated in selected high-value categories. The effect is therefore material, especially in transport, premium equipment, and advanced devices, but not system-wide for manufacturing of goods. That fits **3**.

#### **Weak signals (6):**

- (+) [Functionality] → product lines advertise lighter structures with embedded strain sensing (material becomes active)
  - (+) [Perceived quality] → fatigue-life guarantees extend for composite-intensive goods (lifetime becomes selling point)
  - (+) [Maintenance and repair] → condition monitoring starts using conductivity changes in composite parts (damage becomes visible)
  - (–) [Safety and compliance] → occupational handling rules tighten for nanoparticle-rich inputs (factory procedures change)
  - (–) [Cost-effectiveness] → buyers confine early use to weight-critical products (economics stay selective)
  - (–) [Quality control] → defects at joints and interfaces dominate failure analysis (manufacturing learning curve shows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.051 — Smart Thermal Materials for Energy-Efficient Heating & Cooling**

### **Score: 3 (Impact in GVN 3)**

#### **Justification (3–5 sentences):**

Smart thermal materials can materially improve energy efficiency, heat buffering, and thermal reliability in both factories and products. The effect is broadly useful but often incremental, with main consequences in retrofits, thermal precision, and maintenance rather than a wholesale shift in manufacturing organization. They can reduce peak loads, protect sensitive processes, and simplify some thermal-management designs. That makes **3** appropriate.

#### **Weak signals (6):**

- (+) [Resource efficiency] → thermal buffering materials are added to process lines to smooth peaks (energy profile stabilizes)
  - (+) [Functionality] → products use switchable thermal layers to improve performance (thermal control becomes feature)
  - (+) [Cost-effectiveness] → factories prioritize thermal retrofit materials in energy-saving budgets (materials compete with equipment)
  - (–) [Safety and compliance] → fire and toxicity testing becomes the gating issue for adoption (compliance dominates)
  - (–) [Circularity] → end-of-life separation requirements emerge for encapsulated thermal materials (recycling gets harder)
  - (–) [Perceived quality] → buyers demand proof against cycle-driven degradation (long-life trust required)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 — Rare-Earth-Free Magnets for Sustainable Motors

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

Magnets matter across motors, robotics, automation, tools, and many finished goods, so reducing rare-earth dependence can materially change manufacturing resilience and cost exposure. It redistributes bargaining power away from concentrated upstream supply chains and toward firms that redesign motors and actuators around new magnet behaviors. More stable motor supply also helps robotics and electrification spread faster across the manufacturing base. This is significant enough for 5.

#### Weak signals (9):

- (+) [Cost-effectiveness] → motor and actuator tenders begin accepting rare-earth-free options routinely (sourcing risk matters)
- (+) [Reduced vulnerability] → manufacturers hedge less against magnet supply shocks (input risk eases)
- (+) [Competitive adaptability] → robotics vendors redesign product lines around alternative magnetic profiles (system co-design starts)
- (+) [Local manufacturing] → domestic motor assembly becomes more attractive with less geopolitically concentrated input (reshoring case improves)
- (+) [Variety] → more product categories advertise low-critical-mineral content (materials become market attribute)
- (–) [Functionality] → engineering teams must re-balance torque density or size in some designs (performance trade-offs surface)
- (–) [Market structure] → control shifts toward firms owning optimized motor geometries and drive software (system-level power shifts)
- (–) [Quality control] → aging and demagnetization tests are added to qualification suites (new durability evidence needed)
- (–) [Risk aversion] → buyers keep rare-earth magnets in highest-performance tiers initially (substitution remains selective)

## ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The pathway into manufacturing is mainly through water-intensive plants in water-stressed geographies. That can be important locally, but it is not broad enough to shift the manufacturing GVN in a diversified 5.5M-person society. Its impact is mostly a resilience and utility-cost issue for specific sites. It remains a concrete but limited 1.

#### Weak signals (4):

- (+) [Reduced vulnerability] → water-stressed factories add advanced membrane units on-site (water resilience becomes production issue)
- (+) [Cost-effectiveness] → procurement compares membrane replacement economics against water curtailment risk (operating continuity monetized)
- (–) [Circularity] → concentrate handling remains the sticking point in industrial pilots (external constraint persists)

- (–) [Local employment] → adoption clusters only in drought-prone industrial zones (impact stays geographically narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 — Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

UWBG power devices can materially improve industrial drives, power supplies, heating systems, charging, and compact electrified equipment. They enable smaller, cooler, and more efficient machines and support electrification of processes that currently struggle with heat and voltage constraints. They also strengthen local automation and mobile robotics while shifting leverage to new component suppliers. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Cost-effectiveness] → industrial drive and converter tenders start naming UWBG modules (efficiency enters capex cases)
- (+) [Functionality] → compact high-temperature power electronics appear in factory equipment catalogs (design envelope expands)
- (+) [Resource efficiency] → cooling hardware shrinks in electrified production modules (balance-of-system burden falls)
- (+) [Competitive adaptability] → mobile robots and power tools gain longer duty cycles from more efficient drives (electrified autonomy improves)
- (+) [Reduced vulnerability] → plants pursue electrification of heat or motion where power losses used to block it (process redesign opens)
- (–) [Market structure] → a narrow supplier base for packaged modules becomes a strategic risk (component concentration rises)
- (–) [Safety and compliance] → thermal-cycling and high-voltage package tests are tightened (new failure modes matter)
- (–) [Cost-effectiveness] → adoption is delayed in low-margin equipment despite strong lifecycle savings (upfront cost visible)
- (–) [Maintenance and repair] → service teams require new diagnostics for high-frequency switching faults (repair practices change)

## ART 07.055 — Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Its manufacturing relevance depends on hydrogen becoming an important fuel, feedstock, or buffer in factories and logistics. That is plausible in some sectors, but still too conditional and uneven to move the broader manufacturing GVN strongly. The strongest effect is in niche mobility, backup, or process applications that need safer storage formats. It is therefore a **1**.

**Weak signals (4):**

- (+) [Reduced vulnerability] → plants exploring hydrogen backup or heat start specifying solid-storage options (handling safety matters)

- (+) [Cost-effectiveness] → mobile industrial hydrogen use cases compare material cartridges against tanks (storage format becomes strategic)
  - (–) [Functionality] → release-rate limits keep material storage out of high-demand applications (performance ceiling remains visible)
  - (–) [Safety and compliance] → storage modules face new cycling and contamination rules (institutional pathway still narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 — Fusion Energy Reactors

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

If mature and commercially deployable, fusion gives manufacturing a new source of firm low-carbon electricity and potentially process heat. It can change industrial siting, reduce exposure to fuel volatility, and strengthen energy-intensive domestic manufacturing, while also concentrating power in very capital-intensive infrastructure. It may accelerate electrification and reshape relative competitiveness across sectors. That is significant enough for **5**.

**Weak signals (6):**

- (+) [Cost-effectiveness] → energy-intensive manufacturers seek long-term offtake discussions with fusion developers (firm power gains strategic value)
  - (+) [Local employment] → industrial regions court fusion-linked manufacturing investment (energy geography starts shifting)
  - (+) [Reduced vulnerability] → plant continuity models treat firm low-carbon power as a competitive advantage (reliability premium grows)
  - (–) [Market structure] → access favors large industrial campuses before smaller firms (benefits arrive unevenly)
  - (–) [Risk aversion] → manufacturers wait for financing and uptime evidence before relying on fusion (adoption stays staged)
  - (–) [Safety and compliance] → industrial policy debates focus on licensing and waste handling interfaces (institutional friction remains)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 08.057 — Small Modular Fission Reactors (SMRs)

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

SMRs matter to manufacturing through reliable local electricity and heat for industrial clusters, especially where grid quality or fuel logistics are weak. They can support reshoring of energy-intensive processes and longer planning horizons, while also creating permitting, security, and social-license conflicts. They may strengthen certain regional manufacturing ecosystems over others. This is significant enough for **5**.

**Weak signals (6):**

- (+) [Reduced vulnerability] → industrial parks explore colocated SMR options for firm power and heat (energy reliability monetized)
  - (+) [Cost-effectiveness] → manufacturers compare SMR-backed PPAs with volatile grid supply (price stability matters)
  - (+) [Local employment] → site-selection exercises favor regions with credible nuclear expansion plans (industrial geography shifts)
  - (–) [Safety and compliance] → security and emergency-planning obligations dominate early industrial negotiations (non-energy burdens matter)
  - (–) [Risk aversion] → firms delay commitments until standardization lowers project uncertainty (scale depends on repetition)
  - (–) [Market structure] → large anchor users gain first access to reliable local nuclear output (benefits distribute unevenly)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.058 — Thin-film solar cells

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Thin-film solar matters by broadening where power generation can be embedded: factory roofs and walls, temporary structures, products, and remote industrial assets. It can reduce installer bottlenecks and support local resilience, but usually as an incremental energy layer rather than a manufacturing-system reorganization. It is therefore more a distributed utility enhancement than a core production shift. That makes **3** appropriate.

#### Weak signals (6):

- (+) [Cost-effectiveness] → factory retrofits choose laminated solar skins where rigid panels were impractical (surface economics improve)
  - (+) [Reduced vulnerability] → remote industrial assets gain self-powering skins for sensing or control (service burden drops)
  - (+) [Functionality] → more manufactured products include integrated thin-film generation (energy enters product design)
  - (–) [Perceived quality] → buyers scrutinize lifetime and weathering performance claims (durability trust needed)
  - (–) [Circularity] → recycling pathways lag behind deployment of new laminate chemistries (end-of-life burden rises)
  - (–) [Market structure] → OEMs bundle film supply with proprietary installation methods (ecosystem closes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.059 — Bionic Leaf Technology

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The manufacturing pathway is through distributed low-carbon molecules or intermediates, but that remains conditional on specific chemical demand, feedstock access, and site economics. It could matter in selected industrial chemical chains, yet it does not clearly alter the broader manufacturing GVN. The impact therefore stays narrow and conditional. That keeps it at **1**.

**Weak signals (4):**

- (+) [Resource efficiency] → industrial pilots use panelized artificial-photosynthesis outputs as local process feedstock (molecule production decentralizes)
  - (+) [Reduced vulnerability] → remote sites test local low-carbon chemical generation instead of delivered gas (supply risk becomes driver)
  - (–) [Cost-effectiveness] → deployments remain tied to niche high-value molecules (broad manufacturing link stays weak)
  - (–) [Safety and compliance] → product separation and containment dominate pilot reviews (operational burden stays high)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.060 — Grid-Scale Energy Storage****Score: 5 (Impact in GVN 3)****Justification (3–5 sentences):**

Manufacturing gains through fewer outages, more stable power prices, and easier electrification of processes that cannot tolerate interruptions or costly peaks. Storage changes bargaining between factories and utilities and helps distributed production sites rely more on local energy. It also accelerates electrification and local resilience, while adding fire, siting, and component-dependence risks. That is a clear 5.

**Weak signals (9):**

- (+) [Reduced vulnerability] → factories sign resilience contracts tied to storage-backed supply (blackout risk priced down)
- (+) [Cost-effectiveness] → peak-demand charges fall in site-level energy budgets after storage rollout (electrification economics improve)
- (+) [Local manufacturing] → smaller sites operate viably with storage-supported local energy profiles (central-grid dependence eases)
- (+) [Competitive adaptability] → more process changes are approved because power spikes can be buffered (energy constraint loosens)
- (+) [Resource efficiency] → plants shift energy-intensive tasks into stored low-cost periods (scheduling gets coupled to energy)
- (–) [Safety and compliance] → storage fire planning becomes part of industrial permitting (new site burdens emerge)
- (–) [Market structure] → large firms with storage gain better tariff positions than smaller competitors (advantage widens)
- (–) [Supply chains] → storage deployment bottlenecks move to specific battery or mechanical systems (dependency shifts)
- (–) [Risk aversion] → conservative sectors demand long-duration reliability evidence before relying on storage (trust builds slowly)

**ART 08.061 — Solid-State Batteries****Score: 5 (Impact in GVN 3)****Justification (3–5 sentences):**

Solid-state batteries affect manufacturing both as a product category and as an enabling component



for safer mobile robots, tools, backup systems, and many goods. They can reduce insurance and cooling burdens while reshaping supply chains and recycling. Better battery safety and density also accelerate autonomous handling and electrified products. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Safety and compliance] → warehouses and plants relax some battery-separation constraints for certified solid-state packs (fire burden falls)
- (+) [Cost-effectiveness] → AMRs and tools advertise longer duty cycles with lower thermal management (mobile equipment economics improve)
- (+) [Functionality] → more products are redesigned around slimmer or safer battery packaging (form factors shift)
- (+) [Reduced vulnerability] → site backup storage moves closer to production loads (placement options widen)
- (+) [Competitive adaptability] → electrification projects are approved in harsher environments (battery constraint weakens)
- (–) [Market structure] → early supply concentrates around a few validated cell makers (upstream leverage rises)
- (–) [Circularity] → recycling and pack-disassembly standards lag new chemistries (end-of-life systems scramble)
- (–) [Cost-effectiveness] → low-margin users delay changeover despite safety benefits (upfront premium visible)
- (–) [Maintenance and repair] → service manuals and diagnostics change materially for new failure modes (support practices shift)

## ART 08.062 — Green Hydrogen & Power-to-X

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This is important where manufacturing needs high-temperature heat, reducing agents, or storable low-carbon molecules rather than only electricity. It can create new industrial clusters around power-to-X infrastructure and reduce exposure to fossil price shocks, while also increasing dependence on water, electrolyzer, and safety systems. It may change which manufacturing sectors remain domestically competitive. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Reduced vulnerability] → manufacturers seek local hydrogen or e-fuel offtake rather than imported fossil feedstock (molecule security matters)
- (+) [Cost-effectiveness] → industrial process redesign studies explicitly compare electrification against hydrogen routes (transition pathways harden)
- (+) [Local employment] → regions market integrated power-to-X and manufacturing clusters (industrial geography re-forms)
- (+) [Resource efficiency] → oxygen, heat, or by-products from electrolysis get built into plant economics (integration deepens)
- (+) [Competitive adaptability] → exporters emphasize certified low-carbon molecule use in product marketing (market access shifts)
- (–) [Safety and compliance] → hydrogen handling rules expand into ordinary factory inspections (new hazard regime appears)

- (–) [Market structure] → large firms secure best low-cost clean power and molecule contracts first (benefits distribute unevenly)
- (–) [Water] → siting debates focus on industrial water demand from electrolysis (resource trade-offs sharpen)
- (–) [Risk aversion] → smaller manufacturers wait for carrier and storage standards before adoption (infrastructure sequencing matters)

## ART 08.063 — High-Efficiency Wind Turbines

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Higher-efficiency wind mainly changes manufacturing through electricity cost, supply reliability, and domestic equipment demand rather than factory organization itself. It can support greener industrial clusters and more local energy resilience, but the effects are diffuse and strongly mediated by grid policy and siting. It is meaningful, but mostly through the energy system rather than the production model. That supports 3.

#### Weak signals (6):

- (+) [Cost-effectiveness] → industrial power contracts increasingly tie pricing to nearby wind build-out (energy sourcing shifts)
  - (+) [Local employment] → blade, tower, or maintenance supply chains cluster near manufacturing regions (industrial adjacency grows)
  - (+) [Reduced vulnerability] → more factories pair flexible loads with wind-heavy supply (energy planning adapts)
  - (–) [Market structure] → only firms with strong grid access capture the cheapest wind-linked power (benefits stay uneven)
  - (–) [Supply chains] → material bottlenecks in turbines feed back into industrial power planning (energy transition gets manufacturing-dependent)
  - (–) [Risk aversion] → intermittency still keeps some processes on firm alternatives (impact remains partial)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 — Wireless & Space-Based Power Transfer

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The manufacturing link is mostly niche: powering remote assets, temporary operations, or selected moving equipment where cabling and fuel are awkward. Even in a mature state, safety, efficiency, and regulatory constraints make it unlikely to reconfigure mainstream manufacturing. Its relevance remains bounded to specific access problems. It remains a 1.

#### Weak signals (4):

- (+) [Reduced vulnerability] → remote industrial sites test beam-powered sensors or temporary equipment (access constraint targeted)
- (+) [Maintenance and repair] → temporary installations avoid cable runs in hazardous zones (setup friction drops)

- (–) [Safety and compliance] → exclusion zones dominate operational planning for pilots (beam governance limits scale)
  - (–) [Cost-effectiveness] → fixed wiring remains cheaper for most routine plant uses (mainstream pathway stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 — Advanced geothermal technology

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Advanced geothermal can provide firm local heat and power, which matters for industrial clusters and some energy-intensive manufacturing processes. It can shift siting and reduce exposure to grid and fuel volatility, but the effect depends strongly on geology, drilling economics, and permitting. It is therefore a meaningful but selective source of manufacturing advantage. That makes **3** appropriate.

#### Weak signals (6):

- (+) [Local manufacturing] → site-selection studies start scoring deep geothermal potential alongside logistics (energy geography matters)
  - (+) [Reduced vulnerability] → industrial parks explore shared geothermal heat fields (firm local heat gains value)
  - (+) [Cost-effectiveness] → process industries compare geothermal heat against gas volatility in capex decisions (thermal resilience priced)
  - (–) [Risk aversion] → drilling uncertainty remains the main obstacle in industrial adoption cases (upfront risk dominates)
  - (–) [Safety and compliance] → subsurface permitting and induced-seismicity reviews slow projects (institutional friction rises)
  - (–) [Market structure] → benefits cluster in regions with capital and subsurface know-how (geography stays selective)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 — Resilient microgrids

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

Microgrids directly support local and distributed manufacturing by reducing outage risk and making plant-level energy quality more controllable. They alter the relationship between factories, utilities, and local energy assets and can make smaller sites more viable. They also support reconfiguration, electrification, and regional resilience while increasing cyber and governance complexity. That is clearly significant enough for **5**.

#### Weak signals (9):

- (+) [Reduced vulnerability] → factories invest in islandable power rather than only backup generators (resilience logic matures)
- (+) [Local manufacturing] → smaller sites remain viable because they can guarantee power quality locally (central-grid dependence falls)

- (+) [Cost-effectiveness] → outage-cost analyses become standard in microgrid business cases (reliability gets monetized)
- (+) [Competitive adaptability] → process lines can be reconfigured without waiting for upstream grid upgrades (capacity becomes local)
- (+) [Resource efficiency] → site controllers optimize between local generation, storage, and process demand (energy becomes operational variable)
- (–) [Security] → plant cyber exercises include attacks on microgrid controllers (control plane becomes critical)
- (–) [Market structure] → factories with microgrids gain resilience advantages smaller competitors cannot finance (inequality risk rises)
- (–) [Utility relations] → interconnection disputes increase around industrial self-supply (institutional friction grows)
- (–) [Safety and compliance] → islanding and reconnection protocols become audit targets (governance thickens)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The main manufacturing pathway is through engineered organisms, bio-based materials, more programmable feedstocks, and selected high-value biological products. It can change ownership and control of industrial strains, ingredients, and biological IP while increasing regulation and containment demands. The effect is real in industrial biotech and some materials sectors, but it does not reshape the entire manufacturing landscape. That gives it a clear but still sector-specific effect, so 3.

**Weak signals (6):**

- (+) [Variety and innovation] → industrial strain engineering becomes a routine part of materials and chemical development (biology enters process design)
  - (+) [Resource efficiency] → firms pilot edited organisms to improve yield or reduce toxic inputs (low-temperature routes gain traction)
  - (+) [Subcontractors] → contract biomanufacturers advertise in-house advanced editing capability (upstream specialization rises)
  - (–) [Safety and compliance] → export, containment, and traceability clauses harden around edited production strains (governance thickens)
  - (–) [Intellectual property] → disputes intensify over ownership of edited industrial organisms (biological IP centralizes)
  - (–) [Risk aversion] → use stays concentrated in tightly regulated high-value sectors first (broad linkage remains partial)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 09.068 — mRNA Therapies & Vaccines

**Score: 3 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This ART mainly changes biopharmaceutical manufacturing by making product redesign more software-like and production platforms more reusable. That is material in a major subsector, but it does not broadly alter general manufacturing of goods beyond biomanufacturing spillovers. The strongest effects are in platform flexibility, batch switching, and validation systems. The likely effect is therefore a subsectoral **3**.

#### **Weak signals (6):**

- (+) [Competitive adaptability] → biopharma plants switch products by sequence update rather than full process redesign (platform logic strengthens)
  - (+) [Variety] → smaller-batch and more personalized biological products move through shared facilities (high-mix biomanufacturing rises)
  - (+) [Cost-effectiveness] → standardized production equipment is reused across more products (capital flexibility improves)
  - (–) [Safety and compliance] → release analytics and cold-chain validation dominate scale-up efforts (quality burden remains heavy)
  - (–) [Market structure] → a few delivery-system suppliers control much of the value chain (component dependency grows)
  - (–) [Local manufacturing] → geography still depends on specialized QA and regulatory infrastructure (decentralization stays limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 09.069 — Cellular Agriculture & Cultured Meat**

### **Score: 3 (Impact in GVN 3)**

#### **Justification (3–5 sentences):**

This creates a new factory-style route for some food and protein goods, shifting part of biological production from farms to monitored industrial systems. It changes input supply, siting, labor, and branding around manufactured biology, but the effect is still mostly concentrated in a specific product family. It is therefore more a major food-manufacturing niche than a broad manufacturing-system shift. That fits **3**.

#### **Weak signals (6):**

- (+) [Variety and innovation] → food manufacturing campuses add bioreactor-based protein lines (factory biology scales)
  - (+) [Reduced vulnerability] → protein supply plans rely less on livestock volatility (biological shocks are buffered)
  - (+) [Quality control] → composition and sterility data become core product-marketing claims (process transparency becomes product value)
  - (–) [Cost-effectiveness] → energy and media inputs dominate operating economics (factory dependence stays high)
  - (–) [Market structure] → a few validated media and reactor suppliers gain leverage (upstream concentration rises)
  - (–) [Consumer habits] → brand resistance slows mainstream substitution despite technical success (adoption remains contested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 — Organoids & Tissue Engineering

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The strongest manufacturing pathway is as a niche product category and as a testing tool for selected bio-related goods. That matters to specific sectors, but it does not materially change the broad manufacturing GVN. It remains mainly a specialized biotech and biomedical manufacturing domain. It therefore stays at **1**.

#### Weak signals (4):

- (+) [Variety and innovation] → industrial biolabs start ordering organoid-based testing routinely (specialized R&D method spreads)
  - (+) [Quality control] → tissue constructs become standardized manufactured outputs in niche supply chains (product class stabilizes)
  - (–) [Cost-effectiveness] → sterility and handling keep adoption confined to premium uses (economics stay narrow)
  - (–) [Safety and compliance] → ethical and handling reviews remain heavy even for routine production (institutional drag persists)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 — Synthetic Biology & Designer Microbes

### Score: 5 (Impact in GVN 3)

#### Justification (3–5 sentences):

Designer microbes can shift manufacturing by turning more chemicals, materials, coatings, enzymes, and feedstocks into programmable low-temperature biological processes. They alter supply chains, capital intensity, and IP around strains and fermentation platforms. They can also support distributed local production using waste or simple feedstocks while raising containment and governance concerns. That is significant enough for **5**.

#### Weak signals (9):

- (+) [Resource efficiency] → industrial materials or chemicals move from petrochemical to fermentation routes (process base changes)
- (+) [Reduced need for storage/logistics] → local feedstocks or waste streams are used for biomanufacturing inputs (supply chains shorten)
- (+) [Variety] → firms launch more customized formulations from programmable microbial platforms (recipe flexibility rises)
- (+) [Cost-effectiveness] → small or mid-scale plants become viable where large thermal processes were not (scale threshold falls)
- (+) [Competitive adaptability] → factories switch outputs by changing strains and media rather than heavy hardware (reconfiguration changes type)
- (–) [Safety and compliance] → containment, traceability, and kill-switch evidence become procurement requirements (biosafety formalizes)
- (–) [Intellectual property] → strain licensing becomes a major margin pool (biological IP rents emerge)
- (–) [Market structure] → platform owners with validated chassis dominate downstream producers (ecosystem centralizes)



- (–) [Risk aversion] → buyer acceptance lags where “bio-derived” raises consistency worries (quality trust must be earned)

## ART 09.072 — Microbiome Engineering

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The manufacturing connection is mostly through selected bioprocess optimization, fouling control, water treatment, or contamination management. Those can matter locally, but they do not broadly reorganize manufacturing of goods. The strongest relevance is in utility systems and specialized biological production rather than the core GVN. So this remains a 1.

#### Weak signals (4):

- (+) [Maintenance and repair] → plants use targeted microbiome interventions to stabilize bioreactors or water systems (process biology becomes controllable)
- (+) [Resource efficiency] → wastewater or odor treatment contracts begin specifying designed microbial communities (utility-layer use grows)
- (–) [Safety and compliance] → containment and unintended-spread concerns slow industrial deployment (oversight remains strong)
- (–) [Cost-effectiveness] → benefits stay confined to specialized biological processes (broad linkage stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 — Precision Medicine & Genomic Diagnostics

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

This mostly changes healthcare delivery and diagnostics, not the wider manufacturing system. Some impact exists through specialized diagnostics manufacturing and product demand patterns, but the pathway to broad manufacturing transformation is weak. It therefore remains peripheral to this GVN rather than central to it. That makes 1 appropriate.

#### Weak signals (4):

- (+) [Variety and innovation] → diagnostics manufacturing expands around personalized panels (niche product demand grows)
- (+) [Competitive adaptability] → biotech plants retool for smaller high-mix diagnostic batches (specialized flexibility rises)
- (–) [Market structure] → advanced genomic platforms remain concentrated among a few suppliers (spillover stays narrow)
- (–) [Cost-effectiveness] → broader manufacturing sectors see little direct reason to adopt (linkage remains peripheral)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

The main manufacturing relevance is faster testing for some pharmaceutical, chemical, or biological products and niche hybrid devices. That is concrete, but it does not move the wider manufacturing operating model enough to cross the material threshold. Its strongest role is as a specialized experimental and validation platform. So 1 is appropriate.

#### Weak signals (4):

- (+) [Quality control] → high-value product developers use organ-on-chip testing earlier in scale-up (testing loop shortens)
- (+) [Variety and innovation] → contract R&D services package chips as standardized experimental platforms (specialized ecosystem grows)
- (–) [Cost-effectiveness] → use remains confined to premium regulated sectors (broad manufacturing link stays weak)
- (–) [Safety and compliance] → chip-to-chip consistency becomes the main validation issue (testing trust bottleneck appears)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 — Biological Aging & Longevity Barriers

### Score: 1 (Impact in GVN 3)

#### Justification (3–5 sentences):

Longer healthy working lives could ease skill shortages and reduce fatigue-related variability, especially in highly skilled maintenance or process roles. But that is still an indirect labor-market effect rather than a manufacturing operating-model shift. The impact would mostly appear through workforce composition and retention rather than plant design or production logic. It is therefore worth watching but remains a 1.

#### Weak signals (4):

- (+) [Lack of skills] → older specialist workers stay in critical roles longer with better functional capacity (experience retention improves)
- (+) [Safety] → firms model reduced fatigue and recovery time in workforce planning (human reliability gets revalued)
- (–) [Equality] → only top-paid technical staff access longevity interventions (benefits stay uneven)
- (–) [Labor] → workforce planning assumes slower retirement but not new production models (operating logic stays unchanged)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 — Engineered Living Materials

### Score: 3 (Impact in GVN 3)

#### Justification (3–5 sentences):

Engineered living materials can affect manufacturing by creating self-repairing or carbon-storing components and by shifting some material formation into low-temperature biological processes. They alter maintenance, inspection, and warranty logic, while also creating certification and lifecycle-governance challenges. The strongest effects are likely in construction materials, coatings, and specialized long-life goods rather than across all manufacturing. That gives them a material but still selected impact, so **3**.

#### Weak signals (6):

- (+) [Perceived quality] → building materials or coatings begin advertising self-sealing behavior (maintenance logic changes)
  - (+) [Resource efficiency] → low-temperature bio-based material formation displaces some energy-intensive steps (embodied energy falls)
  - (+) [Maintenance and repair] → inspection intervals lengthen when living materials self-report condition (care burden may drop)
  - (–) [Safety and compliance] → regulators ask how living components stay contained or inactive when needed (governance broadens)
  - (–) [Cost-effectiveness] → materials stay limited to premium applications until shelf-life improves (economics remain selective)
  - (–) [Circularity] → end-of-life handling rules emerge for living composites (waste streams get more complex)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 — Gene Drive Pest Control

### Score: 0 (Impact in GVN 3)

#### Justification (3–5 sentences):

Any manufacturing effect is too indirect, mainly through biomass supply, site management, or certain agricultural inputs. That is not enough to materially shift the manufacturing GVN itself, even if the technology matures. The linkage remains mediated by agriculture and land-use systems rather than factory production. Score **0**.

#### Weak signals (4):

- (+) [Resource efficiency] → manufacturers relying on biomass feedstocks begin tracking gene-drive exposure in supply contracts (linkage would need feedstock dependence)
- (+) [Reduced vulnerability] → industrial sites in pest-heavy zones explore gene-drive stewardship consortia (site-protection pathway would need scaling)
- (–) [Safety and compliance] → ecological governance dominates all deployment conversations (manufacturing remains peripheral)

- (–) [Cost-effectiveness] → no mainstream industrial procurement category is created around gene-drive outcomes (economic linkage absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 — Artificial Wombs & Synthetic Embryos

**Score: 0 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This does not have a clear, scalable pathway into the manufacturing of goods beyond very indirect spillovers in equipment or animal breeding. Those pathways are too distant and contingent to count as meaningful GVN impact. The center of gravity is in reproductive, biomedical, and ethical domains rather than mainstream manufacturing. Score 0.

**Weak signals (4):**

- (+) [Variety and innovation] → livestock or animal-input supply chains start depending on ex vivo gestation systems (linkage would have to pass through industrial breeding)
- (+) [Subcontractors] → equipment vendors market artificial-gestation platforms as industrial production assets (pathway would need industrialization)
- (–) [Safety and compliance] → ethical governance remains overwhelmingly dominant over production logic (manufacturing linkage stays weak)
- (–) [Cost-effectiveness] → no broad goods category depends on the technology for scalable production (economic path absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 — Satellite Mega-Constellations & Space Internet

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This ART combines connectivity, positioning, and Earth observation, which can materially improve remote supplier integration, asset tracking, continuity, raw-material visibility, and situational awareness for distributed manufacturing networks. It weakens the penalty of distance and can support smaller or more remote production sites, while also creating dependence on a few orbital network operators. Better sensing and communications then compound with traceability and planning systems. That is significant enough for 5.

**Weak signals (9):**

- (+) [Reduced vulnerability] → factories add satellite-backed continuity links to business-continuity plans (orbital resilience becomes standard)
- (+) [Subcontractors] → remote suppliers remain eligible once always-on space connectivity is accepted (distance penalty falls)
- (+) [Reduced need for storage/logistics] → shipment and site tracking use continuous satellite layers (supply visibility deepens)

- (+) [Competitive adaptability] → raw-material and disruption monitoring from Earth observation feeds into factory planning (external sensing joins operations)
- (+) [Local manufacturing] → facilities in less connected regions become investable with reliable space internet (geography opens up)
- (–) [Market structure] → manufacturers become dependent on a handful of mega-constellation providers (network power centralizes)
- (–) [Security] → continuity exercises include orbital service outages or spoofing (space dependence becomes risk)
- (–) [Cost-effectiveness] → only plants with remote assets or weak terrestrial links justify full adoption at first (benefits stay uneven)
- (–) [Compliance] → cross-border data and sensing rules complicate multi-country production networks (governance follows capability)

## ART 10.080 — Space Resource Utilization (SRU)

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The link to manufacturing would be through niche new sources of critical materials, but that remains highly indirect and uncertain in how it would affect broad production systems. Even with technical maturity, it is more a possible future raw-material supplement than a manufacturing operating-model change. The strongest pathway is strategic material supply diversification, not day-to-day production transformation. So **1** is sufficient.

**Weak signals (4):**

- (+) [Reduced vulnerability] → industrial buyers start tracking asteroid-derived metal provenance in procurement discussions (supply diversification becomes imaginable)
  - (+) [Cost-effectiveness] → commodity hedging models explicitly include off-Earth material scenarios (materials sourcing broadens conceptually)
  - (–) [Risk aversion] → manufacturers do not redesign products around SRU-dependent inputs (linkage stays too speculative)
  - (–) [Safety and compliance] → reentry and chain-of-custody concerns dominate all commercialization debates (industrial usage remains distant)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 — Closed-Loop Life Support System

**Score: 0 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This has only indirect spillovers into circularity, utilities management, and environmental control. Those spillovers are already better captured by circular manufacturing, sensors, and automation ARTs, so this ART itself does not have a strong standalone pathway into the manufacturing GVN. Its main relevance stays in habitats and extreme environments rather than ordinary goods production. Score **0**.

**Weak signals (4):**

- (+) [Resource efficiency] → Earth factories begin importing life-support-style closed-loop utility modules (spillover would create linkage)
  - (+) [Reduced vulnerability] → extreme-environment industrial sites adopt habitat-style air/water recycling units (analog use would matter)
  - (–) [Cost-effectiveness] → manufacturers keep treating life-support systems as space-specific solutions (spillover remains weak)
  - (–) [Standards] → no industrial certification pathway emerges that maps space life-support evidence to Earth plants (translation absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 10.082 — High-Altitude Platforms & Balloons****Score: 1 (Impact in GVN 3)****Justification (3–5 sentences):**

The main path is temporary or regional connectivity and sensing for remote plants, disrupted areas, or field-heavy manufacturing operations. That is concrete but still too niche to move general manufacturing strongly. Most of the value is in contingency coverage and special-location coordination rather than core production change. So **1** fits.

**Weak signals (4):**

- (+) [Reduced vulnerability] → manufacturers contract temporary aerial connectivity after disasters (continuity niche appears)
  - (+) [Subcontractors] → remote supplier regions use HAP links for continuous production data exchange (distance support grows)
  - (–) [Cost-effectiveness] → routine factory operations still prefer terrestrial or satellite links (mainstream role remains narrow)
  - (–) [Safety and compliance] → airspace permissions dominate deployment timetables (governance limits scale)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**11. Digital Platforms & Collective-Intelligence Systems****ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)****Score: 3 (Impact in GVN 3)****Justification (3–5 sentences):**

The strongest manufacturing pathways are provenance, automated inter-firm rules, file licensing, parts authenticity, and selective data sharing across low-trust ecosystems. They can lower reconciliation and verification costs but also add governance complexity and concentrate power in protocol operators, auditors, or wallet layers. The impact is material in selected chains, especially where provenance and rights matter, but not broad enough to define the whole GVN. So **3** fits.



**Weak signals (6):**

- (+) [Intellectual property] → design-file licensing starts using machine-verifiable usage rights (digital manufacturing meets programmable rights)
  - (+) [Quality control] → provenance proofs are attached to premium components or materials (authenticity becomes saleable)
  - (+) [Subcontractors] → automated payment or compliance triggers appear in multi-party manufacturing pilots (rule execution gets embedded)
  - (–) [Cost-effectiveness] → pilots stall when integration and governance costs outweigh reconciliation savings (overhead becomes visible)
  - (–) [Market structure] → a few protocol or node operators become de facto gatekeepers (decentralization recentralizes)
  - (–) [Risk aversion] → buyers keep parallel legal and spreadsheet processes despite digital proofs (trust remains incomplete)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 11.084 — Platform Cooperatives & Fair Work****Score: 1 (Impact in GVN 3)****Justification (3–5 sentences):**

This can matter in local maker networks, distributed repair, and manufacturing-adjacent labor platforms, especially where ownership and bargaining power are central. But the manufacturing-system effect is mostly institutional and limited to selected organizational models rather than broad production capability. It may shape who captures value in some local networks, but not how most goods are made. It remains a **1**.

**Weak signals (4):**

- (+) [Local employment] → maker or repair networks adopt cooperative digital marketplaces (ownership model diversifies)
  - (+) [Ease of purchasing] → buyers source custom local production through member-owned platforms (small-scale coordination improves)
  - (–) [Cost-effectiveness] → capital constraints keep cooperative platforms out of larger industrial segments (scale remains limited)
  - (–) [Market structure] → incumbent platforms still dominate most manufacturing-adjacent work (alternative stays marginal)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 11.085 — Open Data Sharing Marketplaces****Score: 3 (Impact in GVN 3)****Justification (3–5 sentences):**

Data marketplaces can improve manufacturing by making process, quality, demand, and material data more tradable and comparable across organizational boundaries. They can help smaller actors

access information but may also privilege firms rich in high-value data and shift power toward marketplace operators. The impact is material, especially in fragmented chains, but still more enabling than transformative. So **3** is appropriate.

**Weak signals (6):**

- (+) [Subcontractors] → suppliers begin selling benchmarked process or quality data products (data becomes a manufacturing asset)
  - (+) [Competitive adaptability] → buyers source external demand or material datasets through standardized APIs (decision inputs broaden)
  - (+) [Risk aversion] → marketplace contracts add compute-to-data options for sensitive industrial records (sharing barrier falls)
  - (–) [Market structure] → data-rich firms capture pricing power over data-poor suppliers (informational inequality grows)
  - (–) [Quality control] → disputes arise over provenance and freshness of traded industrial datasets (trust bottleneck appears)
  - (–) [Compliance] → cross-border rules slow data commercialization in manufacturing chains (governance remains uneven)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 — Secure & Resilient Social Platforms

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The main pathway is more reliable coordination across plants, suppliers, workers, and emergency situations, but this remains peripheral to the core manufacturing operating model. It may matter in disruptions or politically sensitive settings, yet broad manufacturing value stays limited. It is therefore more of a coordination-support layer than a production driver. So **1** fits.

**Weak signals (4):**

- (+) [Reduced vulnerability] → industrial networks adopt resilient messaging platforms for disruption response (coordination continuity improves)
  - (+) [Subcontractors] → multi-firm manufacturing groups move critical coordination off fragile mainstream channels (operational trust rises)
  - (–) [Cost-effectiveness] → most routine production coordination remains inside existing enterprise tools (incremental role only)
  - (–) [Governance] → content moderation and identity disputes slow inter-firm adoption (social layer stays contested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.087 — Collective Open Innovation Networks

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

These networks align strongly with the challenger regime's tighter design-manufacturing loop by making it easier to pull in external expertise, test ideas in parallel, and preserve reusable knowledge. They can reduce barriers for smaller firms while also shifting IP governance and exposing firms to new coordination and appropriation risks. Faster externalized problem-solving also accelerates product and process variation. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Variety and innovation] → manufacturers run open challenge campaigns for process and product problems (search scope widens)
- (+) [Subcontractors] → external teams contribute validated fixes or recipes into shared environments (innovation gets networked)
- (+) [Integration of design and manufacturing] → test results and failed pathways are preserved in reusable searchable form (learning compounds)
- (+) [Lack of skills] → SMEs access expertise they could not hire directly (capability diffusion improves)
- (+) [Competitive adaptability] → time from problem statement to trial-ready solution shortens materially (innovation cycle compresses)
- (–) [Intellectual property] → disputes rise over ownership of jointly developed outputs (boundary friction grows)
- (–) [Market structure] → network orchestrators gain leverage over who sees what problems and data (platform power rises)
- (–) [Risk aversion] → sensitive manufacturing problems remain closed due to leakage fears (adoption polarizes)
- (–) [Quality control] → firms demand stronger validation rules for externally sourced solutions (trust needs infrastructure)

## ART 11.088 — Scalable Decentralized Governance

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This can help manufacturing consortia, shared infrastructure, or cooperative networks manage rules and pooled resources, but it is not a major direct driver of manufacturing capability. The effect is mostly organizational and conditional on unusual governance structures. It may matter for some networks, but it does not materially alter how most goods are designed or produced. That leaves it at **1**.

**Weak signals (4):**

- (+) [Subcontractors] → shared industrial consortia adopt software-mediated voting for common assets (governance becomes programmable)
- (+) [Local employment] → cooperative manufacturing networks use formal digital governance for resource allocation (coordination cost falls)
- (–) [Risk aversion] → high-value factories keep governance in conventional legal entities (operational shift stays limited)

- (–) [Security] → governance exploits or identity manipulation become the main fear in pilots (trust barrier remains high)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 — Digital Learning Networks and Skill Credentialing

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The GVN explicitly names lack of skills as an inhibitor, so scalable learning and portable credentialing directly target a core constraint. They speed retraining for robotics, additive manufacturing, digital twins, QA, and maintenance, while changing hiring, labor mobility, and bargaining around who is qualified. They also accelerate the spread of advanced manufacturing methods across regions and firm sizes. That is significant enough for **5**.

**Weak signals (9):**

- (+) [Lack of skills] → employers accept modular digital credentials for technician and operator roles (training bottleneck loosens)
- (+) [Competitive adaptability] → retraining cycles for new equipment shrink from months to weeks (technology adoption speeds up)
- (+) [Local employment] → smaller regions build advanced-manufacturing talent pipelines without local institutions scaling first (geographic capability broadens)
- (+) [Ease of purchasing] → machine vendors bundle certified learning paths with equipment sales (skills become part of product)
- (+) [Maintenance and repair] → portable credentials let scarce specialists work across many sites faster (labor mobility rises)
- (–) [Market structure] → credential platforms become gatekeepers for hiring and advancement (platform power rises)
- (–) [Labor] → employers use micro-credentials to weaken bargaining tied to long apprenticeships (credential politics intensify)
- (–) [Quality control] → firms discover that badge inflation does not equal shop-floor competence (trust in credentials gets tested)
- (–) [Equality] → workers without digital access or language fit lag behind in credential accumulation (capability gaps can widen)

## ART 11.090 — Prediction-Market Forecasting Platforms

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

These platforms can improve certain demand, disruption, or policy forecasts, but the manufacturing pathway is indirect and mainly decision-supportive. They do not by themselves alter how goods are produced. Their strongest effect is on shared uncertainty management, not on the operating model of manufacturing. That makes them worth watching at **1**, not more.

**Weak signals (4):**

- (+) [Competitive adaptability] → firms run internal markets on demand or disruption scenarios (forecasting becomes structured)
- (+) [Reduced vulnerability] → procurement teams use prediction markets around supply shocks or policy changes (risk sensing broadens)
- (–) [Risk aversion] → high-stakes capex decisions still rely on conventional committees and consultants (adoption stays advisory)
- (–) [Governance] → disputes over market settlement rules limit enterprise trust (institutional fit remains weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Interoperability standards attack one of the most stubborn blockers to digitally integrated manufacturing: fragmented devices, proprietary interfaces, and painful system integration. They reduce configuration cost, accelerate sensing and automation rollout, and make brownfield integration far easier. They also redistribute power away from some lock-in strategies while creating fights over certification, profiles, and security baselines. Because they change how connected manufacturing can spread, **10** is warranted.

**Weak signals (9):**

- (+) [Integration of design and manufacturing] → machine and sensor tenders start requiring open interoperability profiles (integration becomes procurement issue)
- (+) [Cost-effectiveness] → retrofits connect heterogeneous equipment without bespoke middleware projects (deployment friction drops)
- (+) [Subcontractors] → supplier plants expose standard telemetry and event schemas to OEMs (data exchange normalizes)
- (+) [Quality control] → audit and trace systems pull data from mixed-vendor fleets reliably (evidence becomes portable)
- (+) [Competitive adaptability] → smaller firms add new connected tools faster because integration effort falls (capability spreads)
- (+) [Maintenance and repair] → common update and fault-reporting pathways reduce troubleshooting time (service becomes more legible)
- (–) [Security] → vulnerability disclosures start affecting widely deployed standard stacks (shared standards share risk)
- (–) [Market structure] → vendors compete to define “reference” certification profiles (standard wars carry power stakes)

- (–) [Risk aversion] → legacy fleets without standard-compliant upgrades become stranded faster (installed-base pressure grows)

## ART 12.092 — Interoperable Digital Twin Ecosystems

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Portable digital twins are central to the challenger regime because they let asset, process, and product knowledge move across tools, contractors, and lifecycle stages instead of being trapped in one vendor's environment. They reduce duplicate modeling and speed diagnosis, planning, and changeovers, while changing responsibility, liability, and bargaining among OEMs, integrators, and operators. They also allow distributed manufacturing chains to coordinate from shared model states. That is transformative enough for **10**.

**Weak signals (9):**

- (+) [Integration of design and manufacturing] → tenders require twin portability across vendor tools (model lock-in becomes procurement issue)
- (+) [Subcontractors] → suppliers deliver assets with synchronized twin packages, not only drawings (digital handoff deepens)
- (+) [Maintenance and repair] → service teams diagnose faults from portable twin states across sites (knowledge becomes mobile)
- (+) [Competitive adaptability] → reconfiguration projects rely on imported twin models rather than rebuilding from scratch (iteration speeds up)
- (+) [Quality control] → batch and asset evidence is tied to shared twin histories (operational truth gets structured)
- (+) [Reduced vulnerability] → ownership changes or contractor swaps no longer break digital continuity (lifecycle resilience rises)
- (–) [Liability] → disputes emerge when twin predictions diverge from physical outcomes (responsibility boundaries tested)
- (–) [Market structure] → major platforms race to become the authoritative twin registry layer (control shifts upward)
- (–) [Security] → altered twin states are treated as cyber-physical sabotage risks (model integrity becomes safety issue)

## ART 12.093 — Global Supply Chain Traceability Networks

**Score: 10 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Traceability networks directly affect a central manufacturing bottleneck: weak visibility across complex supplier chains. They speed recalls, verify origin and composition, reduce counterfeits, and improve compliance. They also reallocate bargaining power between OEMs and smaller suppliers and can impose heavy data burdens on those with less digital capacity, while enabling more automated procurement, sustainability claims, and localized substitution during disruptions. Because they transform how manufacturing networks are governed and trusted, **10** is justified.



**Weak signals (9):**

- (+) [Subcontractors] → large buyers require batch-level provenance as a condition of supply (traceability becomes market entry gate)
- (+) [Quality control] → recalls are executed using linked chain-of-custody data rather than broad product withdrawals (response becomes precise)
- (+) [Reduced vulnerability] → supply teams swap suppliers faster because material histories are comparable (resilience improves)
- (+) [Ease of purchasing] → procurement systems filter offers by verified origin and compliance data (buying gets automated)
- (+) [Perceived quality] → premium goods market provenance as a product attribute (trust becomes customer-facing)
- (+) [Resource efficiency] → returned goods and scrap are routed using known composition histories (circularity gains evidence)
- (–) [Market structure] → smaller suppliers struggle with the cost of mandatory data capture (power tilts upward)
- (–) [Security] → tamper and spoof attempts target identifiers and provenance events (traceability becomes attack target)
- (–) [Risk aversion] → buyers maintain parallel paperwork until digital records win repeated legal trust (transition friction persists)

**ART 12.094 — Personal Data Portability & Trust Frameworks****Score: 1 (Impact in GVN 3)****Justification (3–5 sentences):**

This is useful around workforce data, contractor access, and some customer-linked manufacturing services, but it does not strongly reshape manufacturing operations themselves. The impact is mostly peripheral and institutional rather than a driver of production-system change. It may reduce administrative friction, but not transform the GVN. Score **1**.

**Weak signals (4):**

- (+) [Labor] → workers carry portable training, safety, and access records between plants (verification friction falls)
  - (+) [Ease of purchasing] → after-sales manufacturing services request only minimal verifiable customer data (data sharing gets cleaner)
  - (–) [Cost-effectiveness] → most factories see the issue as HR/admin rather than production-critical (operational relevance stays low)
  - (–) [Governance] → identity recovery and consent disputes dominate pilots (manufacturing linkage remains indirect)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.095 — Interoperable Digital Currency Payment Networks

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Faster and more interoperable payments can reduce some friction in supplier transactions, especially across borders or low-connectivity settings. But payment rails alone do not materially change production capability, product quality, or plant organization. Their effect is supportive and transactional, not operationally transformative. That keeps this at 1.

**Weak signals (4):**

- (+) [Subcontractors] → cross-border suppliers start receiving settlement through interoperable digital-currency rails (transaction friction falls)
  - (+) [Ease of purchasing] → machine-to-machine replenishment pilots include automated conditional payments (rules get embedded)
  - (–) [Risk aversion] → manufacturers keep traditional banking rails for most critical procurement (operational trust stays limited)
  - (–) [Compliance] → identity and AML requirements dominate enterprise adoption talks (payment innovation stays constrained)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

Manufacturing is heavily shaped by product, safety, trade, environmental, and quality rules, so machine-readable regulation can materially lower interpretation and compliance friction. It reduces advantage held by large firms with bigger legal and compliance teams, while also risking rigid software interpretations of ambiguous rules. Faster compliance updates support more agile product and process changes. That is significant enough for 5.

**Weak signals (9):**

- (+) [Safety and compliance] → regulators publish machine-checkable rule packages alongside legal text (compliance becomes programmable)
- (+) [Competitive adaptability] → product changes are pre-checked automatically against updated rules (reconfiguration speeds up)
- (+) [Ease of purchasing] → procurement systems reject non-compliant supplier offers automatically (rules enter transactions)
- (+) [Quality control] → audits accept executable compliance traces from firms (evidence becomes structured)
- (+) [Lack of skills] → smaller firms rely on rules-as-code tools instead of external compliance specialists (capability spreads)
- (–) [Risk aversion] → firms still keep human legal review for edge cases (semantic limits stay visible)

- (–) [Market structure] → software vendors controlling the best regulatory interpreters gain leverage (compliance stack centralizes)
- (–) [Accountability] → disputes emerge over whether software or legal text governs (authority boundary contested)
- (–) [Speed of change] → frequent rule updates stress manufacturing software maintenance teams (operational overhead shifts)

## ART 12.097 — Open Metaverse Interoperability Protocols

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

The manufacturing pathway is mainly through reusable 3D collaboration, training, and design assets across tools. That is useful, but secondary compared with direct digital twin, AR/VR, and standards layers. Its role is mainly to reduce content lock-in in immersive collaboration rather than to alter production itself. So it remains a 1.

**Weak signals (4):**

- (+) [Variety and innovation] → 3D training and design assets move more freely across vendor tools (content lock-in weakens)
  - (+) [Lack of skills] → immersive manufacturing training reuses shared interoperable content libraries (content reuse improves)
  - (–) [Cost-effectiveness] → most firms still treat metaverse layers as optional presentation tooling (core linkage stays weak)
  - (–) [Market structure] → major platforms preserve partial lock-in despite nominal interoperability (benefit remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 — Content Authenticity Infrastructure

**Score: 1 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This can help manufacturing indirectly by authenticating design files, instructions, images, audits, and digital evidence, especially as AI-generated content grows. But the overall effect on production economics and operating models is limited compared with stronger traceability and certification infrastructures. Its main value is in document and media trust, not manufacturing-system redesign. That supports 1.

**Weak signals (4):**

- (+) [Intellectual property] → design files and work instructions start carrying signed provenance metadata (authenticity enters workflows)
- (+) [Quality control] → audits or incident reviews verify image/video provenance before acceptance (digital evidence trust rises)
- (–) [Cost-effectiveness] → plants use authenticity checks only in sensitive processes (broad rollout remains shallow)

- (–) [Market structure] → authenticity verification is bundled into a few creator or platform ecosystems (value capture recenters)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 — Privacy-Preserving Collaboration Protocols

**Score: 5 (Impact in GVN 3)**

**Justification (3–5 sentences):**

These protocols are highly relevant in fragmented manufacturing networks where firms need joint insight on quality, demand, emissions, or failures without revealing sensitive raw data. They reduce data-sharing friction and can help smaller firms join collective optimization efforts, while also creating dependence on cryptographic infrastructure and governance. Shared insight then feeds faster adaptation across whole supplier tiers. That is significant enough for 5.

**Weak signals (9):**

- (+) [Subcontractors] → competitors and suppliers run joint analytics without pooling raw process data (coordination barrier falls)
- (+) [Quality control] → shared defect-pattern studies proceed under secure computation terms (collective learning deepens)
- (+) [Reduced vulnerability] → supply networks compare disruption exposure privately across firms (shared resilience planning improves)
- (+) [Resource efficiency] → emissions or waste benchmarking uses privacy-preserving cross-firm computation (common optimization becomes acceptable)
- (+) [Risk aversion] → stalled data collaborations restart once raw-data exposure is removed (trust unlocks action)
- (–) [Cost-effectiveness] → heavy computation and integration costs slow smaller firms (deployment remains unequal)
- (–) [Market structure] → secure-compute operators become essential intermediaries (new gatekeepers emerge)
- (–) [Security] → governance concerns shift toward output leakage and policy misconfiguration (privacy is not automatic)
- (–) [Compliance] → regulators still ask who is accountable for jointly computed conclusions (responsibility remains shared)

## ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

**Score: 20 (Impact in GVN 3)**

**Justification (3–5 sentences):**

This is a keystone enabler because the challenger regime only scales if flexible, digital, decentralized, and customized manufacturing can still be trusted for safety, quality, and liability. It reduces adoption risk for new machines, processes, and distributed production sites, while reshaping procurement, insurance, finance, labor qualification, and market access. It also determines whether the whole shift toward agile, local, software-defined manufacturing compounds

or stalls under distrust and fragmentation. Because it is a necessary trust layer for the most important operating-model transition in the GVN, **20** is warranted.

### **Weak signals (10):**

- (+) [Safety and compliance] → new manufacturing methods get standardized test artifacts and digital evidence packs (trust infrastructure forms)
- (+) [Quality control] → buyers accept batch-level machine-readable certificates across multiple sites (trust becomes portable)
- (+) [Risk aversion] → insurers and lenders use conformance status in underwriting decisions (finance follows certification)
- (+) [Subcontractors] → small suppliers win work once standardized qualification replaces bespoke audits (market access broadens)
- (+) [Customization] → custom or short-run production becomes acceptable because conformance can still be proven (flexibility gains legitimacy)
- (+) [Integration of design and manufacturing] → process recipes carry certifiable status across updates and sites (digital change becomes governable)
- (+) [Reduced vulnerability] → alternative suppliers are activated faster because comparable conformance evidence exists (resilience gets operationalized)
- (–) [Market structure] → accredited labs and certifiers become new choke points (trust can recentralize)
- (–) [Cost-effectiveness] → smaller innovators complain about certification overhead and slow consensus (entry burden becomes visible)
- (–) [Intellectual property] → disputes arise over how much process detail must be exposed for certification (trust and secrecy collide)

## **GVN 4: Sustenance ART Impact**

### **1. Sensing, Measurement & Connectivity**

#### **ART 01.001 — Global Broadband Connectivity**

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Mature broadband makes continuous monitoring, remote troubleshooting, and platform-based food commerce workable across farms, indoor growers, cold-chain sites, kitchens, and rural households. It directly strengthens the challenger regime's decentralized production logic by making local sites easier to manage and connect into markets. At 2nd order, it weakens some incumbent advantage tied to closed logistics and physical store access, but can also concentrate power in connectivity and platform intermediaries. At 3rd order, outage or cyber dependencies can propagate across food ordering, monitoring, and delivery networks. In a 5.5M-person society, the combined effect on access, coordination, labor, and waste plausibly reaches the €100M–1B band, so 5; 10 would require connectivity to become the decisive bottleneck

across most food flows.

Weak signals (9):

- (+) [Rural food producers] → [greenhouse and packhouse tenders require satellite or mesh backup] (remote ops become feasible)
- (+) [Alternative distribution channels] → [grocery apps guarantee sparse-area delivery slots] (e-commerce becomes routine)
- (+) [Food safety oversight] → [regulators accept remote video and data audits] (site-visit burden falls)
- (+) [Urban agriculture] → [one operator supervises many micro-farms remotely] (small sites scale)
- (+) [Personalized nutrition access] → [diet platforms launch in low-coverage municipalities] (access gap narrows)
- (+) [Crisis resilience] → [municipalities keep food hubs online during outages] (continuity improves)
- (−) [Major operators] → [connectivity bundles get tied to procurement contracts] (platform power concentrates)
- (−) [Supply security] → [telecom outages disrupt ordering or cold-chain control] (new systemic fragility)
- (+) [Labor markets] → [food-tech job ads require remote troubleshooting skills] (workflow digitizes)

## ART 01.002 — Ultra-Low Latency Networks

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Mature ultra-low-latency networks materially improve real-time control for robot kitchens, automated harvesting, synchronized warehouse systems, and remote intervention in controlled production. The direct 1st-order value is better timing and lower instability in cyber-physical food operations. At 2nd order, the gains accrue most where edge infrastructure exists, favoring large operators and dense sites over smaller dispersed ones. At 3rd order, more tasks become remotely supervised rather than locally staffed, shifting labor structures and operational risk. Plausible total impact fits the €10–100M or 5–50M person-hour band, so 3; 5 would require low-latency control to become standard across most food automation.

Weak signals (5):

- (+) [Robot kitchens] → [pilots shift from local-only to remote supervisory control] (network timing becomes sufficient)
  - (+) [Cold-chain warehouses] → [vendors advertise deterministic millisecond control] (automation widens)
  - (+) [Institutional kitchens] → [kitchen robotics contracts specify edge nodes] (service reliability improves)
  - (−) [Small producers] → [edge-service fees appear in vendor quotes] (access inequality widens)
  - (−) [Food logistics] → [latency incident reports trigger production stoppages] (timing risk becomes visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 01.003 — Edge AI for Sensor Data

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Edge AI lets farms, bioreactors, warehouses, and kitchens detect anomalies, grade quality, and trigger interventions without streaming all raw data upstream. This directly supports fresher food, lower waste, and more autonomous local production. At 2nd order, it reduces dependence on scarce experts and reliable broadband, but it also shifts liability toward model vendors and operators when food-safety decisions are automated. At 3rd order, inspection labor is restructured toward exception management and system supervision. In a 5.5M-person society, labor, waste, and quality effects plausibly fall in the €100M–1B band, so 5.

Weak signals (9):

- (+) [Food processing] → [inspection cameras reject defects autonomously] (quality control localizes)
- (+) [Indoor farming] → [controllers auto-correct nutrient or lighting anomalies] (yield stability rises)
- (+) [Grocery backrooms] → [spoilage detection runs on-device on pallets] (waste response quickens)
- (+) [Institutional kitchens] → [appliances flag contamination or undercooking locally] (safety reaction speeds)
- (+) [Rural producers] → [vendors market offline-capable agrifood analytics boxes] (connectivity dependence falls)
- (+) [Regulators] → [audit records include AI-generated event summaries] (oversight adapts)
- (–) [Liability] → [insurers ask whether rejected lots were AI-decided] (accountability shifts)
- (–) [Labor] → [QA job descriptions move from inspection to exception handling] (task mix changes)
- (–) [Security] → [tampering incidents appear in food sensor models] (new attack surface)

## ART 01.004 — Quantum & High-Precision Sensing

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): High-sensitivity sensing can materially improve contaminant detection, nutrient profiling, soil and water diagnostics, and verification of functional-food claims. The 1st-order pathway is better measurement of hazards and subtle quality differences that are otherwise missed or sampled only infrequently. At 2nd order, higher evidence standards can raise barriers for some smaller producers while favoring advanced labs and premium suppliers. At 3rd order, regulatory thresholds and consumer expectations may ratchet upward once subtler contaminants or nutrient differences become measurable. That supports 3 because plausible impacts sit around the €10–100M band; 5 would require routine deployment beyond niche labs into mainstream supply chains.

Weak signals (5):

- (+) [Food safety labs] → [ultra-trace contaminant panels enter standard contracts] (detection threshold drops)
- (+) [Functional foods] → [nutrient claims cite new high-precision assays] (premium differentiation sharpens)

- (+) [Water security] → [utilities test ultra-sensitive irrigation-water sensors] (input quality improves)
  - (−) [Small producers] → [compliance labs raise prices after new test standards] (cost burden rises)
  - (+) [Regulators] → [draft methods reference quantum or high-precision instruments] (niche becomes standard)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 — Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Dense cheap sensors across fields, shelves, storage rooms, fermentation lines, and packages create continuous visibility on temperature, moisture, gases, strain, and contamination. This directly improves freshness control, input efficiency, and early fault detection across both incumbent and challenger food models. At 2nd order, sensing shifts value toward the actors who aggregate and interpret the data, potentially strengthening major retailers, equipment vendors, or platform firms. At 3rd order, pricing, insurance, and regulation can increasingly rely on live condition histories rather than periodic inspection. In a 5.5M-person society, combined effects on waste, input use, recalls, and labor plausibly reach €100M–1B, so 5.

Weak signals (9):

- (+) [Fresh produce] → [crates and shelves ship with embedded sensor patches] (condition data multiplies)
- (+) [Indoor agriculture] → [shelf-level sensing becomes standard in retrofit kits] (micro-control improves)
- (+) [Storage losses] → [continuous silo sensing appears in insurance checklists] (losses become preventable)
- (+) [Fermentation] → [bioprocess vendors bundle disposable sensor arrays] (batch visibility deepens)
- (+) [Retail waste] → [stores auto-mark down items from sensor data] (pricing becomes dynamic)
- (+) [Municipal food security] → [shelters and school kitchens add ambient sensor meshes] (public kitchens digitize)
- (−) [Major retailers] → [suppliers must share raw condition feeds] (buyer power increases)
- (−) [Privacy and trust] → [consumers challenge in-home food sensing defaults] (acceptance becomes contested)
- (−) [Cybersecurity] → [compromised sensor fleets trigger false spoilage alarms] (new systemic risk)

## ART 01.006 — Privacy-Preserving Pervasive Sensing

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Privacy-safe sensing can unlock diet tracking, kitchen monitoring, and personalized nutrition without centralizing intimate household or care-setting data. The 1st-order effect is better support for individual dietary needs and adherence with lower trust friction. At 2nd order, it can widen participation by hospitals, elder care, or households that would reject conventional surveillance-heavy systems. At 3rd order, it may normalize more continuous food-related sensing, but under a governance model that constrains who captures the value from it. That

is material but not transformative, supporting 3.

Weak signals (5):

- (+) [Individual dietary needs] → [nutrition apps market on-device meal inference] (data sharing resistance softens)
- (+) [Institutional kitchens] → [elder-care pilots keep raw camera and audio data local] (acceptability improves)
- (+) [Regulators] → [food-assistive devices get privacy-by-design procurement criteria] (trust becomes operational)
- (–) [Consumer trust] → [watchdog complaints target covert pantry or fridge monitoring] (social limits surface)
- (+) [Health-food data linkage] → [grocers offer privacy-safe diet feedback programs] (personalization becomes usable)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.007 — Quantum-Resilient and Secure Communication Networks

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The food-system linkage is real but narrow, mainly protecting automated plants, logistics, payment, and traceability networks that hold long-lived sensitive data. Its 1st-order value lies in reducing cyber-risk for remote operation and trusted records, not in changing how food is physically produced or consumed. At 2nd and 3rd order, it mostly affects liability, insurance, and the cost of keeping digital food infrastructure trustworthy over time. Because the pathway is enabling rather than transformative inside this GVN, plausible impact stays below the material anchor, so 1.

Weak signals (3):

- (+) [Food processors] → [network refreshes cite post-quantum compliance] (security upgrades enter capex)
- (–) [Supply security] → [cyber insurers surcharge legacy food-control networks] (migration pressure appears)
- (+) [Traceability platforms] → [long-term provenance records adopt quantum-safe signatures] (record trust extends)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 — Integrated Sensing and Communication (ISAC)

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): ISAC could help warehouses, stores, and robotized kitchens monitor movement and congestion using existing wireless infrastructure, but it mostly substitutes for other sensing approaches. The 1st-order effect is modestly cheaper situational awareness in dense automated sites. At 2nd order, invisible radio-based monitoring may intensify worker-surveillance concerns more than it changes food outcomes. At 3rd order, benefits are incremental and concentrated in highly automated facilities rather than the wider sustenance system. That keeps it at 1.

Weak signals (3):

- (+) [Warehouses] → [wireless upgrades advertise built-in occupancy sensing] (dual-use infrastructure emerges)
  - (+) [Robot kitchens] → [vendors bundle radio-based presence mapping] (separate sensors avoided)
  - (–) [Worker trust] → [unions question invisible workplace tracking by networks] (monitoring norms contested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing hardware & non-Von-Neumann paradigms

### ART 02.009 — Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These chips lower the energy and hardware cost of always-on vision, audio, and multisensor inference in farms, kitchens, and packaging lines. The 1st-order pathway is cheaper local automation under tight power, heat, or form-factor constraints. At 2nd order, more small sites can adopt embedded intelligence, but only if they can access compatible vendor ecosystems and toolchains. At 3rd order, condition monitoring and automated QA can spread into previously marginal contexts such as small cold stores or mobile devices. Plausible impact fits the €10–100M band, so 3.

Weak signals (5):

- (+) [Food equipment] → [smart cameras advertise all-shift edge inference] (power barrier falls)
  - (+) [Indoor farms] → [control vendors swap GPU boxes for tiny modules] (hardware footprint shrinks)
  - (+) [Packaging QA] → [handheld defect detectors run untethered all shift] (inspection becomes mobile)
  - (–) [SMEs] → [vendor lock-in complaints cite chip-specific toolchains] (dependency increases)
  - (+) [Appliance makers] → [premium kitchen devices add event-based sensing chips] (consumer automation grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 02.010 — Novel transistor technologies and materials beyond silicon CMOS

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Broad compute-efficiency gains would eventually trickle into food sensors, robotics, and portable diagnostics, but the link is diffuse and mostly mediated by other systems. The 1st-order effect is a better hardware cost-performance envelope for many downstream technologies already scored separately. At 2nd and 3rd order, it could marginally widen deployment of food automation, but not in a way that is distinctive enough to count as a major GVN shift on its

own. That keeps the impact concrete but limited, at 1.

Weak signals (3):

- (+) [Food-tech hardware] → [vendors cite new ultra-low-power chips in roadmaps] (cost floor moves)
  - (+) [Cold-chain devices] → [battery-life claims jump with new process nodes] (maintenance burden eases)
  - (–) [Supply concentration] → [agrifood OEMs complain about dependence on few fabs] (hardware risk persists)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 — Quantum Computing Platforms

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food-relevant uses exist in formulation, optimization, and biochemical simulation, but they are narrow and mostly upstream R&D or planning tools. The 1st-order effect is limited to a small number of high-value problems rather than the day-to-day operating model of sustenance. At 2nd order, access concentrates in large firms and elite research networks, which may widen innovation asymmetries without broad consumer impact. At 3rd order, any gains arrive mostly through other technologies such as new ingredients or better planning. That keeps it below the material-impact anchor, so 1.

Weak signals (3):

- (+) [Ingredient R&D] → [food majors announce quantum optimization pilots] (niche use crystallizes)
  - (+) [Supply planning] → [commodity traders test quantum routing or hedging] (upstream planning experiments)
  - (–) [Market structure] → [only top agrifood firms buy access contracts] (capability centralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 — Photonic and Optical Computing

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Faster, cooler AI and simulation hardware would modestly benefit genomics, digital twins, and large supply optimization, but only as a secondary enabler. The 1st-order gain is lower-cost computation for already-digitized food actors. At 2nd order, benefits are likely to remain concentrated in datacenter-heavy firms and advanced labs rather than local producers or kitchens. At 3rd order, improved analytics may indirectly support better coordination, but not enough to change the sustenance operating model. That supports a score of 1.

Weak signals (3):

- (+) [Food genomics labs] → [optical accelerators enter sequencing-analysis stacks] (throughput improves)
- (+) [Large retailers] → [datacenter upgrades cite lower AI energy cost] (analytics scale cheaper)

- (–) [SMEs] → [advanced compute stays cloud-only and vendor-controlled] (benefit stays concentrated)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 — Next-Gen Memory & Storage

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Better memory and storage help retain sensor histories, provenance records, and diet or genomics data, but mostly as infrastructure plumbing. The 1st-order value is lower friction in keeping large operational histories live and searchable. At 2nd order, this can strengthen traceability, audits, and AI training, but it does not by itself alter how sustenance is produced or accessed. At 3rd order, longer retention may deepen governance and data-power issues more than it changes food outcomes. Plausible impact remains concrete but limited, so 1.

Weak signals (3):

- (+) [Traceability systems] → [retention periods expand without major cost increases] (history becomes richer)
- (+) [Food labs] → [long-running omics datasets move in-house] (analysis continuity improves)
- (–) [Governance] → [disputes emerge over indefinite diet-data retention] (data power increases)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 — Molecular Computing

Score: 0 (Impact in GVN 4)

Justification (3–5 sentences): Even at maturity, the linkage to everyday sustenance remains too speculative and indirect compared with simpler digital or biochemical control tools. Any 1st-order effect would likely be confined to niche laboratory workflows rather than mainstream food production, distribution, or diet support. There is no robust 2nd- or 3rd-order pathway in the provided GVN strong enough to justify a meaningful score today. It stays at 0 unless molecular logic starts being embedded directly in food bioprocessing or safety-control loops.

Weak signals (3):

- (+) [Fermentation control] → [pilot bioreactors use molecular logic for in-situ switching] (direct food-process linkage appears)
- (+) [Food safety] → [shelf-life assays embed molecular computation cartridges] (use case becomes concrete)
- (+) [Regulation] → [novel-food dossiers reference molecular control modules] (oversight acknowledges pathway)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 3. Artificial intelligence & learning systems



## ART 03.015 — Causal Learning & Reasoning

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Causal AI can move food and nutrition decisions from correlation-heavy guesswork toward intervention planning in agronomy, diet design, pricing, preservation, and policy. The 1st-order effect is better intervention quality: which nutrient change, menu change, price change, or preservation step actually improves outcomes. At 2nd order, it advantages actors with richer experiment data and the ability to run controlled changes, while helping policymakers and public institutions justify choices more explicitly. At 3rd order, bad interventions, waste, and mistargeted subsidies or diets can be reduced, though failed causal claims may also trigger new liability disputes. In a 5.5M-person society the avoided waste, mistargeted diets, and poor process changes plausibly sit in the €100M–1B band, so 5.

Weak signals (9):

- (+) [Personalized nutrition] → [diet platforms show counterfactual meal recommendations] (intervention logic becomes explicit)
- (+) [Indoor farming] → [control software compares effects of nutrient changes] (process tuning improves)
- (+) [Food policy] → [subsidy and labeling debates cite causal model outputs] (governance shifts evidence base)
- (+) [Food manufacturers] → [trials are redesigned around causal graphs] (R&D waste falls)
- (+) [Retail pricing] → [markdown systems test intervention effects on waste] (decision quality improves)
- (+) [Hospitals and schools] → [menu systems justify outcomes by causal pathways] (public procurement evolves)
- (–) [Market power] → [firms with privileged experiment data outperform smaller rivals] (data asymmetry deepens)
- (–) [Accountability] → [failed model-guided interventions trigger liability disputes] (causality claims get litigated)
- (+) [Regulators] → [guidance asks how AI-supported claims identify causes] (evidence standards rise)

## ART 03.016 — Federated & Privacy-Preserving Learning

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This directly enables shared models across hospitals, grocers, farms, appliances, and public kitchens without centralizing sensitive diet, health, or operational data. The 1st-order effect is more capable personalization and food-safety intelligence with less legal and trust friction. At 2nd order, it allows smaller municipalities, clinics, and producers to participate in shared learning systems, but it can also favor whoever controls the federation layer or sets the technical standards. At 3rd order, broader collaboration can improve system-wide response to contamination, nutrition targeting, and operational forecasting. In a 5.5M-person society, that plausibly reaches the €100M–1B band through better targeting, lower data friction, and broader participation, so 5.

Weak signals (9):

- (+) [Individual needs] → [grocery and clinic pilots train shared diet models without pooling records] (personalization scales safely)
- (+) [Food safety] → [processors and retailers exchange model updates on contamination signals] (shared vigilance grows)
- (+) [Public kitchens] → [municipalities join regional menu-model federations] (small actors gain capability)
- (+) [Device ecosystems] → [smart fridges and wearables advertise collaborative learning] (household data stays local)
- (+) [Regulators] → [approved privacy metrics appear in food-health AI procurement] (trust becomes operational)
- (–) [Platform power] → [one vendor becomes default federation coordinator] (control centralizes)
- (–) [Data inequality] → [smaller producers drop out due to integration burden] (benefits skew upward)
- (–) [Security] → [model-poisoning incidents appear in shared food AI networks] (collaboration risk becomes visible)
- (+) [Insurers] → [discounts appear for federated safety monitoring] (risk sharing deepens)

## ART 03.017 — Trustworthy AI Systems

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Trusted AI is a gating layer for deploying automation in recipe generation, food safety, nutrient advice, and autonomous processing. The 1st-order value is safer, more auditable use of AI in high-stakes food decisions where explainability, fairness, and override paths matter. At 2nd order, it lowers some regulatory and insurance barriers to adoption, but it can also raise compliance costs and privilege large vendors that can certify their systems. At 3rd order, trustworthy-AI expectations may become the de facto threshold for market entry in AI-enabled food services. The total impact plausibly fits the €100M–1B band, so 5.

Weak signals (9):

- (+) [Food safety] → [procurements require explainable AI with audit logs] (adoption threshold hardens)
- (+) [Nutrition services] → [consumer apps show confidence and evidence trails] (trust becomes productized)
- (+) [Regulators] → [AI validation frameworks appear in food and kitchen guidance] (rules stabilize)
- (+) [Public procurement] → [school and hospital food systems require human override paths] (governance operationalizes)
- (+) [Insurers] → [lower premiums offered for certified trustworthy AI stacks] (risk priced favorably)
- (–) [Small producers] → [compliance costs delay AI rollout among SMEs] (adoption skews large)
- (–) [Incidents] → [AI diet or allergen failures trigger mandatory audits] (failure feedback tightens)
- (+) [Labor] → [QA roles shift toward model monitoring] (oversight work reconfigures)
- (+) [Vendors] → [food-tech marketing highlights robustness and provenance metrics] (market differentiator emerges)

## ART 03.018 — Automated Machine Learning (AutoML)

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): AutoML lowers the skill barrier for producers, kitchens, co-ops, and municipalities to build forecasting, quality, and personalization models. The 1st-order effect is faster experimentation and broader access to predictive tools without scarce specialist labor. At 2nd order, this widens participation in food-system analytics but also increases the chance that weakly governed models spread into operational use. At 3rd order, many local optimizations become feasible, though mistakes in reward design or data quality can scale quickly. Plausible total impact fits the €10–100M or 5–50M person-hour band, so 3.

Weak signals (5):

- (+) [Small producers] → [no-code food analytics tools appear in coop catalogs] (expertise barrier falls)
- (+) [Public kitchens] → [staff build waste-forecast models without data teams] (local optimization widens)
- (+) [Retailers] → [store managers auto-generate markdown models locally] (decision cycles shorten)
- (–) [Safety and liability] → [poorly tuned models mishandle allergens or spoilage] (guardrail gap appears)
- (+) [Training] → [food-tech courses teach prompt-based model building] (capability diffuses)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.019 — Collaborative Multi-Agent AI

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Coordinated agent systems directly enable distributed robot kitchens, autonomous greenhouses, warehouse swarms, store replenishment, and multi-site meal logistics. The 1st-order effect is large-scale substitution of coordinated machine activity for fragmented human monitoring and routine intervention. At 2nd order, labor shifts from execution to supervision, and the actors controlling orchestration layers gain strong structural power. At 3rd order, shared software stacks can create both strong resilience and correlated failures across multiple food sites. In a 5.5M-person society this can change weekly food provision for hundreds of thousands and move more than €1B of value and labor allocation, so 10.

Weak signals (9):

- (+) [Institutional kitchens] → [one supervisor manages fleets of cooking agents] (labor model shifts)
- (+) [Indoor farming] → [vendors sell coordinated grow-harvest-pack agent stacks] (operations decouple from labor)
- (+) [Grocery logistics] → [stores deploy cooperating picking and restocking agents] (distribution automates end-to-end)
- (+) [Municipal food security] → [emergency meal systems rehearse agent-based allocation scenarios] (resilience planning changes)
- (+) [Standards] → [shared task and safety protocols emerge for mixed food robots] (ecosystem solidifies)

- (–) [Labor relations] → [unions bargain over supervisor-to-agent ratios] (work reallocation becomes visible)
- (–) [Security] → [shared software faults disrupt multiple food sites simultaneously] (correlated failure risk)
- (–) [Market structure] → [few orchestration vendors dominate control layers] (control concentrates)
- (+) [Finance] → [lenders underwrite facilities using agent labor baselines] (capex model resets)

## ART 03.020 — Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Hybrid quantum-AI systems could help a few hard food-system problems such as combinatorial formulation, bioprocess optimization, or upstream logistics planning, but the pathway is narrow. The 1st-order effect is mainly in specialized R&D and planning rather than everyday food production, preparation, or access. At 2nd order, benefits would likely concentrate in a small set of large firms and premium research networks, increasing capability asymmetry more than changing the GVN operating model. At 3rd order, any gains would mostly propagate through other technologies rather than directly through this ART. That keeps the impact concrete but limited, at 1.

Weak signals (3):

- (+) [Ingredient discovery] → [premium food-tech labs buy quantum-AI access] (niche capability appears)
- (+) [Commodity planning] → [hedge and routing models cite quantum subroutines] (upstream use narrows)
- (–) [Market power] → [only top firms can fund hybrid stacks] (benefits centralize)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 — AI-Driven Autonomous Scientific Discovery

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Autonomous discovery directly accelerates new proteins, culture media, preservatives, crop traits, microbiome interventions, and personalized nutrition rules, which align closely with the GVN's challenger regime. The 1st-order effect is sharply compressed R&D cycles and larger search across food-design possibilities. At 2nd order, value shifts toward those controlling high-quality data, robotic labs, and IP portfolios, while public research systems may need new oversight and verification practices. At 3rd order, the pace of food innovation can accelerate both beneficial breakthroughs and poorly governed experimentation, changing the rhythm of market entry and regulatory response. In a 5.5M-person society it can move more than €1B across food innovation pipelines and change consumer offerings at scale, so 10.

Weak signals (9):

- (+) [Novel foods] → [time from concept to pilot ingredient drops sharply] (innovation cycle compresses)

- (+) [Cell-ag startups] → [autonomous lab platforms dominate hiring and capex plans] (R&D automates)
- (+) [Functional foods] → [claim substantiation references AI-designed experiments] (product pipeline accelerates)
- (+) [Public research] → [food grants fund autonomous discovery infrastructure] (institutional priorities shift)
- (+) [SME access] → [shared robotic-food labs offer discovery-as-a-service] (entry barrier falls)
- (–) [IP concentration] → [few data-rich firms accumulate broad food patents] (knowledge power centralizes)
- (–) [Biosecurity] → [review boards screen AI-generated food biology workflows] (risk governance tightens)
- (–) [Labor markets] → [routine bench roles shrink while oversight roles grow] (research work reconfigures)
- (+) [Retail pipeline] → [supermarkets pilot fast-rotating AI-origin ingredients] (market uptake speeds)

## 4. Human-machine interaction & augmentation

### ART 04.022 — Immersive Augmented & Virtual Reality

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Immersive systems can materially improve remote support, training, maintenance, and procedural compliance in food plants, farms, kitchens, and nutrition counseling. The 1st-order effect is better transfer of procedural knowledge and reduced setup or troubleshooting time. At 2nd order, firms with scarce expert staff can cover more sites remotely, though adoption may favor larger organizations able to produce or buy the necessary content and devices. At 3rd order, travel, downtime, and training delays can fall, but the core food operating model remains largely intact. That supports 3; 5 would require immersive guidance to become standard across most food labor and consumer decision points.

Weak signals (5):

- (+) [Food plants] → [maintenance vendors switch manuals to AR workflows] (expertise transfer improves)
  - (+) [Kitchens] → [school and hospital staff train on simulated robot lines] (changeover risk falls)
  - (+) [Nutrition services] → [tele-diet platforms add shared 3D meal planning] (engagement deepens)
  - (–) [Labor] → [workers report headset fatigue or monitoring complaints] (acceptance limits surface)
  - (+) [Insurers] → [credits appear for AR-guided sanitation procedures] (errors become measurable)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.023 — Brain-Computer Interfaces (BCI)

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The main sustenance pathway is assistive: helping people with severe impairments communicate food preferences, control feeding devices, or operate kitchen aids. The 1st-order value is improved autonomy and food access for a limited user group. At 2nd order, the technology mostly affects disability and care systems rather than the broad food economy. At 3rd order, its broader importance would come through inclusion and care burden rather than a shift in food production or distribution. That makes it worth considering but still limited, at 1.

Weak signals (3):

- (+) [Disability nutrition support] → [assistive feeding systems start integrating BCIs] (access widens for niche users)
  - (+) [Hospitals] → [rehabilitation meal-choice tools adopt neural input modes] (autonomy improves)
  - (–) [Governance] → [consent rules tighten for neural data in food-care settings] (deployment stays constrained)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 — Advanced Prosthetics & Exoskeletons

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Exoskeletons and advanced prosthetics can materially extend participation in harvesting, warehousing, kitchen work, and home meal preparation, especially in aging societies and labor-short sectors. The 1st-order effect is reduced injury, longer task endurance, and broader inclusion of workers or household users with limited strength or mobility. At 2nd order, these systems can soften labor shortages in food logistics and care but may also be used to intensify work expectations. At 3rd order, they alter labor-market composition and insurance economics rather than the core provisioning model. That supports 3.

Weak signals (5):

- (+) [Food warehouses] → [injury-reduction tenders include exoskeleton pilots] (labor durability improves)
  - (+) [Institutional kitchens] → [lifting-assist suits enter elder-care catering contracts] (staff strain eases)
  - (+) [Small farms] → [cooperative equipment pools add wearable assist devices] (labor shortage softens)
  - (–) [Labor relations] → [unions bargain over pace increases with assistive wearables] (productivity pressure surfaces)
  - (+) [Insurance] → [workers' comp discounts reference ergonomic wearables] (risk economics shift)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 04.025 — Haptic and Multi-Sensory Feedback Systems

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Richer feedback mainly helps teleoperated food handling, delicate inspection, and assistive cooking interfaces. The 1st-order value is better precision and safer control in tasks where vision alone is insufficient. At 2nd order, this supports certain robotic or assistive use cases but does not materially change the economics of mainstream food provision. At 3rd order, its effects are likely absorbed into broader robotics and accessibility systems rather than becoming a major independent driver. So it stays at 1.

Weak signals (3):

- (+) [Delicate food handling] → [teleop systems advertise force and texture feedback] (precision improves in niche tasks)
- (+) [Assistive cooking] → [adaptive kitchen tools add richer tactile cues] (usability improves)
- (–) [Procurement] → [food sites reject systems as too costly] (linkage remains narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 — AI Understanding of Human Intent & Context

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Intent-aware AI directly supports individualized meals, diet adherence, service robotics, household food assistants, and care settings where preferences, allergies, and social context matter. The 1st-order effect is lower cognitive effort and better tailoring of meal choices, reminders, and interactions. At 2nd order, the technology can reshape who controls consumer attention and food choice, potentially favoring platform assistants that mediate brand visibility and interface access. At 3rd order, it may improve dietary adherence and care efficiency while also enabling manipulative nudging and new privacy risks. In a 5.5M-person society, that plausibly affects €100M–1B of food spend, health, and labor time, so 5.

Weak signals (9):

- (+) [Individual needs] → [meal apps infer allergies, timing, and mood from context] (personalization deepens)
- (+) [Elder care] → [assistive kitchen systems adapt prompts to fatigue or confusion] (nutrition compliance improves)
- (+) [Food service] → [canteen kiosks tailor menus to observed context] (interface changes purchasing)
- (+) [Home kitchens] → [appliances anticipate next actions and portion sizes] (effort to prepare falls)
- (+) [Public health] → [diet programs shift from generic nudges to contextual coaching] (adherence improves)
- (–) [Consumer autonomy] → [watchdogs flag manipulative upselling in food assistants] (choice power distorts)

- (–) [Privacy] → [complaints rise about cameras interpreting meals at home] (acceptance becomes contested)
- (–) [Platform power] → [dominant assistants become gatekeepers for brand visibility] (market access concentrates)
- (+) [Liability] → [vendors publish intent-misread incident policies] (risk becomes operational)

## ART 04.027 — Brain-to-Brain Interfaces

Score: 0 (Impact in GVN 4)

Justification (3–5 sentences): Even at maturity, the link to everyday sustenance is too remote and speculative relative to simpler communication, automation, and assistive tools. There is no strong 1st-order pathway to mainstream food production, distribution, or nutrition support in the GVN. Any 2nd- or 3rd-order effects would be highly indirect and likely dominated by other technologies. It remains 0 unless direct food-care or food-control use cases emerge and scale.

Weak signals (3):

- (+) [Care settings] → [feeding teams pilot BBI support for nonverbal meal decisions] (direct use case appears)
  - (+) [High-skill kitchens] → [extreme telecoordination experiments cite BBI channels] (operational linkage emerges)
  - (+) [Regulation] → [neuro-interface guidance mentions food-care applications] (pathway becomes concrete)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 — Memory Prostheses

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The main food-system effect is supporting people whose memory loss impairs shopping, meal preparation, medication-food timing, or dietary compliance. The 1st-order value is better continuity of eating routines and greater independence for a limited but important population. At 2nd order, this could reduce care burdens and change meal-support services, but it does not materially alter the broader food economy. At 3rd order, the main effects lie in inclusion and caregiving rather than production or logistics. That keeps it at 1.

Weak signals (3):

- (+) [Independent living] → [care packages combine memory prostheses with meal routines] (nutrition adherence improves)
  - (+) [Elder nutrition] → [clinicians monitor reduced missed meals after implantation] (direct benefit becomes visible)
  - (–) [Access inequality] → [only premium care systems reimburse the devices] (benefits stay narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

## ART 05.029 — Self-Driving Vehicles

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Autonomous road transport directly changes how food, groceries, ingredients, and prepared meals move from farms and depots to kitchens and households. The 1st-order effect is lower labor dependence, extended service windows, and more predictable routing for food distribution. At 2nd order, it reshapes fleet ownership, distribution geography, and bargaining power, potentially favoring large fleet platforms and integrated retailers while displacing driving work. At 3rd order, cyber incidents, system outages, or platform concentration could propagate quickly across food availability. In a 5.5M-person society it can plausibly reshape weekly food access for hundreds of thousands and move more than €1B in logistics cost and risk, so 10.

Weak signals (9):

- (+) [Grocery distribution] → [retailers sign driverless middle-mile contracts] (cost base restructures)
- (+) [Meal delivery] → [curbside autonomous fleets enter dense urban zones] (last-mile economics shift)
- (+) [Rural access] → [autonomous vans extend grocery routes to thin markets] (distribution gap narrows)
- (+) [Cold chain] → [refrigerated autonomous trucks gain food-safety certification] (high-value loads move)
- (+) [Urban planning] → [loading-bay rules are rewritten for driverless food vehicles] (infrastructure adapts)
- (–) [Labor] → [collective bargaining focuses on dispatcher and safety roles] (work reallocation accelerates)
- (–) [Security] → [attempted hijack or spoofing incidents hit food fleets] (supply-chain cyber risk surfaces)
- (–) [Market structure] → [a few fleet platforms become mandatory intermediaries] (control concentrates)
- (+) [Insurance] → [autonomous-delivery premiums undercut human-driver fleets] (adoption economics turn)

## ART 05.030 — Drone Swarms & Aerial Robots

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Drone swarms directly improve crop scouting, targeted interventions, inventory checks, and emergency delivery of food or inputs. The 1st-order impact is faster, more precise monitoring and response across dispersed agricultural and logistics environments. At 2nd order, they reduce some field labor and increase dependence on specialized service providers and airspace permissions. At 3rd order, drone-collected data can reinforce advisory and platform power while also changing insurance, subsidy, and emergency-response practices. In a 5.5M-person society the combined effect on losses, labor, and resilience plausibly reaches €100M–1B, so 5.

Weak signals (9):

- (+) [Crop management] → [agronomy contracts shift to weekly swarm services] (monitoring frequency jumps)
- (+) [Input use] → [targeted spray logs appear in subsidy paperwork] (precision use becomes auditable)
- (+) [Food resilience] → [municipalities test drone food drops for cut-off communities] (emergency access widens)
- (+) [Warehouses] → [indoor drone inventory scans enter cold-store operations] (counting labor falls)
- (+) [Insurance] → [underwriters request drone imagery for crop-loss claims] (evidence becomes automated)
- (–) [Airspace governance] → [no-fly disputes increase near peri-urban farms] (operating friction rises)
- (–) [Data power] → [service providers keep agronomic swarm data proprietary] (advisory leverage concentrates)
- (–) [Public acceptance] → [complaints target noise and surveillance over food facilities] (social license contested)
- (+) [Labor] → [service firms hire swarm supervisors instead of seasonal scouts] (task mix shifts)

## ART 05.031 — Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly matches the GVN's robotized food preparation pathway and also matters for warehousing, in-store handling, sanitation, and assisted living. The 1st-order effect is replacement or augmentation of repetitive, awkward, and labor-scarce food work in environments already built for humans. At 2nd order, labor markets, kitchen design, maintenance ecosystems, and supplier relationships shift toward firms that own task libraries, servicing capacity, and integration platforms. At 3rd order, food access can improve in labor-scarce settings, but vendor lock-in, safety failures, and correlated software issues can create new systemic risks. In a 5.5M-person society it can change weekly food preparation and service for hundreds of thousands and move more than €1B of labor and capex decisions, so 10.

Weak signals (9):

- (+) [Institutional kitchens] → [hospitals and schools sign multi-year robot-cook contracts] (meal prep industrializes)
- (+) [Retail] → [stores deploy shelf-stocking and fresh-counter humanoids] (store labor model shifts)
- (+) [Care services] → [assisted-living sites use robots for meal prep support] (access improves for vulnerable groups)
- (+) [Apartment buildings] → [new developments add robot-friendly delivery rooms] (built environment adapts)

- (+) [Standards] → [food-safe manipulation certifications emerge for general robots] (ecosystem solidifies)
- (–) [Labor relations] → [kitchen unions negotiate staffing floors around robots] (substitution pressure becomes explicit)
- (–) [Safety] → [contamination or injury incidents drive tighter sanitation protocols] (liability becomes salient)
- (–) [Market structure] → [few vendors lock customers into skill libraries] (capability centralizes)
- (+) [Finance] → [lenders model kitchens using robotic staffing ratios] (investment logic resets)

## ART 05.032 — Soft Robotics & Bio-Inspired Machines

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Soft robots directly fit delicate harvesting, produce handling, sorting, packaging, and cleaning where rigid machines damage food. The 1st-order effect is lower product damage and broader automation of fragile or variable food categories. At 2nd order, this opens automation in sectors where manual labor persisted because of handling sensitivity, while shifting dependency toward vendors with durable soft components and application know-how. At 3rd order, bruising, waste, and labor structures can change across fresh-food supply chains. The total effect plausibly reaches the €100M–1B band through lower loss and labor substitution, so 5.

Weak signals (9):

- (+) [Fresh produce] → [packhouses replace manual grading with soft grippers] (damage rates fall)
- (+) [Harvesting] → [high-value fruit growers buy soft robotic picking services] (labor bottleneck loosens)
- (+) [Seafood and meat handling] → [gentle automation appears in contamination-sensitive lines] (sanitation and throughput improve)
- (+) [Food waste] → [retailer specs track bruising reductions from robotic handling] (quality becomes measurable)
- (+) [SME access] → [service models offer robotic harvesting by hectare] (adoption barrier lowers)
- (–) [Maintenance] → [downtime complaints cite soft actuator wear] (new failure modes appear)
- (–) [Skills] → [technicians trained in soft-robot sanitation become scarce] (support bottleneck forms)
- (–) [Vendor dependence] → [one manipulator platform dominates task libraries] (control concentrates)
- (+) [Insurance] → [claims data show lower bruising on automated lines] (risk economics improve)

## ART 05.033 — Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): These systems extend monitoring and intervention into aquaculture, remote farms, damaged storage sites, and hazardous environments without constant human presence. The 1st-order effect is persistent inspection, mapping, and task execution where human access is slow, expensive, or risky. At 2nd order, expertise becomes more centralized in remote operations centers, potentially helping coverage while reducing local autonomy. At 3rd order, autonomy failures, spoofing, or vendor concentration can create new resilience problems even as physical access improves. Plausible impact fits the €100M–1B band, so 5.

Weak signals (9):

- (+) [Aquaculture] → [farms shift to patrolling autonomous surface and underwater units] (monitoring becomes persistent)
- (+) [Remote agriculture] → [inspection and repair missions run without site visits] (distance costs drop)
- (+) [Disaster response] → [food warehouses use autonomous inspection after flood or fire] (recovery speeds)
- (+) [Biosecurity] → [autonomous samplers enter water and livestock surveillance] (early warning widens)
- (+) [Labor] → [one remote center supervises many dispersed food assets] (expertise centralizes)
- (–) [Security] → [spoofed navigation incidents affect remote food assets] (trust in autonomy challenged)
- (–) [Regulation] → [insurers demand autonomy logs after losses] (accountability formalizes)
- (–) [Market structure] → [fleet providers lock customers into subscriptions] (dependency rises)
- (+) [Procurement] → [public food-resilience plans budget autonomous inspection services] (institutional uptake grows)

## ART 05.034 — Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Robot-readable layouts, docking, localization, and standardized transfer points make food warehouses, stores, kitchens, and micro-farms far easier to automate reliably. The 1st-order effect is lower sensing and coordination burden per machine, which can sharply improve reliability and reduce the skill threshold for deploying autonomy. At 2nd order, this favors capital-rich retrofits and can lock spaces into specific ecosystems, but it also makes many automation projects bankable that otherwise would fail. At 3rd order, food environments can be redesigned around mixed human-machine workflows, altering labor patterns and access to automation. The plausible impact sits in the €100M–1B band, so 5.

Weak signals (9):



- (+) [Warehouses] → [retrofit budgets shift from robots to robot-ready floors and docks] (environment becomes part of automation)
- (+) [Kitchens] → [new institutional kitchens include docking and machine-readable surfaces] (automation-by-design emerges)
- (+) [Residential food delivery] → [apartment codes add parcel and meal robot interfaces] (last-mile integration deepens)
- (+) [Standards] → [cross-vendor conformance tests appear for food-site autonomy infrastructure] (interoperability matters)
- (+) [Insurance] → [premiums fall for certified autonomy-support layouts] (reliability priced in)
- (–) [Small actors] → [retrofit costs exclude independent shops and kitchens] (access gap widens)
- (–) [Vendor lock-in] → [building specs are written around one autonomy stack] (infrastructure power concentrates)
- (–) [Labor] → [site planners redesign workflows around machine-priority corridors] (human movement adapts)
- (+) [Municipal planning] → [markets add robot traffic rules and curb logic] (public-space governance shifts)

## ART 05.035 — Optical/Microwave Power Beaming for Persistent Robotics

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The clearest food link is niche: keeping drones or remote sensors aloft or operational over farms, warehouses, or disaster zones for longer. The 1st-order effect is longer mission duration without battery swaps in a limited set of monitoring contexts. At 2nd order, safety zones and infrastructure ownership likely keep deployment narrow and site-specific. At 3rd order, it may support resilience niches, but not enough to materially shift the sustenance operating model. So it remains 1.

Weak signals (3):

- (+) [Crop monitoring] → [long-endurance agricultural drone corridors get piloted] (mission duration expands)
  - (+) [Emergency food logistics] → [power-beamed comms drones appear in disaster drills] (response niche forms)
  - (–) [Safety governance] → [exclusion-zone rules block routine food-site use] (deployment stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 — Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food-system uses are niche but concrete, mainly in facility inspection, climbing maintenance robots, and handling of smooth delicate surfaces where suction or clamps are unsuitable. The 1st-order value is better access to awkward surfaces and reduced damage in certain manipulation tasks. At 2nd and 3rd order, the technology's effects are too narrow to reshape food production, access, or governance. It improves a small set of operations rather than the GVN as a whole, so 1 is appropriate.

Weak signals (3):

- (+) [Food facilities] → [wall and ceiling inspection robots use dry adhesion] (access improves in niche spaces)
  - (+) [Packaging lines] → [specialty grippers handle smooth fragile items without vacuum marks] (damage falls slightly)
  - (–) [Operations] → [cleaning demands limit broad use of adhesive pads] (practical scope stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 — Multi-Material & Hybrid 3D Printing

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food relevance is mainly through custom tooling, sensorized equipment parts, and rapid prototyping for processing or kitchen systems. The 1st-order effect is shorter iteration time for machinery and maintenance, not direct transformation of food provision. At 2nd order, this can marginally help smaller equipment teams or local maintenance, but mostly as a manufacturing convenience. At 3rd order, any broader effect is mediated through other food technologies rather than this ART itself. That keeps it at 1.

Weak signals (3):

- (+) [Food equipment] → [maintenance teams print composite spare parts on-site] (downtime shortens)
  - (+) [Kitchen robotics] → [end-effectors with embedded sensing are printed in-house] (iteration speeds up)
  - (–) [Certification] → [hygiene approvals slow printed parts in contact zones] (linkage stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 06.038 — Digital Twin & Simulation-Driven Production

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Digital twins directly improve yield, energy use, contamination

control, and changeover speed in food plants, bioreactors, indoor farms, and large kitchens. The 1st-order effect is better foresight and lower risk when adjusting recipes, maintenance, or process settings. At 2nd order, they embed expert knowledge into reusable software, reducing dependence on scarce staff but potentially shifting control toward platform vendors and data-rich operators. At 3rd order, regulators, insurers, and financiers may rely increasingly on twin-based evidence, making simulation a governance layer as well as an operational one. In a 5.5M-person society, those gains plausibly reach the €100M–1B band, so 5.

Weak signals (9):

- (+) [Food plants] → [commissioning documents include mandatory live digital twins] (virtual-first operations emerge)
- (+) [Bioreactors] → [cell-ag facilities test recipe changes in simulation first] (ramp risk falls)
- (+) [Indoor farming] → [twin-based optimization enters service contracts] (energy-yield trade-offs sharpen)
- (+) [Public kitchens] → [large caterers rehearse staffing and equipment changes in twins] (planning formalizes)
- (+) [Maintenance] → [insurers accept twin-derived predictive-maintenance evidence] (downtime risk prices lower)
- (–) [Vendor power] → [data portability disputes arise when plants switch twin platforms] (software lock-in surfaces)
- (–) [Labor] → [tacit operator knowledge gets codified and centralized] (control recentralizes)
- (–) [Security] → [twin tampering appears in food safety investigations] (digital integrity becomes critical)
- (+) [Regulators] → [validation packs include simulation evidence for novel processes] (oversight adapts)

## ART 06.039 — Reconfigurable & Agile Factories

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Modular factories materially support smaller-batch food processing, local production, fast product switching, and individualized meal or ingredient lines. The 1st-order effect is lower changeover cost and faster response to demand, seasonality, or dietary segmentation. At 2nd order, they weaken some economies-of-scale advantages of incumbent mass production, but may also favor firms that control compatible module ecosystems and validated recipes. At 3rd order, more local or experimental production becomes economically plausible, changing market structure and resilience patterns. Plausible total impact fits the €100M–1B band, so 5.

Weak signals (9):

- (+) [Local production] → [regional processors advertise week-scale product changeovers] (batch economics change)

- (+) [Personalized foods] → [nutrition-tailored SKUs move into routine runs] (individualization becomes physical)
- (+) [Cell-ag and fermentation] → [facilities share standardized modular units across products] (capex becomes more fluid)
- (+) [Retail private label] → [grocers contract small agile plants for rapid launches] (buyer power shifts)
- (+) [Workforce] → [training focuses on module swap and recipe governance] (labor generalizes)
- (–) [Standard control] → [few module ecosystems dominate compatibility lists] (platform concentration rises)
- (–) [Safety] → [reconfiguration-related allergen incidents trigger stricter validation] (flexibility incurs governance)
- (–) [Major operators] → [incumbents use module ownership to preserve gatekeeping] (change gets captured)
- (+) [Finance] → [lenders value changeover flexibility in collateral models] (investment criteria evolve)

## ART 06.040 — Circular & Sustainable Manufacturing

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Circular manufacturing matters for packaging, food-equipment parts, and waste-to-value input loops, so its clearest 1st-order effect is lower material waste and lower dependence on virgin inputs around food production and distribution. At 2nd order, it can shift contracts and margins toward actors that control sorting, requalification, and recycled feedstock quality, while also raising new contamination and certification burdens. At 3rd order, stronger circularity can change procurement norms and public expectations around food packaging and equipment lifecycles, but it does not by itself reconfigure how sustenance is mainly produced or accessed. That supports 3: material impact on sustainability and cost, plausibly in the €10–100M annual band for a 5.5M-person society.

Weak signals (5):

- (+) [Packaging] → [recycled or reprocessable food-contact materials enter mainstream contracts] (material loops tighten)
  - (+) [Food waste infrastructure] → [plant by-products become feedstock for new material lines] (waste gains value)
  - (+) [Public procurement] → [school and hospital tenders require circular packaging proofs] (institutional demand hardens)
  - (–) [Quality assurance] → [contamination disputes grow around recycled food-contact inputs] (trust becomes gating)
  - (+) [Equipment makers] → [service contracts include take-back and remanufacture clauses] (asset loops close)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.041 — Bio-fabrication technologies

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): The strongest sustenance linkage is through structured cultured tissues, advanced scaffold design, and bio-manufacturing methods adjacent to cellular agriculture, so the 1st-order impact is in enabling more food-like textures and controlled biological production. At 2nd order, it can shift value toward specialized sterile-manufacturing suppliers, scaffold firms, and lab-to-food equipment vendors. At 3rd order, if commercialized, it helps normalize biomanufacturing as part of the food system, but on its own it remains an enabling layer rather than the main operating-model shift. That supports 3: material but not dominant impact, plausibly in the €10–100M band.

Weak signals (5):

- (+) [Cultivated meat] → [firms tout scaffolded whole-cut products] (food relevance deepens)
  - (+) [Ingredient plants] → [bioprinted cell constructs enter texture-engineering pipelines] (sensory quality improves)
  - (+) [Equipment supply] → [food-tech vendors add sterile biofabrication modules] (ecosystem begins to form)
  - (–) [Regulation] → [authorities demand new contamination and labeling rules] (commercialization path toughens)
  - (+) [Investment] → [joint ventures link tissue-engineering firms and food producers] (adjacent markets converge)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 — 4D Printed & Programmable Materials

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food relevance is niche, mainly through adaptive packaging, self-adjusting greenhouse parts, deployable growing structures, or flow components that react to moisture or temperature. The 1st-order effect is modest performance improvement in selected assets rather than broad change in food production or access. At 2nd and 3rd order, any wider effect is likely absorbed into packaging or equipment markets without materially shifting the GVN's operating model. That keeps the score at 1: concrete and worth watching, but below the material-impact threshold.

Weak signals (3):

- (+) [Packaging] → [pilots test humidity-responsive produce packs] (shelf-life adaptation appears)
  - (+) [Indoor farming] → [self-deploying shades enter demo systems] (maintenance effort falls slightly)
  - (–) [Food-contact approvals] → [regulators delay direct-contact programmable materials] (scope stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 — Volumetric Additive Manufacturing

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Faster one-step printing mainly shortens spare-part and tooling cycles for food equipment, labware, and custom fixtures. The 1st-order benefit is quicker maintenance and prototyping, not a direct change in how food is grown, processed, or consumed. At 2nd and 3rd order, any broader impacts are indirect through equipment responsiveness and are too small to move the GVN materially. That keeps the score at 1.

Weak signals (3):

- (+) [Food plants] → [maintenance suppliers promise minute-scale printed parts] (downtime response quickens)
  - (+) [Lab equipment] → [microfluidic housings are printed on demand] (R&D iteration speeds)
  - (–) [Hygiene certification] → [rapid-printed parts stay excluded from key contact zones] (impact stays bounded)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 — Metamaterials for Novel Optics & Connectivity

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The clearest food-system uses are better greenhouse light control, improved wireless coverage in sensor-dense facilities, and some compact sensing hardware. The 1st-order impact is therefore limited to selected efficiency gains in controlled environments and connected facilities. At 2nd and 3rd order, those gains are too component-level to alter channel structure, food access, or the dominant regime's core logic. That makes the impact concrete but limited, so 1 is appropriate.

Weak signals (3):

- (+) [Greenhouses] → [glazing vendors market spectral-control layers for crops] (specialized linkage appears)
  - (+) [Cold stores] → [signal-steering surfaces improve sensor connectivity] (facility use becomes concrete)
  - (–) [Cost] → [food-site retrofits treat metamaterials as premium add-ons] (mainstream impact stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 07.045 — Room-Temperature Superconductors

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): If realized, the main food relevance would be cheaper power delivery, better refrigeration equipment, and possibly stronger sensing, but these are mostly economy-wide spillovers rather than food-specific transformation. The 1st-order effect inside this GVN is lower



operating cost for energy-intensive food assets. At 2nd and 3rd order, benefits would likely flow through general infrastructure and be hard to attribute specifically to sustenance. That keeps it below the material threshold for this GVN, at 1.

Weak signals (3):

- (+) [Cold chain] → [prototype refrigeration equipment cites superconducting gains] (direct use case appears)
  - (+) [Indoor farms] → [energy-intensive sites pilot superconducting power equipment] (operating-cost linkage emerges)
  - (–) [Adoption] → [food firms wait for grid-wide rather than sector-specific economics] (benefit remains diffuse)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 — Self-Healing & Smart Polymers

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These materials can materially improve greenhouse films, seals, hoses, packaging, and washable surfaces by reducing minor failures, leaks, and maintenance. The 1st-order effect is lower downtime and spoilage risk in cold chains, packaging, and controlled environments. At 2nd order, they can reduce service burdens and make distributed food infrastructure more robust, though recycling and regulatory burdens may rise. At 3rd order, they may shift maintenance norms toward longer replacement cycles and more condition-responsive assets. That supports 3: meaningful value impact plausibly in the €10–100M band.

Weak signals (5):

- (+) [Greenhouses] → [film suppliers guarantee self-healing puncture resistance] (maintenance burden drops)
  - (+) [Cold chain] → [smart gaskets enter standard service contracts] (failure rates decline)
  - (+) [Packaging] → [freshness packs self-reseal or adjust permeability] (shelf-life support improves)
  - (–) [Recycling] → [waste handlers flag sorting issues for advanced polymers] (end-of-life friction grows)
  - (+) [Food plants] → [maintenance intervals extend after polymer retrofits] (downtime economics shift)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 — Nano-Catalysts & Advanced Coatings

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly matters for sanitation, anti-fouling, corrosion control, catalytic ingredient processing, and surfaces that extend shelf life, so the 1st-order impact is lower energy, lower cleaning burden, and better product stability. At 2nd order, it shifts competitive advantage toward actors that can validate and deploy high-performance materials, while also introducing new compliance and migration-testing obligations. At 3rd order, food-contact performance, shelf-life economics, and maintenance intervals can all change in ways that materially

alter operating costs and waste levels across the GVN. In a 5.5M-person society, those effects plausibly reach the €100M–1B band, so 5.

Weak signals (9):

- (+) [Food plants] → [CIP cycles shorten after anti-fouling retrofits] (cleaning burden falls)
- (+) [Packaging] → [retailers test coated packs that slow oxygen damage] (shelf life extends)
- (+) [Cold chain] → [heat exchangers adopt low-fouling coatings] (energy use drops)
- (+) [Ingredient processing] → [catalyst swapouts cut waste in key food inputs] (transformation efficiency improves)
- (+) [Aquaculture and water systems] → [anti-biofouling coatings enter maintenance tenders] (uptime increases)
- (–) [Safety governance] → [new migration tests are mandated for food-contact coatings] (materials evidence tightens)
- (–) [Supply chains] → [scarce catalyst elements trigger cost spikes] (input dependence emerges)
- (–) [Market structure] → [coating IP owners gain leverage over maintenance contracts] (vendor power increases)
- (+) [Insurance] → [corrosion and spoilage claims fall in coated facilities] (risk economics shift)

## ART 07.048 — High-Entropy Alloys & Advanced Metals

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Tougher advanced metals improve equipment lifetime in corrosive, high-temperature, or vibration-heavy food processes, but mostly as a maintenance and capex optimization. The 1st-order effect is longer life for selected machinery and less unplanned replacement. At 2nd and 3rd order, this matters in specific harsh environments but does not substantially change food-system structure, access, or quality at society scale. So the linkage remains concrete but limited, at 1.

Weak signals (3):

- (+) [Processing plants] → [high-corrosion components start specifying HEA grades] (lifetime extends in niche assets)
- (+) [Cold-chain hardware] → [premium equipment uses advanced metals] (replacement cycles lengthen)
- (–) [Procurement] → [higher material cost blocks broad use outside harsh environments] (impact remains bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 — Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food-system relevance comes through climate mitigation and the possibility of supplying captured CO<sub>2</sub> to greenhouses or microbial-food systems, but those are indirect compared with more central food technologies. The 1st-order food effect is limited to some input substitution and resilience benefits. At 2nd and 3rd order, most value is mediated through broader energy and climate systems rather than a direct sustenance pathway. That keeps the impact concrete but below the material threshold, at 1.

Weak signals (3):

- (+) [Greenhouses and fermentation] → [captured CO<sub>2</sub> supply contracts are signed nearby] (direct feedstock linkage appears)
- (+) [Food firms] → [procurement starts counting captured-carbon input provenance] (sustainability claims operationalize)
- (–) [Cost] → [captured CO<sub>2</sub> stays too expensive for mainstream food uses] (impact stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 — Graphene and Nanotube Composites for Lightweight Strength

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Lighter, stronger composites can help refrigerated transport bodies, food equipment, and condition-monitoring structures, but the main contribution is a component-level efficiency gain. The 1st-order effect is lower weight, less fatigue, and some embedded sensing. At 2nd and 3rd order, these benefits do not meaningfully alter food distribution channels, diet personalization, or local production models. So the score remains 1.

Weak signals (3):

- (+) [Food logistics] → [lightweight refrigerated bodies adopt composite panels] (payload efficiency rises)
- (+) [Processing equipment] → [self-sensing composite parts appear in premium machines] (predictive maintenance improves)
- (–) [Safety and regulation] → [nanoparticle handling concerns slow food-contact uses] (scope stays narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.051 — Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly affects refrigeration, thermal buffering, building envelopes, food transport, and indoor farming, all of which are major cost and spoilage points in

sustenance. The 1st-order effect is lower energy demand and better temperature stability across storage, delivery, and controlled production. At 2nd order, it can improve resilience and favor actors able to retrofit or specify smart-thermal assets, while potentially widening capability gaps between large and small operators. At 3rd order, more reliable thermal control changes insurance, outage resilience, and the feasibility of local fresh-food systems. In a 5.5M-person society the combined waste and energy effects plausibly sit in the €100M–1B band, so 5.

Weak signals (9):

- (+) [Cold chain] → [supermarket and warehouse retrofits adopt phase-change buffering] (temperature excursions drop)
- (+) [Food transport] → [delivery boxes market passive thermal smoothing] (last-mile quality improves)
- (+) [Indoor farming] → [smart thermal envelopes appear in new vertical farms] (HVAC burden falls)
- (+) [Homes] → [premium fridges advertise thermal-storage resilience] (consumer resilience grows)
- (+) [Public food security] → [shelters stock passive-cooling food assets] (crisis continuity improves)
- (–) [Access inequality] → [energy-saving retrofits concentrate in large chains] (benefits skew upward)
- (–) [Fire and toxicity rules] → [building approvals tighten around new thermal materials] (compliance becomes gating)
- (–) [End-of-life] → [recyclers flag composite thermal materials as hard to separate] (waste frictions emerge)
- (+) [Insurance] → [spoilage claims fall at smart-thermal sites] (risk pricing shifts)

## ART 07.052 — Rare-Earth-Free Magnets for Sustainable Motors

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Resilient magnet supply materially matters for refrigeration, pumps, conveyors, mixers, farm equipment, and food-delivery electrification. The 1st-order effect is more stable availability and pricing of motor-driven food infrastructure. At 2nd order, it reduces exposure to geopolitically concentrated materials and may alter procurement and resilience strategies across essential food assets. At 3rd order, more predictable electrification can strengthen cold chains and automation rollouts, though mostly as an enabling shift rather than a direct food-model transformation. That supports 3: material value impact in the €10–100M range is plausible.

Weak signals (5):

- (+) [Refrigeration OEMs] → [new motor lines advertise rare-earth-free designs] (supply risk falls)
- (+) [Food plants] → [procurement specs add rare-earth exposure criteria] (resilience becomes explicit)

- (+) [Delivery fleets] → [e-cargo systems switch to rare-earth-free motors] (electrification scales predictably)
- (–) [Performance] → [high-load equipment reports efficiency trade-offs] (adoption pace moderates)
- (+) [Public resilience planning] → [essential food assets prioritize scarce-material-light motors] (geopolitical risk internalized)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination**

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These membranes can materially expand reliable water for irrigation, aquaculture, and food processing where saline or brackish sources are relevant. The 1st-order effect is lower-energy water supply for selected food systems under water stress. At 2nd order, they can shift regional production viability and resilience, though benefits remain geographically uneven and tied to water governance. At 3rd order, lower water-risk exposure can stabilize specific food clusters, but not the whole sustenance model in a western society of 5.5M people. That supports 3.

Weak signals (5):

- (+) [Water-stressed food regions] → [coastal growers sign low-energy desal contracts] (production becomes feasible)
- (+) [Aquaculture] → [recirculating systems switch to upgraded membrane skids] (input-water reliability improves)
- (+) [Food processors] → [plants near saline sources add on-site desal units] (site selection changes)
- (–) [Brine governance] → [local disputes rise over concentrate disposal] (externalities become visible)
- (+) [Insurance and grants] → [drought funds include membrane desal for food hubs] (resilience linkage strengthens)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.054 — Ultra-Wide-Bandgap (UWBG) Power Semiconductors**

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): UWBG power electronics materially improve converters for refrigeration, LED lighting, motors, EV logistics, and microgrids that support food systems. The 1st-order effect is lower electrical losses, smaller power hardware, and better thermal performance in food-relevant electrified assets. At 2nd order, this supports broader electrification and resilience but mainly as an enabling input to other systems such as cold chains and indoor farming. At 3rd order, operational costs and reliability can improve across many sites, though the changes remain infrastructural rather than visibly transformative to consumers. That supports 3.

Weak signals (5):

- (+) [Cold chain] → [premium refrigeration markets smaller cooler power modules] (efficiency improves)
  - (+) [Indoor farms] → [lighting and HVAC vendors cite UWBG converters] (energy overhead falls)
  - (+) [Delivery fleets] → [fast chargers for food depots shrink in footprint] (electrified logistics scales easier)
  - (–) [Supply chain] → [few qualified module suppliers create bottlenecks] (hardware dependence persists)
  - (+) [Microgrids] → [essential food sites specify high-temperature power electronics] (resilience stack deepens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.055 — Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The main sustenance linkage is niche backup power, some fertilizer or processing logistics, and remote-site energy storage. The 1st-order food effect is safer storage of hydrogen in a limited number of relevant sites. At 2nd and 3rd order, meaningful impact would depend on hydrogen becoming a major energy carrier for food systems, which is not necessary for the GVN's core transformation pathways. That keeps it at 1.

Weak signals (3):

- (+) [Remote food hubs] → [backup power pilots use solid hydrogen cartridges] (safe fuel niche appears)
  - (+) [Fertilizer and logistics] → [handling protocols reference solid-storage modules] (upstream linkage becomes concrete)
  - (–) [Economics] → [food operators reject hydrogen as costlier than batteries] (impact stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 — Fusion Energy Reactors

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Abundant steady power and heat would materially improve energy-intensive indoor farming, fertilizer and ingredient synthesis, desalination, cold chains, and food processing. The 1st-order effect is lower volatility and greater availability of clean baseload energy for food-system nodes that are currently cost-constrained by electricity or heat. At 2nd order, access would likely be concentrated around large host sites and long-term contracts, potentially reinforcing centralization even as overall resilience improves. At 3rd order, food production geography and input economics could shift around stable high-density energy, but not in a way that makes fusion the sole linchpin of food transformation. In a 5.5M-person society the food-specific effects plausibly reach the €100M–1B band, so 5.



Weak signals (9):

- (+) [Controlled-environment agriculture] → [projects cluster near planned fusion heat and power sites] (energy geography shifts)
- (+) [Fertilizer and ingredient plants] → [off-take MOUs mention fusion-backed power] (input cost risk narrows)
- (+) [Desalination-food linkages] → [coastal food clusters pair desalination with fusion power] (water-security model changes)
- (+) [Cold chain] → [refrigerated hubs co-locate with fusion-linked microgrids] (reliability improves)
- (+) [Public policy] → [food resilience plans count fusion as strategic baseload] (energy-food coupling formalizes)
- (–) [Centralization] → [only large operators secure early cheap power contracts] (access inequality widens)
- (–) [Siting politics] → [food communities contest reactor-adjacent development] (social license matters)
- (–) [Security] → [critical food hubs enter nuclear-grade protection zones] (infrastructure dependence rises)
- (+) [Finance] → [agrifood capex models assume lower electricity volatility] (investment horizon extends)

## ART 08.057 — Small Modular Fission Reactors (SMRs)

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): SMRs can materially support greenhouses, food processing, desalination, and cold-chain resilience with steady local heat and power. The 1st-order effect is reliable energy and heat for food assets that are otherwise exposed to intermittent power or fuel volatility. At 2nd order, they can enable regional self-sufficiency clusters, but they also favor capital-rich operators and bring security, licensing, and legitimacy burdens. At 3rd order, steady energy could reshape where controlled-environment food production and high-heat food manufacturing locate. In a 5.5M-person society the impact plausibly fits the €100M–1B band, so 5.

Weak signals (9):

- (+) [Greenhouses] → [projects are proposed beside industrial heat from SMRs] (heat-to-food coupling strengthens)
- (+) [Food processors] → [large plants negotiate SMR-backed power deals] (cost volatility narrows)
- (+) [Water-food security] → [SMR-plus-desal packages appear in regional planning] (resource resilience expands)
- (+) [Cold chain] → [essential depots classify SMR-fed microgrids as resilience assets] (continuity improves)

- (+) [Public procurement] → [municipal food-security strategies mention nuclear-backed zones] (policy stance shifts)
- (–) [Social acceptance] → [food brands market non-nuclear sourcing differentiation] (consumer legitimacy contested)
- (–) [Security costs] → [nearby food facilities face higher protection requirements] (operating overhead rises)
- (–) [Market structure] → [power access concentrates around few host sites] (geographic advantage hardens)
- (+) [Insurance and finance] → [models value continuous heat and uptime] (bankability changes)

## ART 08.058 — Thin-film solar cells

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Lightweight integrated solar directly supports warehouses, greenhouses, cold stores, delivery fleets, and rural or rooftop food production without heavy structural retrofits. The 1st-order effect is more distributed on-site power generation for food assets, lowering cost and outage exposure. At 2nd order, it strengthens localized and decentralized production models but also favors actors with usable surfaces, financing, or large building portfolios. At 3rd order, thinner integration can normalize energy-producing food infrastructure and improve resilience for refrigeration and local food hubs. The total impact plausibly sits in the €100M–1B band, so 5.

Weak signals (9):

- (+) [Warehouses] → [reroofing bids routinely include solar skins] (food buildings become generators)
- (+) [Greenhouses] → [semi-transparent films move from trials to acreage] (dual-use surfaces scale)
- (+) [Delivery and cold boxes] → [integrated solar charging becomes a standard option] (distributed loads self-power)
- (+) [Small producers] → [leased solar-film packages appear in cooperative finance offers] (capex barrier lowers)
- (+) [Public kitchens] → [schools and community hubs use integrated solar retrofits] (local resilience improves)
- (–) [Landlord-tenant split] → [leased food sites cannot capture savings] (deployment inequality persists)
- (–) [End-of-life] → [disposal rules tighten for solar laminates on food buildings] (waste governance emerges)
- (–) [Buyer power] → [large chains use cheap energy to pressure suppliers] (advantage concentrates)

- (+) [Outage resilience] → [fridges and freezers with local solar backup get grants] (continuity becomes practical)

## ART 08.059 — Bionic Leaf Technology

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Bionic-leaf systems matter to sustenance mainly by producing low-carbon chemical feedstocks near where food or food inputs are made, especially for microbial proteins, specialty ingredients, and some fertilizer-adjacent processes. The 1st-order effect is more distributed production of reduced compounds that can substitute for centralized fossil-derived inputs in selected food pathways. At 2nd order, this could shift value toward food-adjacent chemical modules and away from some centralized input suppliers, while also raising water, safety, and siting questions. At 3rd order, local chemical autonomy can strengthen resilience in remote or off-grid food hubs, but the pathway is still too selective to restructure the overall food system. That supports 3: material but bounded impact, plausibly in the €10–100M band.

Weak signals (5):

- (+) [Precision fermentation] → [microbial-food projects source intermediates from solar chemical panels] (direct feedstock linkage forms)
  - (+) [Remote food hubs] → [off-grid sites pair water sunlight and chemical panels] (distributed chemistry emerges)
  - (+) [Fertilizer and ingredient R&D] → [vendors market leaf-panels as small input units] (upstream integration begins)
  - (–) [Safety and regulation] → [handling rules tighten around on-site intermediates] (operational friction rises)
  - (+) [Public grants] → [food-resilience programs fund solar-chemical demos] (institutional interest becomes visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 — Grid-Scale Energy Storage

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Long-duration storage materially stabilizes renewable power for cold chains, food plants, controlled-environment agriculture, irrigation, and water treatment. The 1st-order effect is lower outage risk and lower exposure to volatile power prices in food-critical operations that cannot tolerate interruptions. At 2nd order, storage ownership can shift bargaining power toward utilities, site operators, or local energy aggregators, while improving the viability of decentralized food infrastructure. At 3rd order, more stable electricity allows broader electrification of food logistics and processing, strengthening resilience but also creating dependence on storage-heavy infrastructure and its safety governance. In a 5.5M-person society, the food-specific effect plausibly sits in the €100M–1B band, so 5.

Weak signals (9):

- (+) [Cold chain] → [large depots contract multi-day storage behind the meter] (spoilage risk falls)
- (+) [Indoor farming] → [new sites budget storage as core infrastructure] (electricity becomes schedulable)

- (+) [Food processors] → [load-shifting strategies enter procurement documents] (energy costs become manageable)
- (+) [Rural food security] → [community food hubs pair storage with local renewables] (local resilience strengthens)
- (+) [Public planning] → [black-start food infrastructure lists storage-backed facilities] (recovery time compresses)
- (–) [Market power] → [storage owners capture scarcity rents during outages] (dependency shifts upstream)
- (–) [Safety] → [fire or gas incident scrutiny intensifies at food-adjacent sites] (new operational burden)
- (–) [Equity] → [small sites cannot finance long-duration assets alone] (benefits skew large)
- (+) [Insurance] → [refrigerated-loss coverage improves at storage-backed sites] (risk pricing changes)

## ART 08.061 — Solid-State Batteries

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Safer, denser batteries materially help food delivery fleets, warehousing equipment, portable refrigeration, small cold stores, and backup power for homes or community food hubs. The 1st-order effect is safer electrification with better range, lower fire risk, and more flexible siting of battery-backed food assets. At 2nd order, this supports the spread of low-emission delivery and localized resilience, though the main change is still infrastructural rather than a direct transformation of food provision. At 3rd order, battery-backed refrigeration and mobility can reduce outage harm and improve last-mile access in thin markets. That supports 3: meaningful value impact in the €10–100M band.

Weak signals (5):

- (+) [Food delivery] → [refrigerated vans and e-bikes market solid-state packs] (range and safety improve)
- (+) [Small cold stores] → [battery-backed refrigeration enters SME resilience packages] (backup becomes practical)
- (+) [Farm equipment] → [compact electrified machines gain all-day duty cycles] (operational substitution widens)
- (–) [Recycling] → [food-sector buyers wait for robust end-of-life channels] (adoption tempers)
- (+) [Insurers] → [lower premiums appear for lower-runaway battery systems] (financing improves)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 — Green Hydrogen & Power-to-X

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly matters to fertilizer, process heat, long-duration storage, and hydrogen- or carbon-fed microbial food production. The 1st-order effect is more flexible supply of key molecules and high-temperature energy for food-related sectors that are difficult to electrify directly. At 2nd order, it can reduce fossil-input dependence and enable new regional ingredient chains, but it also tends to concentrate around capital-intensive industrial clusters with access to cheap clean power and water. At 3rd order, if hydrogen and synthetic

feedstocks become trusted, traceable food-adjacent inputs, they can alter production geography and resilience while raising safety and water-governance tensions. In a 5.5M-person society, the combined food-input and resilience effects plausibly reach the €100M–1B band, so 5.

Weak signals (9):

- (+) [Fertilizer] → [offtake contracts shift to low-carbon ammonia or hydrogen] (upstream cost structure changes)
- (+) [Microbial proteins] → [new plants cite hydrogen and CO<sub>2</sub> as feedstocks] (novel-food pathway solidifies)
- (+) [Food processing] → [high-heat facilities pilot hydrogen-ready burners] (electrification limits are bypassed)
- (+) [Port and logistics food hubs] → [hydrogen storage pairs with cold-chain backup] (energy resilience broadens)
- (+) [Certification] → [buyers request molecular-origin proof for key inputs] (traceability deepens)
- (–) [Market structure] → [only large industrial clusters secure cheap hydrogen first] (access skews upward)
- (–) [Safety governance] → [zoning fights emerge around hydrogen near food sites] (siting becomes contested)
- (–) [Water competition] → [food actors question hydrogen projects' local water draw] (resource trade-offs surface)
- (+) [Public policy] → [agricultural resilience plans include synthetic-fuel pathways] (sector coupling grows)

## ART 08.063 — High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Cheaper and more reliable wind power materially lowers energy exposure for irrigation, processing, cold storage, and controlled-environment production. The 1st-order impact is lower-cost electricity for food actors that either buy from wind-linked grids or co-locate with wind-heavy energy systems. At 2nd order, wind can influence regional production economics and energy hedging strategies, but mostly through general power markets rather than food-specific restructuring. At 3rd order, better wind performance strengthens renewable-heavy food resilience when paired with storage and local grids, without becoming a dominant food-system driver on its own. That supports 3.

Weak signals (5):

- (+) [Food processors] → [PPAs with wind farms become standard hedging tools] (input volatility narrows)
- (+) [Cold stores] → [sites co-locate with wind-heavy microgrids] (local energy strategies shift)
- (+) [Irrigation and water] → [pumping plans assume cheaper wind-backed power] (resource economics improve)
- (–) [Permitting conflicts] → [food landscapes contest turbine siting] (land-use trade-offs surface)

- (+) [Public resilience] → [rural food hubs add wind plus storage packages] (distributed security improves)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 — Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The food-system linkage is niche, mainly supplying power to remote sensors, temporary food-relief sites, autonomous monitoring platforms, or disconnected agricultural operations. The 1st-order value is reduced wiring or fuel logistics in a small number of special cases. At 2nd and 3rd order, however, safety limits, cost, and infrastructure concentration likely keep the role narrow compared with simpler alternatives such as batteries, cables, or local generation. That keeps it at 1.

Weak signals (3):

- (+) [Disaster food response] → [temporary kitchens use beamed-power receivers] (niche deployment appears)
- (+) [Remote agriculture] → [field sensors are designed around wireless power envelopes] (service niche forms)
- (–) [Safety and spectrum] → [regulatory limits keep routine use tightly bounded] (broad adoption constrained)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 — Advanced geothermal technology

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Steady geothermal heat and power directly support greenhouses, drying, food processing, desalination, and cold-chain resilience in suitable geologies. The 1st-order effect is stable low-carbon heat and electricity for energy-intensive food assets that benefit from constant output. At 2nd order, it can anchor regional food-energy clusters and reduce fuel dependence, but benefits remain uneven and depend on geology, drilling risk, and financing. At 3rd order, geothermal can shift food production geography toward heat-rich nodes and improve resilience where other low-carbon heat sources are weak. In a 5.5M-person society, the food-specific effect plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Greenhouse expansion] → [acreage plans cluster around geothermal heat access] (local production economics shift)
- (+) [Food processing] → [dryers and pasteurizers switch to geothermal supply] (fuel dependence falls)
- (+) [Water-food nexus] → [geothermal sites pair with desalination or nutrient recovery] (resource coupling strengthens)
- (+) [Regional development] → [food parks are marketed around constant geothermal energy] (industrial geography changes)
- (+) [Public procurement] → [municipal food-security plans count geothermal-backed hubs] (resilience value recognized)



- (–) [Seismicity and opposition] → [drilling disputes slow food-energy co-location] (social risk surfaces)
- (–) [Access inequality] → [only geology-favored regions capture benefits] (territorial divergence grows)
- (–) [Finance] → [drilling cost overruns stall producer projects] (capital risk becomes visible)
- (+) [Insurance] → [stable heat contracts improve underwriting for indoor farms] (bankability improves)

## ART 08.066 — Resilient microgrids

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Microgrids directly support food hubs, supermarkets, cold storage, water systems, community kitchens, and controlled-environment farms during grid stress. The 1st-order effect is continuity of refrigeration, processing, and meal provision during outages or grid congestion. At 2nd order, resilience shifts from purely centralized utilities toward site owners, municipalities, and community operators, which can improve local control but also widen inequality between places that can and cannot invest. At 3rd order, food-security planning, insurance, and siting increasingly treat resilient local grids as part of the essential sustenance infrastructure. The plausible food-system effect fits the €100M–1B band, so 5.

Weak signals (9):

- (+) [Cold chain] → [supermarkets and depots start island-capable upgrades] (spoilage risk becomes designable)
- (+) [Community food hubs] → [grants fund microgrid-backed kitchens and storage] (local security strengthens)
- (+) [Farms and indoor growers] → [sites advertise autonomous power continuity] (production fragility falls)
- (+) [Water-food systems] → [pumping and processing are planned on one local grid] (coordination improves)
- (+) [Disaster planning] → [municipal continuity maps prioritize microgridded food assets] (recovery logic changes)
- (–) [Equity] → [wealthier districts secure resilient food access sooner] (resilience gap widens)
- (–) [Utility politics] → [tariff disputes rise over islanding rights] (governance rebalances)
- (–) [Cybersecurity] → [microgrid controllers become attack points for food continuity] (new risk surface)
- (+) [Insurance and finance] → [lenders discount outage risk for microgridded sites] (capex case improves)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Precise gene editing directly affects crop resilience, nutrient profiles, allergen reduction, animal health, pet-food inputs, and optimized cell lines or microbes for new foods. The 1st-order effect is a much broader design space for food traits and production efficiency

than conventional breeding or older GMO techniques. At 2nd order, it can shift value and control toward IP holders, approved breeding pipelines, and large agrifood-biotech actors, while triggering new legitimacy, biosafety, and trade-governance conflicts. At 3rd order, edited organisms can reshape what foods are locally viable, how much input they require, and how consumers and regulators distinguish “natural,” “improved,” and “engineered” food. In a 5.5M-person society it can transform how food is produced and what qualities are feasible, moving more than €1B of value and risk, so 10.

Weak signals (9):

- (+) [Crop pipelines] → [seed catalogs add edited traits for nutrition or allergens] (food qualities become programmable)
- (+) [Pet food and feed] → [edited ingredients enter premium formulations] (cross-species sustenance broadens)
- (+) [Novel-food regulation] → [approval dossiers normalize precise edits] (governance adapts)
- (+) [Indoor farming] → [edited varieties optimized for LED shelves win contracts] (controlled environments specialize)
- (+) [Public procurement] → [institutional buyers specify nutrition or allergen traits] (downstream demand changes)
- (–) [Trade governance] → [export disputes hinge on gene-edit classification] (market fragmentation appears)
- (–) [Power concentration] → [licensing terms lock growers into proprietary lines] (input control centralizes)
- (–) [Biosecurity and trust] → [off-target scares drive public backlash] (legitimacy becomes volatile)
- (+) [Insurance and finance] → [edited-trait performance data change risk models] (capital reallocates)

## ART 09.068 — mRNA Therapies & Vaccines

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The strongest sustenance pathway is indirect, through better livestock disease control, rapid outbreak response, and some improvement in the resilience of animal-derived food supply. The 1st-order effect is therefore mainly on herd health and zoonotic containment rather than mainstream food consumption or production methods. At 2nd order, this matters for food-security planning and supply continuity but sits closer to animal-health infrastructure than to the core challenger regime in the GVN. At 3rd order, its main value is crisis resilience rather than a large day-to-day operating-model change. That keeps the score at 1.

Weak signals (3):

- (+) [Livestock health] → [rapid mRNA vaccine platforms enter herd-health contracts] (food supply resilience gains)
  - (+) [Zoonotic response] → [food-security plans reference fast animal-vaccine manufacturing] (crisis linkage becomes concrete)
  - (–) [Consumer legitimacy] → [food brands highlight mRNA-free animal sourcing] (acceptance remains contested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 — Cellular Agriculture & Cultured Meat

Score: 20 (Impact in GVN 4)

Justification (3–5 sentences): This ART is a direct embodiment of the GVN's challenger regime of biotechnological food production, especially artificial meat and localized protein production. The 1st-order effect is a potential shift of protein production from animal husbandry and long agricultural supply chains into controlled bioreactors near demand centers. At 2nd order, it reorders land use, feed demand, slaughter and processing labor, animal-welfare politics, regulatory categories, and retail bargaining power, while also risking strong concentration in media, bioreactor, IP, and certification layers. At 3rd order, consumer acceptance, public procurement, and resilient local protein capacity can reinforce one another, making this not merely helpful but a linchpin of one of the most important transformative pathways described in the GVN. In a 5.5M-person society it plausibly reconfigures more than €1B of annual food value and the weekly diet of hundreds of thousands, so 20 is warranted.

Weak signals (9):

- (+) [Retail diets] → [supermarkets dedicate routine shelf space to cultured proteins] (consumer adoption crosses novelty)
- (+) [Public procurement] → [schools and hospitals trial cultured proteins in recurring menus] (institutional legitimacy forms)
- (+) [Upstream agriculture] → [feed-crop demand forecasts adjust downward after cell-protein contracts] (land-use shift begins)
- (+) [Local production] → [urban protein bioplants are financed near demand centers] (supply geography changes)
- (+) [Regulation] → [food-safety frameworks shift from slaughter to bioprocess validation] (operating model reclassified)
- (–) [Market concentration] → [few media or scaffold suppliers dominate margins] (protein power recentralizes)
- (–) [Labor transition] → [slaughterhouse roles face retraining programs] (job displacement becomes concrete)
- (–) [Biosecurity] → [contamination or batch-failure recalls trigger repricing] (process risk becomes public)
- (+) [Consumer segmentation] → [menus normalize cultured and blended meat options] (behavioral adoption deepens)

## ART 09.070 — Organoids & Tissue Engineering

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These tools materially improve food testing, gut-response modeling, ingredient screening, and cultured-meat development, reducing slow trial-and-error in food R&D and safety assessment. The 1st-order effect is higher-fidelity biological feedback earlier in formulation and testing cycles. At 2nd order, contract labs and advanced food innovators gain an advantage in screening claims and reducing failed product paths, though mainstream food provision changes only indirectly. At 3rd order, the evidence base behind novel foods and health claims can strengthen, potentially speeding commercialization while also tightening expectations for proof. That supports 3.

Weak signals (5):

- (+) [Ingredient screening] → [food firms replace some animal trials with organoid assays] (iteration accelerates)
  - (+) [Cultured meat] → [product dossiers cite organoid models for optimization] (adjacent tech converges)
  - (+) [Functional foods] → [efficacy claims increasingly rest on tissue-model evidence] (R&D standard shifts)
  - (–) [Regulation] → [authorities question transferability of organoid evidence] (adoption path remains partial)
  - (+) [Contract labs] → [organoid testing becomes a standard food-tech service] (tooling diffuses)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 — Synthetic Biology & Designer Microbes

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Synthetic biology directly underpins precision fermentation, alternative proteins, novel ingredients, waste-to-food conversion, advanced preservation, and some sustainable fertilizer or input pathways. The 1st-order effect is moving significant parts of food production from land- and animal-intensive systems into programmable microbial production. At 2nd order, value shifts from acreage and livestock toward bioreactors, genetic designs, feedstocks, and IP portfolios, while biosecurity and legitimacy become major governance issues. At 3rd order, more modular and localized production can reinforce supply resilience and product diversity, but also intensify platform concentration around dominant microbial chassis and process stacks. In a 5.5M-person society it can move more than €1B of food value and substantially change what gets produced and where, so 10.

Weak signals (9):

- (+) [Precision fermentation] → [major ingredient launches come from engineered microbes] (new production model commercializes)
- (+) [Food waste valorization] → [side-streams feed microbial protein plants] (loops tighten)
- (+) [Functional foods] → [designer microbes generate targeted nutrients or flavors at scale] (individualization expands)
- (+) [Local production] → [regional fermentation plants are financed near demand centers] (supply geography shifts)
- (+) [Regulation] → [approval templates standardize around microbial chassis and kill switches] (governance matures)
- (–) [Biosecurity] → [oversight bodies review dual-use risks in food microbe programs] (risk governance intensifies)
- (–) [IP concentration] → [few chassis owners control licensing terms] (capability centralizes)
- (–) [Consumer trust] → [labeling debates intensify over engineered fermentation] (legitimacy becomes strategic)
- (+) [Upstream agriculture] → [demand weakens for some conventional inputs] (incumbent pressure increases)

## ART 09.072 — Microbiome Engineering

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Microbiome engineering directly supports soil health, animal health, human gut-targeted nutrition, and fermentation stability, which align with the GVN's emphasis on healthiness, sustainability, and individualization. The 1st-order effect is more targeted control of living systems that currently create variability in crops, animals, and dietary outcomes. At 2nd order, value can shift from bulk inputs toward diagnostics, microbial interventions, and firms that own high-quality soil, animal, or gut datasets. At 3rd order, better-managed microbiomes can reinforce yield stability, lower broad-spectrum chemical use, and personalize nutrition, while ecological spillover and claim inflation create real downside pathways. In a 5.5M-person society the aggregate impact plausibly reaches €100M–1B, so 5.

Weak signals (9):

- (+) [Personalized nutrition] → [gut-test-linked food subscriptions move into recurring use] (diet tailoring becomes practical)
- (+) [Agriculture] → [soil microbiome services replace part of fertilizer spending] (input logic shifts)
- (+) [Livestock and pet health] → [microbiome interventions reduce routine antimicrobials] (health-product linkage strengthens)
- (+) [Fermentation] → [plants monitor and steer microbial communities in real time] (batch stability improves)
- (+) [Public health] → [dietary guidance references microbiome-responsive foods] (institutional framing changes)
- (–) [Ecological spillover] → [regulators monitor persistence of introduced strains] (containment becomes central)
- (–) [Data power] → [firms hoard gut and soil datasets as proprietary assets] (advantage concentrates)
- (–) [Consumer trust] → [backlash grows against opaque microbiome claims] (credibility becomes gating)
- (+) [Insurance and finance] → [yield or health predictions tie to microbiome monitoring] (risk pricing shifts)

## ART 09.073 — Precision Medicine & Genomic Diagnostics

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly supports personalized nutrition, allergy management, nutrient targeting, and diet-linked disease prevention, closely matching the GVN's focus on individual needs and healthiness. The 1st-order effect is narrowing food choices and dietary interventions based on more precise biological profiles rather than generic guidance. At 2nd order, food choice, reimbursement, and platform power can shift toward actors controlling the health-food data interface, while privacy and fairness issues become more salient. At 3rd order, more precise nutrition can improve health outcomes and reduce wasteful trial-and-error diets, but may also widen gaps between those with and without access to rich biological profiling. In a 5.5M-person society the combined effects on food spend, health outcomes, and labor time plausibly reach the €100M–1B band, so 5.

Weak signals (9):

- (+) [Individual needs] → [grocers accept genomic or nutrient profiles for recommendations] (diet choice personalizes)
- (+) [Allergy and intolerance] → [diagnosis-to-shopping integrations reduce food trial-and-error] (healthiness improves)
- (+) [Public care] → [clinical nutrition plans reference routine molecular panels] (institutional use scales)
- (+) [Food labeling] → [brands market products to genotype-defined segments] (market segmentation sharpens)
- (+) [Employers and insurers] → [preventive nutrition programs use genomic diagnostics] (food-health finance links)
- (–) [Privacy] → [controversies grow over employers seeing diet-genomic signals] (data misuse risk)
- (–) [Inequality] → [premium personalized diets widen health gaps] (access skews wealthy)
- (–) [Scientific validity] → [consumer-protection actions hit overstated gene-diet claims] (evidence discipline tightens)
- (+) [Platforms] → [APIs emerge to port biomarkers into food ordering] (data infrastructure matures)

## ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These systems materially improve food safety testing, gut-response modeling, ingredient validation, and some fermentation or toxicity screening. The 1st-order effect is faster, more instrumented experimentation with fewer crude proxies or slower animal- or trial-based steps. At 2nd order, this improves the R&D position of food innovators and contract labs, but mostly upstream rather than in everyday food provision. At 3rd order, it can raise the speed and confidence of new product development while tightening the evidentiary baseline for claims and approvals. That supports 3.

Weak signals (5):

- (+) [Novel ingredients] → [safety packages cite gut-on-chip evidence routinely] (testing norm shifts)
  - (+) [Functional foods] → [claims are screened on chips before trials] (R&D filtering improves)
  - (+) [Contract labs] → [organ-on-chip food assay services become standard offerings] (access broadens)
  - (–) [Regulators] → [acceptance standards for chip data remain contested] (translation bottleneck persists)
  - (+) [Manufacturers] → [batch troubleshooting uses chip models for toxicity questions] (feedback loops shorten)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 — Biological Aging & Longevity Barriers

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The main food-system effect is indirect, through changing dietary needs, independent living, and the timing or intensity of nutrition support in older populations. The 1st-order impact is mostly on food demand composition and care-related meal services rather than

production or logistics. At 2nd and 3rd order, it could shift some spending and care burdens, but not enough to change the GVN's main operating model. So the linkage is real but limited, and 1 is appropriate.

Weak signals (3):

- (+) [Elder nutrition] → [food service providers redesign menus around therapy users] (demand mix shifts)
  - (+) [Independent living] → [care budgets delay meal-support intensity after therapies] (service timing changes)
  - (–) [Inequality] → [premium anti-aging care clusters with premium nutrition services] (benefits remain uneven)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 — Engineered Living Materials

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Engineered living materials can materially improve food infrastructure through self-sealing storage surfaces, moisture-regulating environments, low-energy repairs, and possibly carbon-sequestering or regenerative built assets. The 1st-order effect is more durable, responsive food infrastructure rather than direct food production change. At 2nd order, it can reduce maintenance burdens and improve resilience for storage, greenhouses, and food buildings, while also creating hygiene and biosecurity concerns. At 3rd order, longer-lived and self-monitoring infrastructure could lower lifecycle costs and make distributed sites easier to maintain. That supports 3.

Weak signals (5):

- (+) [Food storage] → [crack-sealing or moisture-buffering panels enter cold-room pilots] (maintenance model shifts)
  - (+) [Greenhouses] → [humidity-regulating bio-based materials appear in new builds] (microclimate control broadens)
  - (+) [Sustainability claims] → [food facilities market verified carbon-storing materials] (footprint becomes measurable)
  - (–) [Biosecurity] → [hygiene rules tighten for living materials near food] (acceptance hurdle appears)
  - (+) [Insurance] → [reduced leak and crack claims become visible] (risk economics improve)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 — Gene Drive Pest Control

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): Gene drives could directly change crop protection by shifting pest control from repeated chemical or manual intervention to persistent biological suppression or modification. The 1st-order effect is potentially lower pest pressure, lower pesticide use, and reduced recurring control labor for targeted crops. At 2nd order, this would alter input markets, farm economics, and ecological governance, while raising profound legitimacy, reversibility, and cross-border accountability questions. At 3rd order, persistent biological control can produce large positive feedback in crop viability and resilience, but also strong negative feedback if ecological



side effects or resistance spread beyond intended boundaries. In a 5.5M-person society the upside and downside can both plausibly exceed the transformative threshold for key crops, so 10.

Weak signals (9):

- (+) [Crop losses] → [national pest-control programs design limited gene-drive releases] (persistent control becomes thinkable)
- (+) [Input markets] → [pesticide demand forecasts adjust around drive plans] (upstream disruption begins)
- (+) [Regulation] → [cross-border monitoring protocols get created for food pests] (governance shifts scale)
- (+) [Insurance] → [crop-risk models incorporate expected suppression effects] (capital allocation changes)
- (+) [Labor] → [manual pest-control service demand weakens in targeted sectors] (task substitution appears)
- (–) [Ecological legitimacy] → [environmental protests focus on food-pest gene drives] (social license becomes central)
- (–) [International trade] → [export markets set rules on drive-affected regions] (market fragmentation risk)
- (–) [Reversibility and accountability] → [funding appears for counter-drive measures] (downside governance hardens)
- (+) [Public food security] → [invasive-pest response portfolios include gene drives] (resilience pathway formalizes)

## ART 09.078 — Artificial Wombs & Synthetic Embryos

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Food relevance is limited to niche livestock breeding, conservation, and research support rather than mainstream sustenance. The 1st-order effect is mostly on reproductive management in specific animal systems, not on how most food is produced or distributed. At 2nd and 3rd order, ethical scrutiny, biosecurity, and specialized deployment keep the technology peripheral to the broader GVN. That makes it worth watching, but still only a score of 1.

Weak signals (3):

- (+) [Breeding programs] → [high-value livestock research adds ex vivo gestation support] (niche farm linkage appears)
  - (+) [Conservation and rare breeds] → [agricultural biodiversity programs test synthetic-embryo tools] (food-security fringe use emerges)
  - (–) [Ethics and regulation] → [intense scrutiny prevents broad agrifood deployment] (impact remains narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.079 — Satellite Mega-Constellations & Space Internet

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART materially improves remote farm, fishery, greenhouse, and logistics connectivity while also providing more continuous Earth observation for weather, crop, and disruption monitoring. The 1st-order effect is better coordination, remote troubleshooting, and

situational awareness in parts of the food system where terrestrial networks are weak or fragile. At 2nd order, it can lower barriers for dispersed producers but also concentrate power in a few orbital-network and data-platform operators. At 3rd order, shared orbital connectivity and sensing can tighten feedback loops in crisis response, insurance, and supply coordination, while creating new single-point dependencies. In a 5.5M-person society, the food-specific effects plausibly reach the €100M–1B band through resilience, access, and coordination, so 5.

Weak signals (9):

- (+) [Remote producers] → [farms fisheries and depots adopt always-on space terminals] (coverage barrier falls)
- (+) [Agronomic monitoring] → [insurers and lenders require satellite condition data] (space sensing becomes operational)
- (+) [Supply security] → [governments fuse orbital connectivity with food-resilience monitoring] (situational awareness improves)
- (+) [Small actors] → [cooperatives buy shared satellite analytics subscriptions] (capability diffuses beyond majors)
- (+) [Disaster response] → [food rerouting uses near-real-time orbital damage data] (recovery accelerates)
- (–) [Platform power] → [few constellation providers dominate rural food data] (dependency concentrates)
- (–) [Outage risk] → [constellation faults disrupt remote food operations simultaneously] (shared fragility appears)
- (–) [Data governance] → [disputes grow over ownership of orbital agrifood observations] (control becomes contested)
- (+) [Traceability] → [shipment feeds integrate orbital backhaul by default] (visibility deepens)

## ART 10.080 — Space Resource Utilization (SRU)

Score: 0 (Impact in GVN 4)

Justification (3–5 sentences): Returning space-mined materials to Earth has no clear meaningful pathway to how humans and pets are fed in this GVN. Any 1st-order effect would be generic through global materials markets rather than through food-specific bottlenecks. No strong 2nd- or 3rd-order pathway is visible that would plausibly alter food production, distribution, or nutrition at society scale. It therefore remains 0 unless SRU begins supplying uniquely critical food-system materials in ways terrestrial alternatives cannot.

Weak signals (3):

- (+) [Food equipment] → [critical material shortages are met by space-derived inputs] (direct material linkage appears)
  - (+) [Fertilizer and processing] → [high-value SRU metals are contracted for food hardware] (use case becomes concrete)
  - (+) [Policy] → [food-security material strategies mention off-Earth sourcing] (institutional linkage formalizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 — Closed-Loop Life Support System

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The main food relevance is terrestrial spillover into circular water, air, nutrient, and waste handling for urban agriculture, disaster shelters, isolated food hubs, or extreme-environment production. The 1st-order effect is niche but concrete: tighter closed-loop control of essential food-support systems. At 2nd order, it could improve resilience in a small number of high-dependence settings, though complexity and cost likely keep deployment specialized. At 3rd order, the main impact is as a design reference for extreme food resilience, not as a mainstream food-system architecture. That keeps it at 1.

Weak signals (3):

- (+) [Disaster food hubs] → [closed-loop water and air systems appear in shelters] (extreme-use linkage emerges)
  - (+) [Urban farming] → [vendors market space-derived closed-loop grow modules] (circularity pathway becomes concrete)
  - (–) [Cost and complexity] → [mainstream food sites reject life-support-grade systems] (impact stays niche)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 — High-Altitude Platforms & Balloons

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): High-altitude platforms can materially improve food-system connectivity, crop observation, and emergency coordination where terrestrial and orbital options are insufficient or slower to deploy. The 1st-order effect is persistent sensing and communications coverage over large agricultural or disrupted areas. At 2nd order, this helps resilience agencies and remote producers, but benefits remain bounded by airspace, weather, and service economics. At 3rd order, HAP-based coverage can shorten disaster recovery and strengthen monitoring of dispersed food assets without fundamentally restructuring everyday food provision. That supports 3.

Weak signals (5):

- (+) [Disaster food logistics] → [HAPs enter emergency communications plans] (continuity capability emerges)
  - (+) [Agriculture] → [seasonal crop monitoring contracts include stratospheric platforms] (persistent sensing broadens)
  - (+) [Remote food zones] → [temporary coverage for harvest or fisheries becomes routine] (service model stabilizes)
  - (–) [Airspace governance] → [spectrum and corridor disputes slow service] (operating uncertainty persists)
  - (+) [Public procurement] → [food-resilience agencies budget HAP services] (institutionalization begins)
- Signal density: LOW (linkage weak; additional signals would be speculative).

# 11. Digital Platforms & Collective-Intelligence Systems

## ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Decentralized trust networks can materially improve provenance, automated settlement, selective disclosure of attributes, and cooperative or multi-party coordination in food supply chains. The 1st-order effect is lower reconciliation cost and more auditable records for origin, handling, and transaction events. At 2nd order, they can reduce some dependence on incumbent intermediaries, but in practice may shift power to dominant protocols, custodians, or platform operators. At 3rd order, stronger audit trails can support new premium claims and cross-border coordination, though failures or governance capture can undermine trust quickly. That supports 3.

Weak signals (5):

- (+) [Provenance] → [premium foods carry machine-verifiable chain-of-custody proofs] (trust shifts from paperwork)
- (+) [Small producers] → [cooperative sales platforms use automated payouts] (market entry eases)
- (+) [Compliance] → [export or sustainability claims are checked against shared trails] (verification speeds up)
- (–) [Market structure] → [usage concentrates on few custodial wallets or nodes] (decentralization recentralizes)
- (–) [Fraud and incidents] → [bridge or contract failures affect food settlements] (operational trust tested)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.084 — Platform Cooperatives & Fair Work

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly addresses a named inhibitor in the GVN: dependence on dominant operators and the lack of alternative distribution channels. The 1st-order effect is more producer-, worker-, or community-controlled marketplaces for meals, groceries, local delivery, and procurement. At 2nd order, it can redistribute margins, data rights, and rule-setting power away from incumbent platforms, though financing, governance quality, and logistics scale remain serious constraints. At 3rd order, successful cooperative channels can reinforce local sourcing, fairer labor conditions, and consumer loyalty, changing bargaining power across the food system. In a 5.5M-person society the effect on access, labor, and channel structure plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Local food channels] → [farmer and meal platforms launch with member ownership] (distribution structure diversifies)
- (+) [Delivery labor] → [couriers negotiate platform rules through votes] (work governance changes)

- (+) [Municipal procurement] → [cities route school food through cooperatively governed platforms] (institutional demand supports alternatives)
- (+) [Small producers] → [onboarding fees and data terms undercut incumbent apps] (entry barrier drops)
- (+) [Consumer behavior] → [loyalty programs reward participation in locally governed apps] (demand backs new channels)
- (–) [Governance strain] → [member disputes slow platform decisions] (coordination limits surface)
- (–) [Capital gap] → [co-op platforms struggle to fund logistics infrastructure] (growth bottleneck appears)
- (–) [Incumbent response] → [major grocers use predatory discounts against co-ops] (power conflict sharpens)
- (+) [Policy] → [competition or local-food strategies explicitly support platform co-ops] (institutional leverage grows)

## ART 11.085 — Open Data Sharing Marketplaces

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): These marketplaces can materially improve access to agronomic, logistics, nutrition, and food-safety data for firms and institutions that cannot build privileged data pipelines on their own. The 1st-order effect is easier access to fragmented information that supports forecasting, quality control, and personalization. At 2nd order, this can reduce some asymmetries while also commodifying data and allowing powerful buyers or platforms to shape access terms. At 3rd order, better data liquidity can improve coordination and innovation, but also intensify disputes over ownership and usage rights. That supports 3.

Weak signals (5):

- (+) [Food safety] → [contamination and recall data are offered through exchanges] (visibility broadens)
  - (+) [Small producers] → [co-ops subscribe to demand and price data bundles] (capability diffuses)
  - (+) [Nutrition services] → [food-health datasets are licensed under compute-to-data terms] (personalization options widen)
  - (–) [Data ownership] → [disputes grow over who can sell food data] (rights become contested)
  - (–) [Market power] → [large platforms bundle data access with procurement leverage] (information asymmetry persists)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 — Secure & Resilient Social Platforms

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): The sustenance linkage is mainly through crisis coordination, food-assistance communities, mutual aid, and trustworthy peer-to-peer organization rather than direct food provision. The 1st-order effect is more reliable communication during outages, misinformation spikes, or politically contested situations. At 2nd and 3rd order, benefits are mostly social-coordination and continuity effects, not a major shift in how food is produced or distributed. So the impact is real but limited, at 1.

Weak signals (3):

- (+) [Community food aid] → [mutual-aid and pantry networks migrate to resilient platforms] (coordination survives disruptions)
  - (+) [Food recalls] → [trusted local groups use authenticated channels for rapid alerts] (response quality improves slightly)
  - (–) [Mainstream use] → [commercial food actors stay on incumbent social platforms] (impact remains narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.087 — Collective Open Innovation Networks

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Collective open innovation networks can materially speed shared food-tech problem solving across ingredients, preservation, packaging, farming practices, and local distribution models. The 1st-order effect is lower search and coordination cost for assembling expertise and testing solutions to specific food-system challenges. At 2nd order, this can widen participation beyond major R&D centers, though incentives, IP conflicts, and data access remain limiting factors. At 3rd order, faster diffusion of solutions can improve system adaptability, but the main effect remains upstream innovation rather than an immediate operating-model shift. That supports 3.

Weak signals (5):

- (+) [Food-tech challenges] → [consortia post open calls on proteins or waste reduction] (problem-solving broadens)
  - (+) [SMEs] → [small producers access shared testbeds and solutions] (innovation capacity widens)
  - (+) [Public research] → [funding is routed through open challenge networks] (institutional model shifts)
  - (–) [IP conflicts] → [contributors dispute ownership of successful food solutions] (governance bottleneck appears)
  - (+) [Negative results] → [failed food-process pathways become searchable shared assets] (wasted effort declines)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.088 — Scalable Decentralized Governance

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Decentralized governance could help food cooperatives, community kitchens, pooled local assets, and shared resilience infrastructures make auditable decisions. The 1st-order effect is lower overhead for certain collective-governance arrangements, not a direct transformation of food production or nutrition. At 2nd and 3rd order, it matters mostly in niche governance settings and is unlikely to alter mainstream sustenance at society scale. So the score remains 1.

Weak signals (3):

- (+) [Community food assets] → [shared kitchens adopt formal digital voting and budgeting] (governance use becomes concrete)
  - (+) [Local resilience funds] → [pooled food-security budgets use auditable automated releases] (coordination niche forms)
  - (–) [Participation] → [voter fatigue or manipulation complaints slow use] (scaling remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 — Digital Learning Networks and Skill Credentialing

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Digital learning materially expands the supply of people who can run indoor farms, food-safe automation, robot kitchens, nutrition services, and decentralized production systems. The 1st-order effect is lower training bottlenecks and faster redeployment of labor into emerging food roles. At 2nd order, it can shift who gets access to these jobs and reduce dependence on traditional institutions, though quality assurance and practical competence remain key issues. At 3rd order, more fluid reskilling can help the food system adapt to automation and new production models without as much labor scarcity. That supports 3.

Weak signals (5):

- (+) [Food-tech labor] → [employers accept portable digital credentials for grow-ops roles] (entry barriers fall)
  - (+) [Local production] → [municipalities use online credentialing for community food sites] (capability scales)
  - (+) [Care food services] → [personalized-nutrition training moves online at scale] (specialist capacity broadens)
  - (–) [Quality assurance] → [mismatch appears between credentials and practical competence] (trust in credentials challenged)
  - (+) [Workforce transition] → [retraining targets displaced logistics workers into food-tech roles] (labor mobility becomes visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.090 — Prediction-Market Forecasting Platforms

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Prediction markets can sharpen forecasts for demand, crop risk, outages, or policy timing, but mainly as a decision-support niche. The 1st-order value is better aggregation of dispersed judgments, not a direct change in food production or access. At 2nd and 3rd order, they could slightly improve planning quality, but participation, manipulation risks, and verification limits keep likely impact small within this GVN. So the score is 1.

Weak signals (3):

- (+) [Commodity and food agencies] → [structured forecast markets are used for supply disruptions] (collective forecasting enters practice)
- (+) [Retail planning] → [firms compare forecast-market signals with standard demand models] (decision niche forms)



- (–) [Governance] → [low participation or manipulation concerns prevent reliance] (impact stays bounded)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Interoperable device standards directly cut integration cost across farms, cold chains, kitchens, water systems, and home nutrition devices, which is highly relevant to the GVN’s decentralized and individualized challenger pathways. The 1st-order effect is faster deployment of monitoring and control without bespoke integration for every device, site, or vendor combination. At 2nd order, this lowers entry barriers for smaller actors and makes regulation and procurement simpler, though standards bodies and dominant cloud layers can still capture structural power. At 3rd order, smoother interoperability accelerates sensorization, automation, and decentralized food production, while also making shared vulnerabilities and legacy-stranding issues more visible. In a 5.5M-person society the total effect plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Indoor farming] → [new equipment tenders require open device schemas and APIs] (vendor lock-in weakens)
- (+) [Cold chain] → [retailers demand interoperable telemetry from all suppliers] (data flows standardize)
- (+) [Kitchens and home food tech] → [appliances exchange diet and inventory data across brands] (consumer ecosystem opens)
- (+) [Small producers] → [off-the-shelf sensor kits work without custom integration] (adoption cost drops)
- (+) [Regulation] → [certification marks for food-site IoT interoperability appear] (standard becomes enforceable)
- (–) [Platform power] → [one cloud layer dominates open implementations] (interoperability recentralizes)
- (–) [Security] → [cross-device exploits drive stricter baselines] (shared weaknesses become visible)
- (–) [Legacy divide] → [older food equipment becomes stranded or discounted] (transition costs surface)
- (+) [Public procurement] → [school and hospital food systems specify open interoperability] (institutional adoption scales)

### ART 12.092 — Interoperable Digital Twin Ecosystems

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Portable digital twins help food assets move models and operational histories across vendors, owners, regulators, and service firms. The 1st-order effect is lower duplication and faster troubleshooting for complex food plants, farms, or cold-chain assets. At 2nd order, interoperability reduces some software lock-in and makes multi-party coordination easier, though liability and model governance become more important. At 3rd order, broader reuse of twins

can improve system learning and remote intervention, but the main effect remains a coordination improvement rather than a major operating-model shift. That supports 3.

Weak signals (5):

- (+) [Food assets] → [owners require twin export and import rights] (portability becomes valued)
- (+) [Regulators and insurers] → [common twin formats are accepted for audits] (oversight becomes easier)
- (+) [Multi-site operators] → [farm-to-warehouse models share state across vendors] (coordination improves)
- (–) [Liability] → [disputes arise when different twins disagree in incidents] (governance bottleneck appears)
- (+) [SME support] → [service firms offer reusable twin templates for small sites] (expertise diffuses)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.093 — Global Supply Chain Traceability Networks

Score: 10 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly changes how food safety, provenance, sustainability, fraud control, allergen management, and recall response are handled across the sustenance system. The 1st-order effect is finer-grained visibility into where products came from, what happened to them, and which batches are affected when something goes wrong. At 2nd order, traceability shifts bargaining power: it can help trusted small producers enter premium channels, but it can also let large buyers impose costly data burdens and exclude actors who cannot comply. At 3rd order, live provenance data can reshape consumer trust, procurement standards, insurance, and enforcement in a way that materially alters how the food system is governed. In a 5.5M-person society it can affect weekly food choices and more than €1B of cost and risk, so 10.

Weak signals (9):

- (+) [Retail] → [buyers require unit- or batch-level provenance from origin to shelf] (traceability becomes mandatory)
- (+) [Food safety] → [recalls shrink from broad category pulls to precise batches] (response precision improves)
- (+) [Sustainability claims] → [carbon water and welfare data travel with products] (attributes become contestable)
- (+) [Alternative proteins] → [novel-food inputs carry full process histories by default] (new foods gain legitimacy)
- (+) [Small producers] → [cooperatives use shared traceability rails to enter premium channels] (market access broadens)
- (–) [Compliance burden] → [suppliers complain about unpaid data-entry demands] (buyer power increases)
- (–) [Cybersecurity] → [tampering or outages disrupt market access] (digital dependency deepens)
- (–) [Exclusion] → [uncertified small actors are blocked from formal channels] (market structure hardens)

- (+) [Regulators and insurers] → [audit and recall workflows rely on live traceability feeds] (governance model shifts)

## ART 12.094 — Personal Data Portability & Trust Frameworks

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): Portable, consented diet, health, purchase, and device data directly support individualized nutrition while reducing lock-in between grocers, clinics, apps, appliances, and care providers. The 1st-order effect is easier transfer of relevant personal data into meal planning, diet support, and special-diet services. At 2nd order, this can redistribute some power from closed platforms to users and smaller service providers, though new intermediaries may arise around consent and identity management. At 3rd order, more portable data can make personalized nutrition scalable and more contestable, while concentrating privacy and security risk into unified food-health identities. In a 5.5M-person society the effect on personalized food markets, care, and consumer autonomy plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Personalized nutrition] → [users move shopping biomarker and diet histories between services] (switching costs fall)
- (+) [Clinical food support] → [clinics export diet-relevant profiles into meal providers] (care coordination improves)
- (+) [Smart homes] → [consent dashboards share only selected food-health fields] (data flows become legible)
- (+) [Consumer markets] → [food apps advertise bring-your-own-data-wallet onboarding] (portability becomes competitive factor)
- (+) [Public programs] → [special-diet entitlements carry across retailers digitally] (access friction falls)
- (–) [Data brokers] → [new intermediaries manage permissions and monetize profiles] (power recentralizes differently)
- (–) [Inequality] → [people with richer histories receive better food offers] (data-rich get more value)
- (–) [Security] → [account takeovers expose unified food-health identities] (risk concentrates)
- (+) [Regulation] → [machine-readable consent receipts become standard in integrations] (trust framework institutionalizes)

## ART 12.095 — Interoperable Digital Currency Payment Networks

Score: 3 (Impact in GVN 4)

Justification (3–5 sentences): Interoperable digital payment rails materially help food assistance, remittances, local producer payments, and cross-platform food commerce. The 1st-order effect is lower transaction friction and faster settlement for food-related purchases and transfers, especially across institutional or platform boundaries. At 2nd order, this can improve cash flow and market access for smaller actors, though compliance and programmable-payment rules can also increase administrative burden. At 3rd order, more fluid payments can strengthen crisis response and local food access, but the change is still more transactional than transformative to food production. That supports 3.

Weak signals (5):

- (+) [Food assistance] → [benefit payments work across retailer and delivery platforms] (access friction falls)
  - (+) [Small producers] → [cross-platform instant settlement reduces working-capital strain] (cash flow improves)
  - (+) [Cross-border households] → [remittances convert directly into local food purchases] (household resilience strengthens)
  - (–) [Compliance] → [merchants face heavier identity and reporting on programmable payments] (small-actor burden rises)
  - (+) [Crisis response] → [offline-capable digital vouchers are used in emergencies] (resilience use case solidifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART directly addresses a stated inhibitor in the GVN by making food safety, labeling, additive, and novel-production rules easier to interpret and operationalize for smaller or newer actors. The 1st-order effect is lower compliance ambiguity and faster adaptation when rules change or new methods enter the system. At 2nd order, it can reduce entry barriers and regulatory overhead, but also create new gatekeeping power for compliance-software providers and those who can quickly encode or test against rules. At 3rd order, codified rules may make decentralized food innovation more feasible while also hardening whatever biases or delays exist in the regulatory model. In a 5.5M-person society the effect on entry barriers, oversight cost, and innovation speed plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Novel food entrants] → [compliance tools auto-check dossiers against coded rules] (entry friction falls)
- (+) [Small producers] → [co-ops validate labels and sanitation records in software] (compliance democratizes)
- (+) [Robot kitchens] → [safety logic links directly to codified food rules] (automation becomes certifiable)
- (+) [Recall and inspection] → [regulators receive traces showing which rules were applied] (oversight speeds up)
- (+) [Public procurement] → [tender systems reject non-compliant food submissions automatically] (rule enforcement standardizes)
- (–) [Formalization burden] → [edge cases without codified logic leave small actors stranded] (discretion shrinks unevenly)
- (–) [Vendor dependence] → [few compliance-software providers become gatekeepers] (regtech power grows)
- (–) [Policy lag] → [outdated coded rules block safe new food methods] (innovation bottleneck becomes visible)
- (+) [Training and labor] → [compliance roles shift from interpretation to system auditing] (task structure changes)

## ART 12.097 — Open Metaverse Interoperability Protocols

Score: 0 (Impact in GVN 4)

Justification (3–5 sentences): Interoperable immersive environments have no clear meaningful link to the operating model of sustenance beyond generic collaboration, training, or marketing spillovers. The 1st-order pathways are weak and easily substitutable by less immersive tools. No strong 2nd- or 3rd-order pathway appears that would materially change food provision, food safety, or nutrition in this GVN. It therefore remains 0 unless food production, training, or commerce becomes directly dependent on interoperable immersive spaces.

Weak signals (3):

- (+) [Food operations] → [multi-site kitchen control runs through interoperable 3D environments] (direct workflow linkage appears)
  - (+) [Food training] → [buyers require immersive interoperable simulations for certification] (operational dependence emerges)
  - (+) [Commerce] → [persistent interoperable food marketplaces affect procurement volumes] (channel linkage becomes concrete)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 — Content Authenticity Infrastructure

Score: 1 (Impact in GVN 4)

Justification (3–5 sentences): Content authenticity infrastructure has a narrow but real food relevance around misinformation, brand trust, origin claims, and evidentiary media in audits, inspections, or recalls. The 1st-order effect is lower verification cost for selected digital content tied to food provenance or incidents. At 2nd and 3rd order, it may slightly strengthen trust and dispute resolution, but it does not materially alter how food is produced, distributed, or personalized. That keeps the score at 1.

Weak signals (3):

- (+) [Provenance media] → [food claims and farm footage carry verifiable credentials] (trust documentation improves)
  - (+) [Recalls and investigations] → [authenticated media enter standard evidence packs] (dispute costs fall slightly)
  - (–) [Adoption] → [major food platforms accept unverifiable media anyway] (impact stays limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 — Privacy-Preserving Collaboration Protocols

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): These protocols directly unlock joint food-safety analytics, retailer-manufacturer cooperation, public-health nutrition analysis, and cross-organization optimization without forcing raw data pooling. The 1st-order effect is more frequent and higher-quality collaboration on sensitive food, consumer, and operational datasets. At 2nd order, this lowers some legal and trust barriers while also favoring actors able to invest in high-assurance computation and

shared governance arrangements. At 3rd order, privacy-safe collaboration can strengthen early warning, policy targeting, and supply coordination, though it may also concentrate control in a few trusted compute or orchestration providers. In a 5.5M-person society the resulting improvements in safety, targeting, and efficiency plausibly reach the €100M–1B band, so 5.

Weak signals (9):

- (+) [Food safety] → [competing firms run joint contamination analytics without sharing raw records] (shared vigilance becomes feasible)
- (+) [Nutrition policy] → [public agencies and retailers compute diet patterns privately] (evidence base widens)
- (+) [Alternative proteins] → [suppliers and buyers share yield insights without exposing trade secrets] (ecosystem learning speeds)
- (+) [SMEs] → [cooperatives access shared analytics through managed privacy networks] (capability broadens)
- (+) [Cross-border trade] → [compliance checks run on protected datasets across jurisdictions] (data-border friction falls)
- (–) [Cost and complexity] → [only larger actors afford high-assurance implementations first] (benefits skew upward)
- (–) [Governance] → [disputes emerge over whether safe outputs still leak structure] (trust model is tested)
- (–) [Vendor power] → [few providers dominate the neutral compute layer] (coordination recentralizes)
- (+) [Regulators and insurers] → [accepted privacy-safe audit templates appear] (institutional trust grows)

## **ART-12.100 — A manufacturing-specific Standards, Conformance Testing & Certification infrastructure**

Score: 5 (Impact in GVN 4)

Justification (3–5 sentences): This ART is highly relevant because the challenger regime depends on novel food production, robotics, local micro-factories, cultured systems, and new processing equipment that must still be trusted, insurable, and governable. The 1st-order effect is lower uncertainty when adopting unfamiliar food-production tools and faster qualification of new machinery or processes. At 2nd order, it can lower adoption risk and insurance costs while also creating new gatekeeping if certification burdens are too heavy for smaller entrants. At 3rd order, standardized conformance can accelerate safe scaling of food innovation and make performance claims more comparable across sites and vendors. In a 5.5M-person society the impact on speed of safe deployment and market access plausibly reaches the €100M–1B band, so 5.

Weak signals (9):

- (+) [Novel production] → [cultivated and fermented food equipment gets recognized conformance suites] (trust shifts from vendor claims)
- (+) [Robot kitchens] → [food-contact and sanitation certification becomes portable] (deployment friction falls)
- (+) [SMEs] → [shared accredited test facilities open for small entrants] (entry barrier lowers)

- (+) [Insurers] → [premiums drop for certified autonomous or bioprocess lines] (risk pricing changes)
- (+) [Public procurement] → [buyers require machine-readable certificates for new systems] (institutional demand standardizes)
- (–) [Gatekeeping] → [certification costs block smaller regional producers] (compliance burden skews market)
- (–) [Standard wars] → [competing test regimes fragment market acceptance] (interoperability slows)
- (–) [Liability] → [uncertified incidents make buyers more conservative category-wide] (failure feedback amplifies)
- (+) [Finance] → [lenders condition funding on conformance evidence] (capital allocation formalizes)

## GVN 5: Energy Supply ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Reliable ubiquitous connectivity materially improves the operation of remote wind, solar, storage, heat, fuel, and microgrid assets by reducing site visits, speeding fault isolation, and making distributed control commercially viable. Second-order effects matter almost as much: rural energy projects become easier to finance, new service providers can supervise many sites centrally, and telecom platform power becomes a new dependency in energy security. In a 5.5M-person society, avoided outage time, lower O&M, faster restoration, and wider participation in smart tariffs can plausibly reach the €100M–1B band, but it is not a system linchpin because energy can still be supplied through less connected architectures.

**Weak signals (9):**

- [Remote wind/solar sites] → O&M contracts bundle satellite/5G links by default (remote expertise scales)
- [Distribution operators] → field crews use live video for fault triage (repair loops shorten)
- [Community microgrids] → grants pair power assets with broadband backhaul (autonomy becomes practical)
- [Fuel logistics] → depots and pipelines gain continuous tracking in dead zones (supply visibility rises)
- [Rural consumers] → dynamic tariffs expand into poor-coverage regions (market access widens)
- [Grid control rooms] → remote commissioning replaces many site visits (labor productivity rises)
- – [Cybersecurity teams] → blackout drills assume telecom-path failures (communications become critical)



- – [Energy regulators] → dual-path communications become mandatory for DER aggregators (dependency recognized)
- – [Incumbent utilities] → exclusive deals with connectivity providers appear (platform power concentrates)

## ART 01.002 - Ultra-Low Latency Networks

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART matters where supply becomes inverter-heavy and geographically distributed: millisecond-grade communications support protection, frequency control, islanding, and coordinated storage/EV response. Second-order effects include a shift from slow centralized dispatch toward software-defined local balancing, plus new cyber-safety obligations because communications faults can become power faults. The likely magnitude sits in the €100M–1B range if it becomes standard in protection-grade DER coordination; a higher score would require it to become the dominant architecture of distribution control rather than a high-value niche.

**Weak signals (9):**

- [Distribution protection schemes] → pilots replace fixed settings with networked adaptive relays (control becomes dynamic)
- [Battery fleets] → ancillary-service contracts specify millisecond response guarantees (speed priced explicitly)
- [Microgrids] → islanding tests rely on edge-network timing bounds (resilience becomes software-defined)
- [Industrial users] → private 5G/edge nodes appear with onsite generation (latency monetized locally)
- [Grid codes] → inverter standards reference deterministic communications classes (communications enter compliance)
- [System operators] → congestion management shifts from hourly to sub-second products (finer control valued)
- – [Cyber regulators] → telecom outages are classified as grid-security incidents (coupling risk recognized)
- – [Vendors] → bundled edge-cloud/control stacks dominate tenders (lock-in risk grows)
- – [Insurers] → coverage questions target communications latency failures (fault attribution changes)

## ART 01.003 - Edge AI for Sensor Data

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Edge AI lets energy assets classify anomalies, compress data, and trigger local actions without waiting for cloud analysis, which is highly valuable in substations, wind farms, storage sites, buildings, and pipelines. Second-order effects include less dependence on centralized experts, more vendor differentiation through model quality, and new audit demands when machine judgments affect outages or safety. At society scale, the combination of lower downtime, fewer false alarms, and faster response can plausibly reach the €100M–1B band.

**Weak signals (9):**

- [Substations] → cameras and acoustic sensors start producing local anomaly scores (inspection becomes continuous)
- [Wind operators] → turbine controls flag blade/gearbox faults onboard (repair windows widen)
- [Battery sites] → thermal anomalies trigger local isolation before cloud confirmation (safety loop shortens)
- [Building energy systems] → controllers optimize loads from local sensor fusion (demand flexibility improves)
- [Pipelines/fuel assets] → leak signatures are classified at the edge (response starts sooner)
- [Utilities] → alarm volumes fall while detection rates rise (noise gets filtered)
- – [Regulators] → utilities must log model decisions affecting protection or safety (AI becomes auditable)
- – [Labor relations] → remote analysts replace some routine inspection roles (skills mix shifts)
- – [Cybersecurity teams] → model-update channels become a critical control point (software trust central)

## ART 01.004 - Quantum & High-Precision Sensing

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

High-precision sensing can materially improve geothermal prospecting, subsurface reservoir monitoring, line sag measurement, hydrogen leak detection, timing, and navigation in difficult environments. These are meaningful but bounded niches rather than a new operating model for the whole GVN. The plausible impact sits around the €10–100M / 5–50M person-hour anchor unless the sensors become routine in exploration, grid timing, and hard-to-monitor assets simultaneously.

**Weak signals (5):**

- [Geothermal developers] → tenders add gravimetry/quantum survey requirements (better siting pays)
  - [Grid timing systems] → pilot substations use ultra-stable clocks locally (timing resilience rises)
  - [Hydrogen operators] → high-sensitivity leak sensing enters safety cases (hazard detection deepens)
  - [Underground storage] → reservoir monitoring trials replace some destructive sampling (continuous insight improves)
  - – [Regulators] → certification pathways appear for precision sensing in safety-critical assets (niche becomes standardized)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Very cheap dense sensor networks make energy infrastructures far more observable: cables, blades, panels, pipes, tanks, buildings, and district heat assets can all be monitored at many more points than today. This supports predictive maintenance, localized optimization, and earlier fault detection, while also shifting bottlenecks toward data governance and interpretation. Across a large asset base,

this is plausibly a €100M–1B effect through reduced losses, outages, and maintenance labor.

### Weak signals (9):

- [Distribution grids] → utilities shift from sparse meters to dense feeder sensing (visibility per feeder rises)
- [Wind blades/towers] → strain patches become standard in warranties (degradation becomes priced)
- [Solar fleets] → panel-level environmental sensing spreads beyond premium assets (performance granularity improves)
- [District heat networks] → distributed flow/temperature specks map hidden inefficiencies (losses become visible)
- [Fuel infrastructure] → tank, valve, and pipe condition points multiply (inspection becomes continuous)
- [Building portfolios] → landlords aggregate room-level thermal sensing for demand response (load shaping improves)
- – [Data platforms] → utilities add edge summarization to cope with sensor floods (raw data becomes unmanageable)
- – [Privacy watchdogs] → occupant-level inference concerns arise from energy sensor density (social acceptability tested)
- – [Waste regulators] → disposal rules target sensor-laden materials at end-of-life (embedded hardware accumulates)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 3** (Impact in GVN 5)

### Justification (3–5 sentences):

The main value is not better physics but better social license: energy systems can observe household, building, and mobility behavior closely enough for flexibility services without triggering as much privacy backlash. That matters for demand response, local generation, and distributed storage markets, but the direct technical effect is bounded. The impact is material mainly through enabling adoption and reducing compliance friction, which fits the €10–100M range rather than a full operating-model shift.

### Weak signals (5):

- [Retail electricity providers] → demand-response offers emphasize on-device analytics (privacy becomes a selling point)
  - [Building owners] → smart-energy contracts allow aggregate-only data export (trust barrier lowers)
  - [Energy regulators] → tariff pilots approve privacy-preserving metering methods (compliance path opens)
  - – [Consumer advocates] → complaints shift from data capture to algorithmic terms (politics moves upstream)
  - – [Utilities] → procurement adds secure chips/local processing requirements (privacy becomes infrastructure)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

As energy supply becomes more digital and remotely operated, secure communications become part of security of supply rather than an IT afterthought. This ART directly reduces the risk of long-lived control data being compromised and indirectly enables more aggressive automation, cross-organizational coordination, and remote expert support. The avoided downside from major cyber disruption plus the upside from safer digitalization plausibly reaches the €100M–1B band.

**Weak signals (9):**

- [Transmission operators] → crypto-upgrade roadmaps are linked to grid modernization plans (security joins capex)
- [DER aggregators] → control contracts specify post-quantum key management (automation needs trust)
- [Substation vendors] → hardware refreshes market secure-by-design interfaces first (control paths harden)
- [Cross-border interconnectors] → operators standardize stronger link protection (coordination risk falls)
- [Emergency planners] → blackout exercises include compromised communications scenarios (cyber-physical link acknowledged)
- [Energy insurers] → cyber coverage requires upgraded network cryptography (financial pressure appears)
- – [Small utilities] → migration costs widen capability gaps vs large operators (inequality risk grows)
- – [Vendors] → proprietary security stacks re-create lock-in around upgrades (interoperability weakens)
- – [Regulators] → mandatory crypto transition dates are issued for critical energy systems (security becomes compulsory)

## ART 01.008 - Integrated Sensing and Communication (ISAC)

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

ISAC can turn communications infrastructure around substations, depots, plants, and ports into an added sensing layer for movement, intrusion, occupancy, and coarse asset tracking. That is useful for safety, site logistics, and remote operations, but it is not central to generation, storage, or fuel conversion. The impact is therefore material but bounded, likely in the €10–100M range unless it becomes standard across large energy campuses and logistics corridors.

**Weak signals (5):**

- [Substation operators] → wireless upgrades include site-awareness functions in specs (dual use becomes normal)
- [Hydrogen/fuel terminals] → perimeter sensing shifts onto network equipment (security costs consolidate)
- [Grid depots] → vehicle and equipment tracking piggybacks on communications nodes (yard operations tighten)

- – [Privacy regulators] → worker-surveillance concerns emerge at energy sites (acceptability tested)
  - – [Telecom vendors] → energy-site packages bundle comms, sensing, and analytics together (vendor scope expands)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## 2. Computing hardware & non-Von-Neumann paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

These chips matter mainly by pushing useful analytics and anomaly detection into very low-power field devices, which helps dense sensing and autonomous control in the grid edge. That reduces bandwidth and energy overheads but does not itself redefine energy supply architecture. The likely magnitude is in the €10–100M band unless such chips become the standard platform for millions of DER, storage, and building controllers.

**Weak signals (5):**

- [Metering vendors] → next-generation controllers advertise local AI at milliwatt budgets (edge analytics becomes cheap)
  - [Battery/BMS suppliers] → packs adopt always-on anomaly chips (safety logic moves onboard)
  - [Utilities] → field-device tenders prioritize local inference over cloud dependence (connectivity burden drops)
  - – [Software teams] → energy analytics stacks split by chip family (toolchain fragmentation appears)
  - – [Cyber auditors] → model behavior on embedded chips enters certification scope (edge autonomy scrutinized)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The energy-GVN impact comes through better controllers, sensors, converters, and long-life electronics, especially where heat, power, or maintenance limits current devices. That is materially useful across grid-edge equipment and harsh environments but still mostly an enabling layer rather than a visible system change. The score stays at 3 because the societal effect is likely to sit around the material anchor unless combined with broader power-electronics or sensor revolutions.

**Weak signals (5):**

- [Grid-edge hardware] → new controller families emphasize extreme-temperature/low-power operation (electronics fit harsher sites)
- [DER vendors] → smaller standby loads become a marketed feature (parasitic losses fall)

- [Remote assets] → replacement cycles lengthen for embedded electronics (maintenance burden drops)
  - – [Manufacturers] → dual-sourcing becomes difficult for novel-device components (supply concentration rises)
  - – [Standards bodies] → new qualification profiles appear for beyond-CMOS control hardware (migration becomes formal)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Quantum computing could help optimization, materials discovery, and some high-complexity planning tasks in energy supply, but those effects remain indirect and likely concentrated in a small number of system operators, traders, or R&D groups. It is worth tracking, yet the plausible near-system impact stays below the €10–100M material anchor unless it clearly outperforms classical methods in dispatch, market design, or energy materials.

**Weak signals (4):**

- [System operators] → grid-optimization pilots include quantum services (niche use appears)
  - [Battery/fuel R&D] → energy firms fund quantum materials workflows (discovery route opens)
  - – [Utilities] → quantum work stays in lab partnerships, not operations budgets (impact remains indirect)
  - – [Market operators] → no new products depend on quantum-class computation (operational pull stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Its main energy-supply relevance is indirect: lower-energy data processing for control rooms, simulations, forecasting, and data centers that serve the sector. That is non-trivial, but it does not strongly target the core bottlenecks described in this GVN unless energy operations become dominated by compute-heavy digital twins and real-time simulation. The impact is therefore worth watching but remains below the material anchor.

**Weak signals (4):**

- [Grid simulation teams] → photonic accelerators enter contingency-analysis workloads (specialized compute finds niche)
- [Energy traders] → forecast platforms market lower-latency optical compute (speed becomes monetized)
- – [Utilities] → procurement still treats this as generic IT hardware (sector pull remains weak)

- – [Regulators] → no energy-specific standards mention photonic compute stacks (linkage stays indirect)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

More capable memory/storage helps energy digitalization, but mostly as background IT infrastructure for logging, simulation, and edge devices. The direct pathway to lower cost, better security of supply, or decentralization is limited, so this remains worth considering rather than system-shaping. Material impact would require energy operators to become much more dependent on very large stateful simulations and archival optimization than assumed here.

**Weak signals (4):**

- [Digital twin platforms] → energy datasets stay live rather than archived offline (stateful operations deepen)
- [Substations] → local controllers retain richer histories for diagnostics (forensics improve)
- – [Utilities] → memory upgrades are absorbed into normal IT refresh cycles (impact stays generic)
- – [Asset financiers] → no change in financing terms tied to storage architecture (GVN effect remains weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

There is no strong, near-system linkage from molecular computing to the core energy-supply goal, operating model, or challenger regime described here. Any influence would be highly indirect through niche sensing or chemical environments, not through generation, storage, distribution, or market organization. That does not clear the threshold for meaningful impact in this GVN.

**Weak signals (3):**

- [Fuel-processing labs] → molecular-compute pilots appear inside harsh chemical monitoring setups (would create a niche)
- [Hydrogen/CCUS plants] → embedded chemical logic is tested for onsite safety control (would create direct use)
- – [Energy operators] → no procurement language references molecular computation (linkage absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 3. Artificial intelligence & learning systems



## ART 03.015 - Causal Learning & Reasoning

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Energy supply increasingly needs intervention logic, not just prediction: what happens if a tariff changes, a feeder is reconfigured, storage is repositioned, or a synthetic-fuel pathway is added. Causal AI can materially improve operational decisions, policy design, and investment sequencing, while also reducing costly false inferences that come from purely correlational models. Across planning, demand flexibility, maintenance, and regulation, the value can plausibly sit in the €100M–1B band, though it remains an enabler rather than the physical linchpin of the regime shift.

**Weak signals (8):**

- [System planners] → hosting-capacity studies start using intervention models (policy becomes testable)
- [Retail suppliers] → tariff design tools estimate causal demand shifts (flexibility design improves)
- [Grid operators] → root-cause analysis systems distinguish weather, load, and equipment effects (misdiagnosis falls)
- [Energy regulators] → sandboxes require counterfactual evidence from utilities (decision quality rises)
- [Industrial users] → efficiency and DR platforms simulate action impacts, not just forecasts (interventions get priced)
- – [Model auditors] → disputes focus on causal assumptions, not accuracy alone (governance deepens)
- – [Incumbents] → firms with privileged operational data gain policy influence (knowledge power concentrates)
- – [Courts/regulators] → causality-based decisions in outages or pricing face challenge (explainability becomes critical)

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART is highly relevant because energy data is fragmented across utilities, prosumers, buildings, OEMs, and regulators, while privacy and commercial sensitivity often block pooling. Federated learning enables better forecasting, asset-health models, and flexibility services without forcing central raw-data control, which directly supports social acceptability and distributed participation. That can plausibly reach the €100M–1B band if it becomes standard for DER, building, and mobility coordination.

**Weak signals (8):**

- [Utilities and OEMs] → shared model programs launch without raw-data pooling (coordination barrier lowers)
- [Building portfolios] → local controllers join common learning pools (small actors benefit)
- [EV/charger fleets] → battery-health models train across many operators privately (predictive quality rises)

- [Regulators] → privacy-safe model-sharing becomes approved compliance route (governance path opens)
- [Community energy] → cooperatives access benchmark models without surrendering data (participation widens)
- – [Cloud providers] → a few orchestration platforms dominate federated energy analytics (new gatekeepers emerge)
- – [Model bias audits] → local conditions are under-served where participation is patchy (uneven value appears)
- – [Contract terms] → disputes move from data ownership to model-update rights (power shifts to orchestration)

## ART 03.017 - Trustworthy AI Systems

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

The energy transition described in the GVN depends on more automation in dispatch, maintenance, trading, and customer interaction, but only if it is auditable and safe enough for regulators and operators. Trustworthy AI reduces adoption friction, limits harmful failures, and makes autonomous control more acceptable in high-stakes environments. Its impact is therefore both direct and institutional, plausibly in the €100M–1B band through faster safe deployment and fewer costly errors or rollbacks.

**Weak signals (8):**

- [Grid operators] → AI tools must expose confidence and fallback modes (trust becomes procureable)
- [Energy regulators] → audit trails become mandatory for AI-assisted dispatch or pricing (governance hardens)
- [DER aggregators] → certified AI safety cases enter market participation rules (automation becomes formal)
- [Insurers] → premiums differentiate between audited and unaudited AI control stacks (risk pricing shifts)
- [Control rooms] → human override time is logged as a formal KPI (shared control matures)
- – [Incident reporting] → AI near-misses in grid and battery operations are centrally tracked (failure visibility rises)
- – [Smaller utilities] → compliance costs slow AI adoption outside major firms (capability gap grows)
- – [Vendors] → black-box performance claims lose tenders to audited systems (market structure shifts)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

AutoML lowers the skill barrier for forecasting, anomaly detection, asset-health models, and customer-side optimization, which matters for smaller utilities, local aggregators, and community energy schemes. But it mostly accelerates model production rather than transforming the physical supply model itself. The likely effect is material but bounded, around the €10–100M / 5–50M person-hour anchor, unless local actors use it to scale distributed energy management far beyond

current staffing limits.

### Weak signals (5):

- [Small utilities] → model-building cycles shrink from months to weeks (skill bottleneck loosens)
  - [Community aggregators] → off-the-shelf forecasting becomes affordable (entry barriers fall)
  - [OEM service firms] → predictive-maintenance packages require less specialist tuning (deployment broadens)
  - – [Regulators] → poor reward design or opaque models trigger rollback clauses (governance tightens)
  - – [Energy firms] → model sprawl outpaces validation capacity (quality control becomes bottleneck)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 10** (Impact in GVN 5)

### Justification (3–5 sentences):

This ART directly matches the challenger regime: millions of distributed generators, batteries, flexible loads, chargers, and microgrids coordinating in near real time rather than waiting for centralized dispatch. Second-order effects are major: new aggregators, new rules for autonomy, bargaining shifts between households and incumbents, and greater cyber-safety exposure. If it becomes a standard control layer for DER-rich grids, it changes how the GVN goal is realised and can exceed the >€1B / weekly-life-of-hundreds-of-thousands anchor, though it is not scored 20 because alternative coordination architectures still exist.

### Weak signals (9):

- [DER aggregators] → fleets of devices bid as coordinated agent groups (control becomes distributed)
- [Distribution grids] → local balancing is delegated to autonomous portfolios (central dispatch recedes)
- [Microgrids] → peer assets negotiate islanding and restoration roles automatically (resilience becomes collective)
- [Households] → home batteries/EVs join multi-agent flexibility contracts (consumer assets become system actors)
- [Market operators] → products shift from single-resource bids to portfolio behaviors (rules adapt to swarms)
- [System operators] → congestion management uses agent-to-agent coordination zones (granularity deepens)
- – [Cybersecurity teams] → red-team exercises target emergent agent behavior (new failure modes appear)
- – [Regulators] → accountability rules are rewritten for autonomous collective action (liability must move)
- – [Incumbent utilities] → platform ownership becomes more valuable than physical ownership alone (power recentralizes digitally)

## ART 03.020 - Quantum-Accelerated AI Systems

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The likely pathway is indirect: faster optimization for specific planning or design problems, not a broad reorganization of energy supply. That makes it worth watching, especially for system planning and materials search, but the GVN-level effect remains limited unless it clearly outperforms classical AI in live operational contexts. Hence the score stays below the material-impact anchor.

**Weak signals (4):**

- [System planners] → hybrid quantum-AI pilots are used in capacity planning (niche operational pull)
  - [Energy R&D] → materials teams buy quantum-accelerated model access (design pathway opens)
  - – [Control rooms] → no real-time operating workflows depend on quantum-AI (system pull remains low)
  - – [Utilities] → spending stays in exploratory budgets rather than core OT (linkage remains weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

The challenger regime explicitly depends on faster improvements in storage, catalysts, fuels, PV, and other conversion technologies; this ART accelerates those improvements rather than just optimizing today's assets. Its biggest effect is third-order: shortening the innovation loop for the entire energy system and redistributing advantage toward actors with strong data and experimentation infrastructure. The aggregate impact can plausibly reach the €100M–1B band by speeding the arrival and adaptation of better energy technologies.

**Weak signals (8):**

- [Battery/catalyst programs] → AI-led experiment cycles outpace human-led programs (innovation loop compresses)
- [Utilities] → technology roadmaps are updated more frequently from AI discovery outputs (adoption speeds up)
- [National labs/startups] → autonomous labs focus on storage, fuels, and materials (energy gets priority)
- [Investors] → funding shifts toward platform-style discovery teams (capability concentration grows)
- [Standards bodies] → test methods adapt to faster materials iteration (qualification pipeline responds)
- – [IP disputes] → ownership conflicts emerge over AI-generated energy inventions (value capture destabilizes)
- – [Incumbents] → firms without automated R&D fall behind in component performance (competitive gap widens)

- – [Regulators] → safety review capacity becomes the pace limiter, not lab throughput (governance bottleneck moves)

## 4. Human-machine interaction & augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

AR/VR can materially improve maintenance, remote expert support, training, and planning for complex energy sites, especially where skilled staff are scarce or assets are hazardous. The main effect is on labor productivity, safety, and speed of deployment rather than on the core supply architecture. That fits the €10–100M / 5–50M person-hour band unless immersive remote operation becomes routine across large shares of field work.

**Weak signals (5):**

- [Grid field crews] → work orders include AR overlays and remote guidance (expertise travels digitally)
  - [Wind/offshore operators] → training hours shift from classroom to immersive simulators (skill ramp accelerates)
  - [Substation planners] → digital rehearsals are used before outages and retrofits (errors are preempted)
  - – [Labor agreements] → remote expert-to-technician ratios are renegotiated (work organization shifts)
  - – [Utilities] → hardware refresh stalls outside high-risk sites (impact remains bounded)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

### ART 04.023 - Brain-Computer Interfaces (BCI)

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

BCI has only niche relevance here, mainly for accessibility, specialized control-room work, or extreme remote operation cases. It does not directly address the main energy-supply bottlenecks of generation, storage, conversion, or market structure. Its effect is therefore concrete but limited, below the material anchor.

**Weak signals (4):**

- [Control-room accessibility] → utilities test hands-free interfaces for disabled operators (niche inclusion gains)
  - [Hazardous robotics] → experimental remote control uses neural inputs (extreme teleoperation niche)
  - – [Energy firms] → BCI remains absent from mainstream OT procurement (core linkage stays weak)
  - – [Safety regulators] → no energy-specific operating standards emerge for BCI use (adoption remains marginal)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The relevant pathway is workforce productivity and retention in maintenance, construction, and inspection. That is useful, but too bounded to significantly alter the energy-supply operating model or major cost structure at society scale. It remains worth considering for specific labor bottlenecks, not as a material GVN shaper.

**Weak signals (4):**

- [Grid maintenance contractors] → exosuits enter repetitive lifting and climbing tasks (injury risk falls)
  - [Offshore energy sites] → assistive wearables appear in high-fatigue jobs (workforce retention improves)
  - – [Utilities] → CAPEX remains focused on automation rather than augmentation (labor pathway stays secondary)
  - – [Insurers] → no broad premium changes yet tied to exoskeleton adoption (scale remains small)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Its value is mostly in teleoperation and training for remote inspection/repair in hazardous energy environments. That is non-trivial, but it improves a narrow work mode rather than the core energy supply model. The impact stays below the €10–100M material band unless remote manipulation becomes common across many critical assets.

**Weak signals (4):**

- [Remote robotics pilots] → operators gain force-feedback tools for valve/cable work (precision at distance rises)
  - [Training programs] → haptic simulators replace some live-risk practice (safety learning improves)
  - – [Energy contractors] → teleoperation remains confined to specialist sites (use stays narrow)
  - – [Procurement] → no standard requirement emerges for feedback-rich control stations (mainstream pull limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 - AI Understanding of Human Intent & Context

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Context-aware AI can improve operator interfaces, technician support, and customer engagement, but its energy-supply impact is mainly incremental usability improvement. It does not directly unlock the main challenger-regime elements of distributed generation, storage, or fuel conversion. The likely value is real but limited.

**Weak signals (4):**

- [Control rooms] → assistants adapt alerts to operator workload and role (cognitive load eases)
  - [Technician tools] → maintenance copilots infer task stage from context (documentation burden drops)
  - – [Regulators] → no new energy-market structures depend on intent-aware AI (system linkage weak)
  - – [Utilities] → adoption stays inside support software, not core control loops (impact remains bounded)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 04.027 - Brain-to-Brain Interfaces****Score: 0** (Impact in GVN 5)**Justification (3–5 sentences):**

No clear, meaningful pathway links BBIs to the core energy-supply goal or the challenger regime in this assessment. Any effect would be speculative and highly indirect. That is insufficient for a non-zero GVN score.

**Weak signals (3):**

- [Extreme-operations research] → energy-sector telepresence experiments use direct neural communication (would create a niche)
  - [Crisis coordination labs] → BBI trials target multi-operator synchronization under stress (would create a niche)
  - – [Energy operators] → no procurement, standards, or pilots reference BBI (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 04.028 - Memory Prostheses****Score: 0** (Impact in GVN 5)**Justification (3–5 sentences):**

Memory prostheses may matter for healthcare and individual capability, but they do not have a strong direct or systemic pathway to energy generation, storage, distribution, or fuel systems. Any influence would be tertiary through workforce health, which does not clear the threshold here.

**Weak signals (3):**

- [Critical-operations workforce] → neuro-assistive retention programs are tested in safety-critical roles (would create a labor niche)
  - [Remote operations] → cognitive-assist implants appear in experimental operator support (would create a niche)
  - – [Energy policy] → no energy-specific standards or investments mention memory prostheses (no clear linkage)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART affects energy supply through demand architecture: autonomous fleets can shift when, where, and how transport energy is consumed, whether through electric charging depots, fleet-managed fueling, or smoother traffic patterns. Second-order effects include new load concentrations, new storage and flexibility opportunities, stranded legacy fueling assets, and stronger bargaining power for fleet operators over energy infrastructure. In a 5.5M-person society, transport-energy reconfiguration can clearly exceed the >€1B / weekly-life-of-hundreds-of-thousands anchor, so this is transformative even though it is not a keystone of the broader energy transition.

**Weak signals (9):**

- (+) [Fleet operators] → depot charging/fueling contracts scale faster than private-home demand (load centralizes)
- (+) [Distribution planners] → feeder upgrades cluster around autonomous mobility hubs (transport reshapes grid)
- (+) [Retail tariffs] → fleet-specific dynamic charging products proliferate (large buyers gain leverage)
- (+) [Fuel distributors] → highway refueling assets are written down or repurposed (demand geography changes)
- (+) [System operators] → mobility fleets appear in flexibility markets (transport becomes balancing resource)
- (+) [Urban planners] → curbside energy rules are rewritten for autonomous fleets (public space changes)
- (–) [Incumbent utilities] → fleet-platform deals concentrate demand control in few hands (bargaining power shifts)
- (–) [Cybersecurity teams] → transport-energy coupling enters black-start and outage exercises (system interdependence rises)
- (–) [Households] → energy-price exposure shifts from drivers to mobility platforms (consumer agency changes)

### ART 05.030 - Drone Swarms & Aerial Robots

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Drone swarms directly cut inspection time and risk for lines, substations, wind farms, solar fields, pipelines, fuel depots, and disaster response. Second-order effects include fewer routine field visits, faster post-storm restoration, more centralized supervision, and new airspace and privacy governance around energy infrastructure. The aggregate savings and reliability gains can plausibly reach the €100M–1B band, but the ART improves operation more than the underlying supply architecture.

**Weak signals (8):**

- (+) [Transmission operators] → line inspection frequency rises without proportional staffing growth (coverage becomes scalable)
- (+) [Storm restoration teams] → first situational awareness comes from drone fleets, not patrol trucks (response starts faster)
- (+) [Wind/solar operators] → swarm inspections replace many manual blade/panel checks (O&M costs drop)
- (+) [Pipeline/fuel terminals] → aerial leak and perimeter monitoring becomes routine (hazard exposure falls)
- (+) [Energy insurers] → premiums reward drone-backed inspection records (risk becomes auditable)
- (–) [Aviation regulators] → beyond-visual-line-of-sight corridors are opened around energy assets (governance adapts)
- (–) [Labor relations] → unions contest remote-supervision staffing ratios (job structure shifts)
- (–) [Security agencies] → anti-drone protections expand at critical power sites (dual-use risk rises)

## ART 05.031 - Humanoid and General-Purpose Robots

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

General-purpose robots matter where energy infrastructure still depends on scarce human labor for repetitive, risky, or irregular physical tasks: switching, inspection, cleaning, minor repair, construction support, and fuel or plant servicing. The second-order pathway is strong in labor markets and resilience, especially in remote or harsh sites where staffing is difficult. A broad but not dominant rollout can plausibly reach the €100M–1B band through lower downtime, faster maintenance, and reduced labor bottlenecks.

**Weak signals (8):**

- (+) [Substations and plants] → robot-ready task lists replace some routine manual rounds (presence becomes automatable)
- (+) [Offshore sites] → operators substitute crew transfers with robotic interventions (hazard exposure falls)
- (+) [Solar/wind operators] → cleaning, inspection, and simple repairs are bundled robotically (service models change)
- (+) [Utilities] → spares inventories shift toward robot-compatible tools and fixtures (workflow standardizes)
- (+) [Contractors] → remote expert oversight scales across many sites (scarce skill stretches farther)
- (–) [Safety regulators] → proximity rules for human-robot work at live equipment are codified (deployment formalizes)
- (–) [Labor markets] → entry-level field roles shrink while supervisory roles grow (career ladders change)
- (–) [Vendors] → a few platform ecosystems dominate task libraries and updates (digital lock-in risk)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Soft and bio-inspired robots help in narrow but meaningful niches: delicate inspection, confined-space maintenance, contaminated environments, and handling irregular components. The benefits are real for safety and labor, yet the deployment surface is smaller than for drones or general-purpose robots. The impact is therefore material but bounded, around the €10–100M range.

**Weak signals (5):**

- (+) [Confined energy assets] → internal inspections shift to soft robots in tanks and ducts (access improves safely)
  - (+) [Hazardous maintenance] → contamination-prone tasks adopt compliant manipulators (human exposure falls)
  - (+) [Cable/pipe infrastructure] → serpentine inspection devices appear in O&M contracts (hidden spaces become visible)
  - (–) [Utilities] → soft robots remain niche tools, not standard fleets (impact stays bounded)
  - (–) [Certification bodies] → specialized safety standards emerge only for select tasks (adoption stays vertical)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART is particularly relevant for offshore wind, subsea cables, hydro, geothermal, pipelines, and inaccessible terrain where continuous human presence is expensive or dangerous. Second-order effects include longer maintenance windows, lower travel dependencies, and more centralized expert control, alongside higher reliance on autonomous-failure management. That combination plausibly reaches the €100M–1B band in avoided downtime, travel cost, and safety incidents.

**Weak signals (8):**

- (+) [Offshore wind] → subsea cable inspections move from crewed vessels to autonomous vehicles (weather windows widen)
- (+) [Hydro and dams] → underwater surveys become higher-frequency and lower-cost (asset visibility improves)
- (+) [Remote grids] → autonomous ground robots handle routine right-of-way checks (travel burden falls)
- (+) [Geothermal and pipelines] → autonomous platforms take over hazardous sampling routes (specialist scarcity eases)
- (+) [Emergency response] → disaster damage mapping shifts to autonomous fleets first (restoration accelerates)
- (–) [Regulators] → unsupervised-operation approvals are granted around critical energy assets (governance moves)
- (–) [Cybersecurity teams] → vehicle command and map integrity become a critical risk area (autonomy enlarges attack surface)

- (–) [Workforce] → more field roles move to remote supervision hubs (geography of work changes)

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Robot-readable sites, docking points, standardized access zones, and shared coordination layers can materially lower the cost of robotic O&M in energy systems. But this mostly matters if autonomy is already scaling; on its own it is an enabling layer. The impact is therefore material but bounded unless autonomous maintenance becomes widespread across grids and energy plants.

**Weak signals (5):**

- (+) [New substations] → layouts include robot docks, markers, and safe lanes (sites become autonomy-ready)
  - (+) [Wind/solar parks] → EPC specs add machine-readable access infrastructure (retrofit burden falls)
  - (+) [Utilities] → maintenance depots procure shared robot-support equipment (ecosystem begins forming)
  - (–) [Legacy assets] → retrofit costs stall autonomy-support upgrades at older sites (brownfield friction persists)
  - (–) [Standards bodies] → site-readiness certification emerges for robotic O&M (infrastructure becomes formal)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The energy-supply relevance is narrow: persistent inspection robots, remote sensors, or temporary emergency support around critical assets. That can solve a niche servicing bottleneck, but it does not materially change generation, storage, or distribution economics at society scale. The impact remains concrete but limited.

**Weak signals (4):**

- (+) [Transmission corridor monitoring] → trials use beamed power for persistent aerial inspection (service interval extends)
  - (+) [Remote sites] → sensor/robot packages specify line-of-sight recharging options (maintenance niche forms)
  - (–) [Utilities] → no grid-planning documents treat power beaming as a supply asset (core linkage weak)
  - (–) [Safety regulators] → constraints keep deployment near experimental zones (use remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART has a useful but narrow role in climbing inspection robots for panels, blades, towers, tanks, and smooth industrial surfaces. That can shave cost and risk from maintenance, yet it does not materially alter the energy-supply operating model. The likely impact stays below the material anchor.

**Weak signals (4):**

- (+) [Wind blade inspection] → climbing robots displace rope-access teams on select tasks (hazard falls locally)
- (+) [Solar facades/tanks] → dry-adhesion service tools appear in maintenance catalogs (surface access improves)
- (–) [Asset owners] → adoption remains task-specific, not fleet-wide (impact stays niche)
- (–) [Safety codes] → no broad infrastructure standards reference dry-adhesion robotics (mainstream pull absent)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Its main energy relevance is faster iteration and localized production of specialized components: power-electronics housings, flow parts, heat-exchange geometries, sensor-integrated spares, and repair parts for distributed assets. That helps deployment speed and resilience, but it is still a supporting industrial capability rather than a primary energy-supply architecture. The impact fits the material anchor, not the transformative one.

**Weak signals (5):**

- (+) [Energy equipment OEMs] → spare-part catalogs shift to printable digital inventories (logistics shorten)
- (+) [Field maintenance] → remote assets print non-critical replacement parts locally (downtime drops)
- (+) [Power-electronics suppliers] → integrated thermal/electrical designs move into production (performance improves)
- (–) [Certifiers] → printed energy components face slow approval pathways (qualification becomes bottleneck)
- (–) [Utilities] → use stays focused on niche spares, not mainstream hardware (impact remains bounded)

Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 06.038 - Digital Twin & Simulation-Driven Production

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Because the energy transition depends on scaling turbines, batteries, power electronics, and fuel systems, better manufacturing twins can materially reduce ramp-up delays and quality losses in energy equipment supply chains. Still, the effect is one step removed from the GVN's operating model. The plausible impact is material via faster equipment availability, but not itself transformative for how energy is supplied.

**Weak signals (5):**

- (+) [Battery/inverter factories] → production changes are validated in live twins before rollout (ramp-up risk falls)
  - (+) [Energy OEMs] → yield and downtime improvements become a sales differentiator (manufacturing quality matters)
  - (+) [Public support programs] → domestic energy-tech scaling funds require digital twins (policy links manufacturing to energy)
  - (–) [Legacy plants] → retrofit difficulty keeps adoption uneven across suppliers (benefits stay patchy)
  - (–) [Utilities] → operator procurement rarely rewards twin-enabled manufacturing directly (linkage stays indirect)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 06.039 - Reconfigurable & Agile Factories

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Reconfigurable factories matter by easing shortages and demand swings for energy-transition equipment such as batteries, chargers, heat-pump components, sensors, and power electronics. That improves supply resilience and innovation speed, but mostly through manufacturing-system flexibility rather than core energy operations. The impact is material, especially under volatile equipment demand, yet still indirect to the GVN.

**Weak signals (5):**

- (+) [Energy equipment makers] → plants switch between adjacent product families with short retool times (supply responsiveness rises)
  - (+) [Governments] → resilience policies fund modular local production of key energy components (domestic capacity matters)
  - (+) [EPC projects] → lead-time volatility falls for balance-of-system components (deployment timing improves)
  - (–) [Certification bodies] → each reconfiguration still triggers lengthy requalification (agility hits governance wall)
  - (–) [Small suppliers] → capex barriers limit agile-factory benefits to larger firms (market concentration grows)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 06.040 - Circular & Sustainable Manufacturing

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART directly affects the political economy of energy supply by reducing virgin-material dependence for batteries, power electronics, magnets, composites, and other transition hardware. It strengthens social acceptability, supply security, and cost stability while shifting value toward recovery, refurbishment, and material-recapture actors. At system scale, reduced material volatility and lower waste-handling burdens can plausibly reach the €100M–1B band.

**Weak signals (8):**

- (+) [Battery and turbine supply chains] → recycled-content requirements enter procurement contracts (virgin dependence weakens)
- (+) [Utilities] → end-of-life plans become part of project financing packages (lifecycle risk priced early)
- (+) [Local industry] → waste streams are recast as feedstock in energy-tech clusters (circular loops localize)
- (+) [Regulators] → digital product passports are required for major energy components (traceability becomes operational)
- (+) [Communities] → opposition shifts from extraction to processing-site impacts (externalities move location)
- (–) [Material quality teams] → performance drift from recycled streams becomes a visible issue (quality control matters)
- (–) [Incumbent importers] → virgin-material traders lobby against recycled quotas (distributional conflict rises)
- (–) [Insurers/certifiers] → warranty terms start differentiating virgin and circular inputs (trust infrastructure forms)

## ART 06.041 - Bio-fabrication technologies

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

Bio-fabrication is important in health and biomaterials, but it has no strong direct pathway to the energy-supply goal in this GVN. Possible spillovers through specialty materials are too indirect to clear the threshold. The linkage is therefore too weak for a non-zero score.

**Weak signals (3):**

- (+) [Energy-material labs] → bioprinted bio-based separators or membranes enter power-device research (would create a niche)
  - (+) [Building materials] → biomanufactured thermal materials appear in energy retrofits (would create a niche)
  - (–) [Utilities/OEMs] → no energy procurement language references bio-fabrication (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 06.042 - 4D Printed & Programmable Materials

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The main energy value lies in self-deploying, self-adjusting, or self-protecting components for thermal systems, building envelopes, solar orientation, and harsh-site equipment. Those gains are material where maintenance is sparse or conditions change rapidly, but the deployment surface remains limited relative to the full energy system. This supports a score of 3 rather than 5.

**Weak signals (5):**

- (+) [Building energy retrofits] → adaptive facades/vents move from demo to procurement specs (passive control matters)
- (+) [Solar/thermal systems] → shape-changing elements reduce manual adjustment needs (maintenance burden drops)
- (+) [Remote assets] → self-protecting components are marketed for harsh environments (site access matters)
- (–) [Certification] → dynamic-material behavior becomes a new approval hurdle (governance catches up)
- (–) [Asset owners] → use clusters in specialty applications, not commodity hardware (impact remains bounded)

Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Faster fabrication of specialized parts can reduce downtime and prototyping delays for energy equipment, but this is a narrow manufacturing-side benefit. It does not materially reshape generation, storage, or distribution economics on its own. The impact is concrete but limited.

**Weak signals (4):**

- (+) [Maintenance depots] → urgent fluidic or sealing parts are produced volumetrically onsite (repair delay shrinks)
- (+) [Energy OEM prototypes] → test cycles for custom components compress sharply (design iteration speeds)
- (–) [Qualification teams] → printed parts remain confined to non-critical classes (core impact limited)
- (–) [Utilities] → spare strategies still center on inventory, not fast local production (adoption remains niche)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

## ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The energy relevance is real but bounded: better antennas, compact communications, sensing, and some wave-control functions for remote assets and industrial sites. It can lower hardware bulk and improve reliability in hard-to-cover environments, but it does not directly change the main energy conversion or storage pathways. The likely magnitude is material rather than transformative.

**Weak signals (5):**

- (+) [Remote energy assets] → low-profile high-gain antennas enter standard packages (coverage improves in harsh sites)
  - (+) [Substations and plants] → reflective surfaces are retrofitted to remove dead zones (digital reliability rises)
  - (+) [Monitoring systems] → compact wave-control optics appear in sensing hardware (measurement quality improves)
  - (–) [Procurement] → uptake stays in communications/sensing subsystems, not core plant hardware (impact bounded)
  - (–) [Vendors] → performance claims depend on narrow conditions, limiting broad standardization (deployment remains selective)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 07.045 - Room-Temperature Superconductors

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

If reliable and deployable, this ART changes how energy can be transmitted, stored, and converted: lower losses, denser cables, smaller high-current equipment, stronger magnets, and easier integration of advanced generators and storage. Second-order effects include large stranded-asset risks for parts of the existing grid hardware base, major shifts in grid siting and urban network design, and new supply dependencies for superconducting materials. That is a transformative change to how the GVN goal is realised and can plausibly exceed the >€1B anchor, but it is not a 20 because the energy transition can proceed without it.

**Weak signals (9):**

- (+) [Transmission planners] → urban cable projects start comparing superconducting routes seriously (network design changes)
- (+) [Grid operators] → loss-reduction plans shift from software to conductor replacement (hardware rethink begins)
- (+) [Fusion/SMR vendors] → magnet and balance-of-plant designs are rewritten around ambient superconductors (new plant architectures open)
- (+) [Industrial sites] → high-current process users sign pilots for compact superconducting links (space constraints ease)
- (+) [Substation OEMs] → protection and fault-current designs are reworked for denser conductors (system rules adapt)
- (–) [Incumbent equipment suppliers] → write-down risk appears for conventional cable and transformer lines (stranded assets surface)

- (–) [Material supply chains] → governments treat superconductor inputs as strategic materials (geopolitics intensifies)
- (–) [Safety regulators] → new rules target quench/fault behavior in ambient systems (risk envelope changes)
- (–) [Tariff regimes] → recovery rules shift where lower losses alter cost-allocation debates (pricing politics follows)

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

These materials directly improve cable insulation, seals, coatings, blades, housings, and building-envelope components whose failure drives maintenance cost and outages. Second-order effects include longer warranty periods, lower insurance risk, and slower replacement cycles, which alter supplier economics and labor demand. Across the energy asset base, avoided downtime and longer service life can plausibly reach the €100M–1B band.

**Weak signals (8):**

- (+) [Cable and connector suppliers] → self-healing insulation enters medium-voltage product lines (failure rates can fall)
- (+) [Wind OEMs] → blade/coating warranties lengthen due smart-polymer uptake (lifecycle economics shift)
- (+) [Storage systems] → seals and thermal barriers advertise self-repair cycles (safety margins widen)
- (+) [Building retrofits] → smart membranes are sold on energy and maintenance savings together (demand-side value grows)
- (+) [Insurers] → reduced premiums follow materials with verified self-healing performance (risk becomes priced)
- (–) [Recyclers] → mixed smart-polymer chemistries complicate end-of-life handling (circularity tension appears)
- (–) [Certifiers] → long-duration proof requirements slow adoption in critical assets (evidence burden rises)
- (–) [Procurement] → buyers shift from lowest upfront cost to lifecycle metrics (market logic changes)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART is central to several challenger-regime pathways: electrolysis, synthetic fuels, fuel processing, corrosion control, lower-friction equipment, cleaner heat exchange, and surface durability across renewable and storage assets. It improves both conversion efficiency and asset longevity, while also shifting value toward catalyst/coating IP owners and away from legacy process intensity. The total effect can exceed the >€1B anchor because it changes both operating costs and the feasibility of new energy-conversion chains.

**Weak signals (9):**

- (+) [Electrolyzer and fuel-synthesis vendors] → performance jumps come from catalyst revisions, not just scaling (chemistry becomes the bottleneck lever)
- (+) [Thermal plants and industry] → retrofit programs center on coatings that cut fouling/corrosion (legacy assets regain efficiency)
- (+) [Offshore wind/solar] → anti-fouling and anti-corrosion coatings enter warranty language (maintenance burden drops)
- (+) [Hydrogen hubs] → catalyst replacement schedules become a key operating KPI (consumables gain strategic weight)
- (+) [Fuel distributors] → surface-treated storage/transport assets handle harsher synthetic fuels (new molecules become practical)
- (–) [Strategic materials policy] → rare catalyst inputs get supply-security treatment (resource dependency rises)
- (–) [OEM competition] → value shifts from plant integrators to catalyst/coating specialists (power in supply chain moves)
- (–) [Safety regulators] → coating degradation monitoring enters inspection rules (surface failure becomes systemic)
- (–) [Recycling sector] → spent catalyst recovery markets expand rapidly (waste becomes valuable feedstock)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

HEAs and advanced metals matter in high-temperature, high-pressure, corrosive, and fatigue-intensive energy environments: turbines, geothermal wells, reactors, hydrogen systems, and power electronics packaging. They reduce maintenance cycles and expand the feasible operating envelope of clean-energy hardware. That can plausibly reach the €100M–1B band, though the effect is concentrated in critical equipment classes rather than the whole operating model.

**Weak signals (8):**

- (+) [Geothermal and reactor vendors] → tender specs call for advanced alloy components (operating envelope widens)
- (+) [Hydrogen equipment] → embrittlement-resistant alloys become a differentiator (fuel systems harden)
- (+) [Wind/turbomachinery] → higher-temperature or lighter designs enter service (performance ceiling rises)
- (+) [Asset financiers] → lifetime assumptions improve for harsh-environment plants (bankability strengthens)
- (+) [Maintenance teams] → replacement intervals extend in corrosive service (downtime falls)
- (–) [Supply chains] → strategic-element content drives national-security scrutiny (materials politics intensifies)
- (–) [Machine shops] → fabrication/joining capability becomes a bottleneck (skills shift upstream)
- (–) [Certifiers] → long reliability trials delay scaling in nuclear/critical assets (qualification stays slow)

## ART 07.049 - Advanced COCapture Materials for Climate Mitigation

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Advanced capture materials matter in three ways: lowering emissions from legacy thermal assets, supplying carbon feedstock for Power-to-X pathways, and broadening politically acceptable decarbonization strategies. They do not automatically create a new energy architecture, but they materially change transition options, asset lives, and siting politics. That is a significant €100M–1B scale effect where capture is tied to heat, fuels, or industrial-energy nodes.

**Weak signals (8):**

- (+) [Thermal and industrial sites] → capture retrofits shift from bespoke systems to cartridge/module logic (deployment simplifies)
- (+) [Power-to-X hubs] → carbon-source contracts reference advanced sorbent performance (feedstock chain stabilizes)
- (+) [Project finance] → legacy plants win extensions only with capture pathways (asset life becomes conditional)
- (+) [Carbon markets] → capture-quality monitoring gets standardized around material performance (verification deepens)
- (+) [Local politics] → opposition shifts from plant closure to CO<sub>2</sub> transport/storage concerns (transition conflict moves)
- (–) [Energy balances] → regeneration energy demand becomes a visible planning issue (capture competes with supply)
- (–) [Sorbent supply chains] → utilities secure replacement media as strategic consumables (operational dependence grows)
- (–) [Regulators] → safety/waste rules tighten around sorbent degradation and disposal (end-of-life matters)

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

These composites affect energy supply through lighter, stronger, more fatigue-resistant blades, structures, tanks, cables, and monitored components, plus some gains in conductivity and embedded sensing. They support larger wind machines, lighter storage vessels, longer-lived assets, and better condition monitoring. The likely societal impact is significant but not system-keystone: €100M–1B is plausible across major equipment classes.

**Weak signals (8):**

- (+) [Wind OEMs] → larger blades rely on nano-reinforced composite recipes (capture area expands)
- (+) [Hydrogen storage vendors] → lighter vessels with embedded damage sensing enter the market (storage safety improves)
- (+) [Grid components] → structural parts start self-reporting strain through conductive composites (inspection burden drops)

- (+) [Offshore assets] → corrosion-protection strategies shift toward composite-heavy designs (maintenance mix changes)
- (+) [EPC projects] → transport and installation constraints ease for large components (logistics costs fall)
- (–) [Workplace safety] → nanoparticle handling rules tighten in manufacturing and repair (production complexity rises)
- (–) [Recyclers] → end-of-life recovery routes lag behind deployment (waste governance tightens)
- (–) [Supply chains] → premium materials concentrate value in specialist suppliers (component power shifts)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART changes energy supply by reducing and reshaping demand at scale in buildings, industry, storage, and thermal networks. Lower peaks, smoother loads, less waste-heat loss, and better passive control reduce how much generation, network capacity, and backup the system must build. Because the GVN goal includes supplying buildings and industrial processes, this is a transformative demand-side change that can clearly exceed the >€1B anchor and affect everyday life broadly.

**Weak signals (9):**

- (+) [Building codes] → adaptive insulation and phase-change materials enter mainstream compliance paths (demand profile changes)
- (+) [District heat networks] → thermal buffering materials displace some active balancing equipment (passive flexibility rises)
- (+) [Industrial heat users] → retrofit packages sell thermal materials as capacity deferral (peak demand falls)
- (+) [Utilities] → network reinforcement plans credit thermal-material demand reductions (planning assumptions shift)
- (+) [Households] → comfort and bill savings are marketed together in upgrades (consumer adoption broadens)
- (+) [Insurers] → overheating/fire-risk models explicitly include new thermal materials (risk framework adapts)
- (–) [Landlords/tenants] → benefit-sharing disputes appear around passive energy savings (distribution conflict emerges)
- (–) [Regulators] → performance-verification standards tighten after quality-drift cases (measurement becomes central)
- (–) [Supply chains] → premium thermal materials become strategic retrofit inputs (new bottlenecks appear)

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

Rare-earth-free magnets directly affect wind turbines, motors, generators, pumps, compressors,

EVs, heat pumps, and many balance-of-system components critical to an electrified energy system. Their biggest systemic value is reducing exposure to geopolitical concentration and enabling faster, more politically resilient deployment. That makes the impact transformative at the system level and plausibly above the >€1B anchor, even though the transition is not strictly impossible without them.

**Weak signals (9):**

- (+) [Wind and motor OEMs] → designs shift to magnet chemistries with lower strategic-material exposure (deployment risk falls)
- (+) [Public procurement] → supply-security criteria favor rare-earth-light equipment (policy changes buying logic)
- (+) [Heat pump/EV supply chains] → long-term contracts move toward alternative magnet families (electrification bottleneck eases)
- (+) [Grid equipment makers] → contingency inventories diversify away from rare-earth dependence (resilience planning changes)
- (+) [Project finance] → material-risk stress tests improve for magnet-diversified designs (bankability strengthens)
- (–) [Performance engineering] → larger system redesigns are needed to offset magnet differences (cost moves elsewhere)
- (–) [Incumbent suppliers] → lobbying intensifies around standards and test methods (market power is contested)
- (–) [Recycling sector] → magnet recovery markets bifurcate by chemistry class (circular flows reorganize)
- (–) [Trade policy] → strategic-stockpile behavior shifts from rare earths to alternative inputs (geopolitics rebalances)

## **ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination**

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The strongest link is through the water-energy nexus: hydrogen production, thermal plant cooling, geothermal, and remote or arid-area energy projects all benefit from lower-energy water treatment. That is material in specific geographies and project classes, but not a primary system driver for the whole GVN. The impact therefore fits the €10–100M band unless water constraints become a dominant cap on energy expansion.

**Weak signals (5):**

- (+) [Hydrogen projects] → water-treatment energy intensity becomes a decisive siting metric (water starts constraining energy)
- (+) [Arid-region solar/geothermal] → desalination is bundled into plant designs more often (project feasibility widens)
- (+) [Remote communities] → microgrids co-deploy desalination and power assets (shared infrastructure value rises)
- (–) [Permitting] → concentrate disposal, not membrane efficiency, remains the key blocker (system effect stays bounded)



- (–) [Utilities] → membrane advances stay in water budgets, not core power-planning assumptions (linkage remains partial)  
Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART directly upgrades the nervous system of an electrified energy economy: inverters, converters, chargers, motor drives, HVDC links, storage interfaces, and protection equipment all benefit. Smaller, cooler, faster, and more efficient power conversion materially changes how distributed renewables, storage, mobility, and industrial electrification are built and operated. That is a transformative operating-model effect with plausible >€1B scale.

**Weak signals (9):**

- (+) [Inverter vendors] → next product generations market efficiency and size jumps from new modules (conversion hardware steps up)
- (+) [Grid planners] → substation footprints shrink in designs using higher-frequency conversion (space constraints ease)
- (+) [Fast-charging and storage] → thermal-management requirements fall for comparable power levels (site economics improve)
- (+) [HVDC and interconnection projects] → converter upgrades shift feasibility of long links (network architecture broadens)
- (+) [Industrial electrification] → high-power drives become easier to retrofit in constrained sites (electrification spreads)
- (–) [Supply chains] → defect-free wafer access becomes a strategic bottleneck (materials concentration appears)
- (–) [Safety/standards] → new failure and thermal-cycling tests are added to certification (qualification adapts)
- (–) [Incumbent silicon suppliers] → asset write-down risk grows in legacy module lines (stranded manufacturing appears)
- (–) [Recyclers] → new device chemistries complicate end-of-life electronics treatment (waste system lags)

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Safe, dense, lower-pressure hydrogen storage materially improves the practicality of local hydrogen use, backup systems, distributed Power-to-X, and remote or off-grid energy autonomy. It especially affects the GVN's independence and security-of-supply values by making hydrogen less infrastructure-heavy and less hazardous to handle. The likely effect is significant, plausibly in the €100M–1B band, but still complementary to broader generation and conversion choices.

**Weak signals (8):**

- (+) [Industrial users] → onsite hydrogen storage shifts from cylinders/tanks to material cartridges (handling risk falls)

- (+) [Microgrids] → hydrogen backup systems appear where batteries alone are insufficient (duration economics improve)
- (+) [Fuel logistics] → transport and warehousing rules are revised for solid-storage modules (infrastructure burden drops)
- (+) [Emergency power] → resilient facilities procure safer hydrogen reserves for long outages (backup diversification grows)
- (+) [OEMs] → storage modules are sold with digital state-of-charge diagnostics (operations become more predictable)
- (–) [Thermal integration] → heat management for release becomes a visible balance-of-system issue (system complexity remains)
- (–) [Materials supply] → specific hydride/porous media inputs gain strategic importance (new bottlenecks emerge)
- (–) [Codes and standards] → safety classes differentiate solid and gaseous hydrogen systems (regulatory pathways diverge)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

Fusion would reintroduce a new kind of dense, low-carbon firm generation and high-temperature heat, directly affecting cost, security of supply, and sustainability. It would also reshape institutions: centralization could strengthen some incumbents, long-lived assets would be revalued, and demand-side flexibility needs would change if firm supply expands. That is transformative in how the GVN goal is realised and can plausibly exceed the >€1B anchor, but it is not a keystone because alternative clean-system architectures exist.

**Weak signals (9):**

- (+) [National energy plans] → firm low-carbon capacity scenarios start including fusion explicitly (planning horizon shifts)
- (+) [Industrial heat users] → offtake discussions include future fusion-based heat/electricity supply (new customer class appears)
- (+) [Grid planners] → transmission and siting studies treat fusion as anchor generation (network expectations change)
- (+) [Talent pipelines] → utilities and EPC firms create fusion operations tracks (institutional preparation starts)
- (+) [Finance] → infrastructure-style financing terms appear for first commercial plants (bankability emerges)
- (–) [Incumbent thermal/nuclear fleets] → asset extension choices change around future fusion competition (stranded-asset risk rises)
- (–) [Security regulators] → fusion-specific remote maintenance and materials regimes are codified (new safety state forms)
- (–) [Public politics] → land/water/host-community debates shift from emissions to siting and resilience (acceptability reconfigures)
- (–) [Supply chains] → superconducting and specialty-material bottlenecks shape deployment calendars (new dependencies matter)

## ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

SMRs materially change the energy mix by making firm low-carbon electricity and heat deployable in smaller units, including industrial clusters and some district-heating contexts. Second-order effects include stronger nuclear-grade supply chains, different regional cost politics, new security obligations, and potential crowding-out of some decentralized alternatives. The likely impact is transformative and plausibly above the >€1B anchor if even a limited national fleet is built.

**Weak signals (9):**

- (+) [Industrial clusters] → heat and power decarbonization studies start listing SMRs as core options (firm heat becomes credible)
- (+) [District heating systems] → urban heat plans compare SMRs with electrification/geothermal (heat architecture shifts)
- (+) [Nuclear supply chains] → factory-module capacity becomes a national industrial policy target (serial production logic appears)
- (+) [Utilities] → siting and workforce teams are reorganized around modular deployment (project model changes)
- (+) [Capital markets] → investors price learning-curve assumptions from repeat builds (economics hinge on series)
- (–) [Community politics] → regional cost-equality debates intensify around host and non-host areas (distribution conflict rises)
- (–) [Security regimes] → digital and physical protection rules expand for smaller distributed plants (governance burden grows)
- (–) [Renewables/storage developers] → market outlooks factor in SMR competition for firming value (portfolio strategies shift)
- (–) [Waste/decommissioning policy] → back-end responsibilities become a bigger public debate (long-tail liabilities remain)

## ART 08.058 - Thin-film solar cells

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART directly supports the challenger regime's shift toward embedded, local generation by turning roofs, facades, vehicles, and infrastructure surfaces into energy assets. That changes who can produce power, where generation can be placed, and how much the system depends on centralized buildout and dedicated land. The resulting shift in everyday buildings and local autonomy can plausibly exceed the >€1B anchor, though it is not scored 20 because decentralized generation can still grow through other solar pathways.

**Weak signals (9):**

- (+) [Building materials market] → solar surfaces are bought as envelope products, not specialist energy add-ons (integration normalizes)
- (+) [Local governments] → permitting rules treat solar facades/skins as standard building upgrades (friction falls)

- (+) [Households and landlords] → retrofit packages bundle energy generation with façade renewal (adoption piggybacks on maintenance)
- (+) [Distribution grids] → more generation appears on non-roof surfaces and vertical planes (siting geography broadens)
- (+) [Community energy] → shared-property and urban projects use surfaces previously considered unusable (participation widens)
- (+) [Insurance and finance] → solar-output assumptions enter building valuations and mortgages (energy becomes property value)
- (–) [Incumbent utilities] → revenue erosion from self-generation intensifies tariff redesign pressure (cost-recovery politics sharpen)
- (–) [Waste/recycling systems] → surface-integrated PV creates new end-of-life building-material streams (circularity challenge appears)
- (–) [Aesthetics/preservation disputes] → heritage and streetscape conflicts rise with integrated PV (social acceptability rebalanced)

## ART 08.059 - Bionic Leaf Technology

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART matters because it collapses some of the gap between sunlight capture and fuel production, supporting distributed molecule-making rather than only centralized electricity production. That directly serves the GVN's interest in synthetic fuels and reduced reliance on the electricity grid, while also shifting value toward modular chemical-surfaces and local fuel users. The likely effect is significant but not yet system-linchpin, placing it in the €100M–1B band.

**Weak signals (8):**

- (+) [Remote/off-grid sites] → fuel supply studies compare bionic-leaf panels with electrolyzer chains (local molecules become credible)
- (+) [Agricultural and transport users] → distributed liquid-fuel pilots appear near point of use (grid dependence loosens)
- (+) [Building-integrated energy] → façade/roof systems are assessed for chemical as well as electric output (surface value broadens)
- (+) [Safety codes] → small-scale reactive-product handling rules are drafted for distributed systems (deployment pathway forms)
- (+) [Project finance] → modular fuel-output guarantees are insured like generation assets (bankability emerges)
- (–) [Water and feedstock access] → siting rules tie panel productivity to water/carbon inputs (resource coupling remains)
- (–) [Utilities] → metering and market rules struggle to classify solar-chemical output (institutional fit lags)
- (–) [Incumbent fuel distributors] → partnerships or resistance emerge around local synthetic-fuel production (channel conflict grows)

## ART 08.060 - Grid-Scale Energy Storage

**Score: 20** (Impact in GVN 5)

**Justification (3–5 sentences):**

This is a keystone of the challenger regime. Without large-scale storage, high shares of variable

renewables, resilient microgrids, and low-curtailment local generation become much costlier, more fragile, and politically harder to sustain. Storage directly changes dispatch, network investment, tariff design, peaker-plant economics, and household/industrial expectations, with powerful third-order feedbacks as more storage enables more renewables and more renewables raise storage value; that comfortably supports a >€1B, weekly-life-at-scale impact.

### Weak signals (10):

- (+) [Capacity markets] → multi-hour and multi-day products become separate, valued classes (duration gets priced)
- (+) [Transmission planners] → storage is approved instead of some wires upgrades (architecture starts changing)
- (+) [Renewable portfolios] → curtailment falls despite higher solar/wind penetration (surplus is absorbed)
- (+) [Industrial users] → behind-the-meter storage PPAs move from resilience niche to mainstream (onsite autonomy rises)
- (+) [Retail tariffs] → households see stronger arbitrage and backup value from storage (everyday energy behavior changes)
- (+) [Emergency planning] → critical services require islandable storage-backed power as standard (resilience becomes normal)
- (+) [Thermal peakers] → write-downs or lower running hours are tied to storage buildout (incumbents lose role)
- (–) [Safety regulators] → storage-specific siting, fire, and incident-reporting regimes tighten (risk management scales)
- (–) [Critical-mineral policy] → recycling and offtake deals become utility strategy, not OEM detail (resource politics intensify)
- (–) [Market power] → a few large storage aggregators gain leverage over balancing prices (new concentration risk)

## ART 08.061 - Solid-State Batteries

**Score: 10** (Impact in GVN 5)

### Justification (3–5 sentences):

Safer, denser batteries materially change where storage can be placed, how much cooling and protection it needs, and how widely electrified transport and buildings can participate in the energy system. This affects not only vehicles but also homes, commercial sites, microgrids, and backup power, creating strong second-order effects in insurance, permitting, and flexibility markets. The total impact is transformative and plausibly above the >€1B anchor.

### Weak signals (9):

- (+) [Building-integrated storage] → safety rules allow batteries in more valuable indoor/urban locations (siting constraints ease)
- (+) [EV fleets] → larger usable capacity becomes available for managed charging and V2X (transport-storage coupling deepens)
- (+) [Microgrids] → battery-only resilience designs replace some hybrid backup systems (duration/safety calculus shifts)
- (+) [Insurers] → premium gaps open between solid-state and liquid-electrolyte systems (risk re-priced)

- (+) [Fire codes] → spacing and containment rules are revised around lower thermal-runaway risk (permitting accelerates)
- (–) [Manufacturing] → interface-quality and yield become the new bottleneck in deployment scale (production risk moves)
- (–) [Recycling sector] → collection and process standards are rewritten for new chemistries (end-of-life system must adapt)
- (–) [Incumbent suppliers] → legacy Li-ion assets face write-down pressure (technology turnover accelerates)
- (–) [Distribution grids] → planners assume more behind-the-meter storage participation than before (control complexity rises)

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 20** (Impact in GVN 5)

**Justification (3–5 sentences):**

This is another keystone of the challenger regime because it converts variable renewable electricity into storable, transportable molecules for industry, transport, seasonal balancing, and local autonomy. It directly supports the GVN's stated move toward synthetic fuels and reduced dependence on centralized electricity grids, while also reshaping pipelines, ports, industrial clusters, carbon accounting, and cross-border trade. If deployed at meaningful scale, the total impact clearly exceeds >€1B and restructures everyday energy and industrial supply chains.

**Weak signals (10):**

- (+) [Renewables developers] → projects are financed with co-located electrolysis or synthesis, not grid export alone (molecules become core outlet)
- (+) [Industrial heat/feedstock users] → long-term offtake contracts shift from fossil molecules to certified green ones (demand hardens)
- (+) [Ports and logistics hubs] → storage, bunkering, and conversion infrastructure enter mainstream capex (energy geography changes)
- (+) [Grid operators] → excess-renewable planning assumes flexible hydrogen load as balancing demand (sector coupling becomes systemic)
- (+) [Carbon accounting] → origin and intensity certification become commercially decisive (traceability becomes infrastructure)
- (+) [Rural/remote sites] → local fuel production is considered instead of stronger grid extension (independence logic strengthens)
- (–) [Water policy] → siting conflicts emerge where electrolysis competes with other water uses (resource politics intensify)
- (–) [Pipeline/gas incumbents] → repurposing battles and asset write-down debates accelerate (stranded-asset conflict rises)
- (–) [Safety regulators] → hydrogen-handling norms expand from industrial niche to broad infrastructure layer (governance load grows)
- (–) [Power markets] → large electrolysis buyers gain price-setting leverage during surplus periods (new market power emerges)

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**



Wind remains a core large-scale renewable supply pathway, and higher-efficiency turbines directly change generation costs, siting economics, maintenance regimes, and network planning. Second-order effects include larger offshore industrial clusters, new materials dependencies, different land/sea politics, and more pronounced balancing needs. At national scale this is clearly transformative and plausibly above the >€1B anchor, though not a unique keystone because other renewable routes also exist.

#### Weak signals (9):

- (+) [Project developers] → repowering plans dominate new capacity growth (hardware efficiency beats greenfield expansion)
- (+) [Offshore grids] → transmission planning assumes larger unit sizes and farther-from-shore projects (spatial logic shifts)
- (+) [Composite/material suppliers] → blade-section logistics and repair capability become strategic (maintenance industrializes)
- (+) [Wind PPAs] → capture-price assumptions improve due better control and output profiles (economics strengthen)
- (+) [Condition monitoring] → embedded sensing becomes standard to protect larger assets (uptime becomes data-driven)
- (–) [Local politics] → acceptance debates intensify around project scale even as turbine counts fall (social license reconfigures)
- (–) [Ports and vessels] → installation infrastructure becomes the real bottleneck (system dependency shifts)
- (–) [Balancing markets] → stronger wind buildout increases demand for storage/flexibility products (feedback to system architecture)
- (–) [End-of-life systems] → blade disposal and recycling become a visible governance issue (waste becomes strategic)

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score: 3** (Impact in GVN 5)

#### Justification (3–5 sentences):

The strongest energy-supply value is for remote, temporary, military/civil-emergency, islanded, or hard-to-cable situations rather than mainstream bulk supply. That can materially improve resilience and access in selected contexts, but it is not likely to reorganize the dominant supply model for a 5.5M-person society. The impact is therefore material but bounded.

#### Weak signals (5):

- (+) [Emergency power planning] → beam-based power appears in resilience exercises for isolated sites (temporary supply niche forms)
  - (+) [Remote industry/microgrids] → feasibility studies compare wireless transfer to cabling/fuel logistics (distance barrier is tested)
  - (+) [Defense-civil infrastructure] → dual-use transmitter/receiver sites are proposed near critical assets (resilience pull emerges)
  - (–) [Grid planners] → mainstream network plans do not treat beamed power as bulk supply (core linkage remains weak)
  - (–) [Safety and spectrum rules] → approvals stay narrow and site-specific (scaling remains constrained)
- Signal density: LOW (linkage moderate; additional signals would be speculative).



## ART 08.065 - Advanced geothermal technology

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

Advanced geothermal can provide firm low-carbon electricity and high-grade heat with a much broader geographic footprint than conventional geothermal, directly affecting security of supply, district heat, and industrial decarbonization. It also changes the political economy of energy independence by substituting a domestic subsurface resource for imported fuels or some variable renewable balancing needs. That is a transformative operating-model shift with plausible >€1B scale if multiple sites are developed.

**Weak signals (9):**

- (+) [Heat-intensive industry] → site-selection studies start treating deep heat as a core utility (industrial energy logic shifts)
- (+) [District heating systems] → long-term decarbonization plans include superhot rock options (heat architecture broadens)
- (+) [Grid planners] → geothermal is modeled as firm regional anchor power (balancing assumptions change)
- (+) [Drilling supply chains] → high-temperature tooling and casing capacity expands locally (industrial capability forms)
- (+) [Finance] → reservoir-risk sharing and insurance instruments mature (bankability improves)
- (–) [Seismic governance] → induced-seismicity monitoring becomes central to licensing and public consent (social acceptability becomes decisive)
- (–) [Water and land rights] → subsurface-use conflicts increase where projects cluster (governance complexity rises)
- (–) [Legacy fuel suppliers] → local firm heat threatens existing gas and thermal market roles (incumbent resistance grows)
- (–) [Regulators] → subsurface data access becomes a contested strategic asset (information power matters)

## ART 08.066 - Resilient microgrids

**Score: 20** (Impact in GVN 5)

**Justification (3–5 sentences):**

Resilient microgrids are a keystone of the challenger regime because they operationalize local autonomy, distributed renewables, storage, and flexible consumption into a workable system. They directly change how energy is produced, balanced, priced, and governed at site, district, and community level, while also generating third-order feedbacks: once critical sites and communities succeed with microgrids, political support and vendor ecosystems strengthen rapidly. In a 5.5M-person society, widespread microgrid deployment can easily exceed the >€1B anchor and alter weekly everyday energy experience for hundreds of thousands.

**Weak signals (10):**

- (+) [Critical services] → hospitals, waterworks, and telecom sites require islandable local power by default (resilience baseline changes)

- (+) [Municipalities] → new districts are planned around local generation-storage-control bundles (urban energy logic shifts)
- (+) [Industrial parks] → shared microgrids are financed as infrastructure, not side projects (local balancing institutionalizes)
- (+) [Retail tariffs] → customers pay for resilience and islanding capability, not kWh alone (value model broadens)
- (+) [Distribution operators] → interconnection rules distinguish microgrids from passive customers (governance changes)
- (+) [Community energy] → cooperatives gain operational control roles, not just ownership shares (power distribution changes)
- (–) [Incumbent utilities] → cost-recovery disputes intensify as more users partly exit one-way supply (tariff politics harden)
- (–) [Cybersecurity teams] → many small control domains create a larger defensive surface (attack surface decentralizes)
- (–) [Equipment vendors] → bundled microgrid stacks risk creating new closed ecosystems (interoperability becomes political)
- (–) [Inequality watchdogs] → affluent sites gain resilience faster than vulnerable ones (energy security stratifies)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The plausible link is through engineered feedstocks, microbes, and biomass traits that improve bioenergy or reduce materials/resource pressure elsewhere in the system. That is real but indirect, and not central to the challenger regime described here. The likely impact remains below the material anchor unless edited organisms become a major energy-feedstock or materials route.

**Weak signals (4):**

- (+) [Bioenergy crop R&D] → edited varieties target drought, yield, or composition for energy uses (would strengthen direct link)
  - (+) [Industrial biotech] → editing programs explicitly target fuel molecules or process enzymes (conversion pathway opens)
  - (–) [Energy plans] → gene editing remains absent from mainstream supply scenarios (linkage stays weak)
  - (–) [Public acceptance] → food/agri regulation blocks energy-use deployment routes (scale remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 09.068 - mRNA Therapies & Vaccines

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

There is no meaningful direct pathway from mRNA therapeutics to energy generation, storage, conversion, or distribution in this GVN. Any effect would be broad societal health spillover, not an

energy-supply impact. That does not justify a non-zero score here.

**Weak signals (3):**

- (+) [Biomanufacturing energy demand] → regional power plans explicitly respond to major mRNA production loads (would create an indirect link)
  - (+) [Cold-chain energy systems] → utilities build dedicated supply for mRNA manufacturing clusters (would create an indirect link)
  - (–) [Energy-sector strategy] → no supply pathway depends on mRNA platforms (no direct linkage)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART affects energy supply mainly through demand reallocation: more controlled-environment production can shift food energy use from land-intensive biological systems toward electricity- and heat-intensive industrial systems, while also changing land availability for solar/wind and methane/fertilizer dynamics. Those second- and third-order effects can be material, but they sit outside the direct energy operating layer. The score therefore stays at 3.

**Weak signals (5):**

- (+) [Utility load forecasts] → food-biotech clusters become visible new demand centers (industrial electricity load rises)
  - (+) [Land-use planning] → agricultural land release is linked to renewable siting options (energy-space tradeoff changes)
  - (+) [Heat recovery systems] → cultured-food plants sign for low-carbon process heat (new customer class forms)
  - (–) [Energy planners] → effect stays regional and clustered, not systemwide (impact remains bounded)
  - (–) [Policy debates] → power-price scrutiny rises around energy-intensive food production (cross-sector politics emerge)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART has no strong direct pathway to the core energy-supply goal. Possible spillovers through materials or testing infrastructure are too indirect and weak for this GVN.

**Weak signals (3):**

- (+) [Battery/fuel-cell R&D] → organoid platforms are unexpectedly used to test energy-toxicity exposures for workforce safety (would create an indirect niche)
- (+) [Biomaterials] → tissue-engineering methods spin out energy-relevant membranes or scaffolds (would create a niche)

- (–) [Energy-sector plans] → no procurement or policy linkage appears (linkage absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART can materially affect fuels, carbon utilization, low-temperature chemical production, waste-to-value pathways, and some energy materials. It directly supports alternative conversion pathways and indirectly changes feedstock dependence, siting logic, and the balance between centralized petrochemical systems and modular bio-based production. The impact is significant but not clearly a single system keystone, fitting the €100M–1B band.

**Weak signals (8):**

- (+) [Waste and biogas streams] → engineered microbes upgrade low-value carbon into higher-value fuels/chemicals (conversion efficiency rises)
- (+) [Power-to-X ecosystems] → biohybrid routes compete with purely electrochemical routes (technology portfolio widens)
- (+) [Industrial parks] → fermentative energy-chemical production is co-sited with low-carbon power (new cluster logic emerges)
- (+) [Fuel standards] → bio-derived synthetic molecules gain clearer certification paths (market access improves)
- (+) [Rural economies] → distributed bio-conversion plants appear near feedstock sources (value localizes)
- (–) [Biosecurity regulators] → containment and traceability requirements intensify (governance burden rises)
- (–) [Incumbent petrochemical actors] → lobbying targets classification of bio-based energy molecules (market-entry politics sharpen)
- (–) [Utilities] → power demand from biotech conversion becomes a planning variable (cross-sector coupling deepens)

## ART 09.072 - Microbiome Engineering

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The main energy relevance is through biogas systems, waste treatment, soil-carbon interactions, biofouling control, and agricultural inputs to bioenergy. Those are niche but concrete pathways, not broad system drivers in this GVN. The likely impact remains below the material anchor.

**Weak signals (4):**

- (+) [Biogas operators] → microbiome-control packages are sold as yield stabilizers (digester performance becomes tuneable)
- (+) [Water/heat systems] → microbiome management is used to reduce fouling or contamination (maintenance niche opens)
- (–) [Power-system planning] → microbiome engineering stays absent from mainstream energy scenarios (linkage remains weak)

- (–) [Regulation] → interventions face high ecological scrutiny, limiting scale (deployment stays niche)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

Precision medicine changes healthcare, not energy supply. Any effect on workforce capability or biotech electricity demand is too indirect to count as meaningful GVN impact here.

**Weak signals (3):**

- (+) [Health-biotech campuses] → genomic diagnostics clusters create large new power loads (would create an indirect link)
- (+) [Critical workforce health] → energy operators use genomic monitoring for extreme-environment staffing (would create a tiny labor niche)
- (–) [Energy policy] → no core supply pathway depends on precision medicine (linkage absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

There is no strong direct pathway from this ART to the energy-supply operating model. Possible spinouts are too speculative and indirect for a non-zero score.

**Weak signals (3):**

- (+) [Materials R&D] → biohybrid chips are used in energy-material discovery workflows (would create indirect relevance)
- (+) [Safety testing] → energy-chemical exposure screening adopts organs-on-chips (would create a niche)
- (–) [Utilities/OEMs] → no operational or procurement linkage appears (linkage absent)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The pathway is indirect via workforce availability, skill retention, and perhaps higher long-run energy demand from older populations with longer active lives. Those are worth watching but not central to energy supply transformation. The effect remains below the material anchor unless labor scarcity becomes the dominant limiting factor in deployment and maintenance.

**Weak signals (4):**

- (+) [Energy employers] → aging-workforce strategies start pricing biomedical performance support (labor scarcity becomes acute)
  - (+) [Retirement-age field experts] → retention programs expand in critical maintenance roles (human capital matters)
  - (–) [System planners] → demand and supply models largely ignore longevity effects (linkage stays weak)
  - (–) [Public debate] → longevity policy is treated separately from energy infrastructure planning (cross-sector link remains thin)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 - Engineered Living Materials

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Engineered living materials can matter to energy supply through self-healing building envelopes, carbon-sequestering construction, moisture-managing materials, and lower-temperature repair/formation processes. They directly support sustainability and can cut maintenance and embodied-energy burdens, especially in buildings and long-lived infrastructure. The aggregate effect is significant but not a sole system linchpin, fitting the €100M–1B band.

**Weak signals (8):**

- (+) [Building retrofits] → living/self-repairing materials are sold on both energy and maintenance savings (dual value strengthens adoption)
- (+) [District infrastructure] → crack-sealing or moisture-managing materials enter long-life civil assets (service life extends)
- (+) [Carbon accounting] → materials with verifiable long-lived CO<sub>2</sub> uptake gain project-credit value (sustainability monetizes)
- (+) [Remote sites] → low-maintenance living materials are preferred where repair access is costly (site economics improve)
- (+) [Public procurement] → embodied-carbon criteria start favoring regenerative materials (buying logic shifts)
- (–) [Safety/certification] → biological stability and survivability become central approval questions (governance burden rises)
- (–) [Maintenance practice] → operators need new routines for activation/conditioning, not just replacement (labor changes)
- (–) [Public acceptance] → “living infrastructure” triggers debate about control and failure modes (social acceptability tested)

## ART 09.077 - Gene Drive Pest Control

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The most plausible relevance is protecting biomass/feedstock yields, rights-of-way, or disease/pest vectors affecting energy crops and some field labor. That is real but niche relative to the overall GVN. The effect remains below the material anchor unless biomass-based supply becomes far more central than assumed.

**Weak signals (4):**

- (+) [Bioenergy crop regions] → pest-control debates explicitly reference feedstock security (would strengthen direct linkage)
  - (+) [Transmission corridor management] → biological control is explored for invasive vegetation/pest issues (niche O&M route opens)
  - (–) [Energy planners] → gene drive remains absent from mainstream supply portfolios (linkage stays weak)
  - (–) [Ecological governance] → high controversy slows any energy-adjacent deployment (scaling remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART has no meaningful direct pathway to the energy-supply goal, infrastructure, or operating model. Any indirect demographic effects are too speculative and remote for a non-zero GVN impact.

**Weak signals (3):**

- (+) [Biotech campuses] → large reproductive-technology clusters create notable local power demand (would create only an indirect link)
  - (+) [Demographic planning] → energy-demand forecasts begin explicitly incorporating this technology (would create a long-range link)
  - (–) [Energy strategy] → no supply pathway depends on artificial wombs or synthetic embryos (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART improves energy supply through resilient connectivity, remote asset management, weather and earth observation, and faster post-disruption situational awareness. Those effects are especially important for rural assets, offshore projects, interconnections, and emergency restoration, and they also redistribute power toward actors controlling the space layer. The combined value can plausibly reach the €100M–1B band.

**Weak signals (8):**

- (+) [Remote wind/solar and grid assets] → routine O&M assumes satellite backhaul and imagery (distance penalty falls)
- (+) [Storm response] → utilities use constellation data for rapid damage triage (restoration accelerates)
- (+) [Weather-dependent generation] → forecast products increasingly integrate space-based sensing directly (dispatch quality improves)



- (+) [Microgrids] → islanded sites procure space-based connectivity as part of resilience packages (communications become utility-like)
- (+) [Cross-border coordination] → shared observation improves interconnector and weather-risk management (regional planning strengthens)
- (–) [Critical infrastructure security] → dependency on a few constellation providers enters risk registers (platform concentration grows)
- (–) [Regulators] → energy-resilience planning begins requiring independent communications paths beyond terrestrial networks (governance adapts)
- (–) [Space policy] → orbital congestion or service outages are treated as energy-security concerns (cross-domain dependency matures)

## ART 10.080 - Space Resource Utilization (SRU)

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Its only plausible energy pathway is future material supply for strategic metals used in clean-energy hardware. That is highly indirect and unlikely to matter materially within the operating logic of this GVN unless terrestrial material constraints become severe and SRU becomes commercially real. The score therefore stays at 1.

**Weak signals (4):**

- (+) [Critical-mineral policy] → energy-transition material strategies explicitly mention off-world sources (would deepen the link)
  - (+) [Magnet/battery supply chains] → long-term procurement discussions consider SRU outputs (would create direct relevance)
  - (–) [Energy OEMs] → no near-term design or sourcing choices depend on SRU (linkage remains weak)
  - (–) [Finance] → energy investors treat SRU as speculative, not infrastructure-relevant (impact stays remote)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

Although conceptually related to closed-loop utility management, this ART is not meaningfully tied to the terrestrial energy-supply GVN. Spillovers to remote habitats or submarines do not amount to a clear societal energy impact here.

**Weak signals (3):**

- (+) [Extreme remote sites] → polar/mining energy bases adopt direct life-support spin-offs (would create a niche)
  - (+) [Microgrids] → vendors market habitat-style integrated utility loops for isolated communities (would create a niche)
  - (–) [Energy planning] → no mainstream supply pathway references life-support technology (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

HAPs can materially improve outage response, remote sensing, communications resilience, and weather or line monitoring over large territories. That helps security of supply and operational coordination, but mainly as an enabling surveillance and communications layer rather than a core supply technology. The likely impact is material but bounded.

**Weak signals (5):**

- (+) [Storm-prone grids] → utilities contract temporary HAP coverage for restoration and comms (response capability broadens)
- (+) [Remote generation] → persistent aerial sensing improves forecast and asset-visibility quality (situational awareness rises)
- (+) [Emergency planners] → HAPs enter black-start and disaster communication plans (resilience toolkit widens)
- (–) [Airspace governance] → restricted corridors and permits slow routine energy use (scaling stays partial)
- (–) [Utilities] → most adoption remains event-driven rather than continuous (impact stays bounded)

Signal density: LOW (linkage moderate; additional signals would be speculative).

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

The strongest energy pathway is trusted coordination among many actors who do not fully trust one another: peer-to-peer trading, flexibility settlement, origin certification, equipment provenance, and community energy governance. Second-order effects include new intermediaries, new financialization risks, and shifts in bargaining power from incumbent retailers toward platform operators or cooperatives. The overall impact is significant and plausibly in the €100M–1B band, but not a physical-system linchpin.

**Weak signals (8):**

- (+) [Peer-to-peer energy markets] → real settlement moves from pilots to recurring community operations (trusted local trading scales)
- (+) [Guarantees of origin] → tamper-evident certificate rails enter mainstream renewable contracts (traceability becomes operational)
- (+) [Flexibility markets] → small DER assets are paid through automated rules, not manual reconciliation (transaction costs fall)
- (+) [Community energy] → shared ownership and voting rights are encoded digitally (governance becomes programmable)
- (+) [Cross-border energy products] → trust layers reduce reconciliation between many counterparties (coordination friction drops)

- (–) [Regulators] → fraud, consumer-protection, and market-manipulation cases increase scrutiny (governance tightens)
- (–) [Platform operators] → “decentralized” services recentralize around wallets/oracles and major nodes (power reconcentrates)
- (–) [Energy poverty advocates] → access gaps widen where participation requires new digital literacy/tools (inclusion risk appears)

## ART 11.084 - Platform Cooperatives & Fair Work

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The main energy relevance is through community energy ownership, distributed maintenance workforces, and fairer digital coordination of local services. That can materially improve social acceptability and participation, but it does not by itself transform generation or storage architecture. The likely impact is therefore material but bounded.

**Weak signals (5):**

- (+) [Community energy] → co-op software begins handling member tariffs, voting, and payouts (local ownership becomes administratively easier)
  - (+) [Installer/maintenance labor] → cooperative platforms coordinate local energy-work marketplaces (labor access broadens)
  - (+) [Municipal energy projects] → procurement favors member-governed digital platforms (governance model matters)
  - (–) [Capital access] → growth stalls where co-ops cannot fund infrastructure expansion (scale constraint persists)
  - (–) [Incumbent platforms] → dominant marketplaces imitate co-op features without ownership transfer (power remains centralized)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Energy systems increasingly depend on sharing data across utilities, DER owners, OEMs, buildings, markets, and public authorities, and open data marketplaces can materially lower the friction of that exchange. This improves forecasting, flexibility participation, maintenance, and investment decisions while also changing who controls and monetizes energy information. The likely system effect is significant, plausibly €100M–1B.

**Weak signals (8):**

- (+) [Utilities and aggregators] → machine-readable energy datasets are bought and sold under standard terms (data becomes tradable infrastructure)
- (+) [Small actors] → community or SME participants gain paid access to high-quality forecasts/benchmarks (information asymmetry narrows)
- (+) [OEMs] → equipment-performance data is increasingly monetized rather than hidden (aftermarket power shifts)

- (+) [Regulators] → compute-to-data arrangements are approved for market monitoring and planning (privacy-safe exchange matures)
- (+) [Investors] → asset valuation increasingly depends on third-party operational data feeds (capital markets datafy)
- (–) [Market power] → a few exchanges dominate terms and schemas for critical datasets (data gatekeepers emerge)
- (–) [Privacy disputes] → granular energy-use data triggers stronger consent and purpose limits (trust remains contested)
- (–) [Liability] → disputes over dataset quality and stale feeds become common (governance hardens)

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

The pathway to energy supply is mainly around crisis coordination, public communication, and community organization rather than generation or operations. That matters in outages and contested infrastructure debates, but the direct system impact is limited. Hence the score stays at 1.

**Weak signals (4):**

- (+) [Blackout response] → utilities and municipalities rely on resilient community channels during outages (coordination niche strengthens)
  - (+) [Community energy groups] → organizers shift to secure platforms for project governance (local trust infrastructure improves)
  - (–) [Grid operations] → core control and market layers remain separate from social platforms (direct linkage stays weak)
  - (–) [Adoption] → use stays event-driven rather than embedded in daily energy operations (impact remains limited)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.087 - Collective Open Innovation Networks

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

These networks can materially accelerate energy-technology problem solving, standards formation, and cross-organizational experimentation. That supports innovation culture and deployment speed, but it remains an indirect capability rather than a direct energy-supply architecture. The impact is therefore material but bounded.

**Weak signals (5):**

- (+) [Energy challenge platforms] → utilities and OEMs post operational bottlenecks openly with shared test data (problem-solving broadens)
- (+) [Public R&D] → challenge-based collaboration becomes a standard route for storage/grid issues (innovation process changes)
- (+) [SMEs] → smaller firms win energy-sector pilots through network participation (entry barriers fall)

- (–) [IP disputes] → open collaboration slows where value-capture rules stay unclear (governance limits scale)
  - (–) [Utilities] → critical OT problems remain too sensitive for open-network treatment (impact stays partial)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 11.088 - Scalable Decentralized Governance

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART can help community microgrids, local energy markets, pooled storage, and shared infrastructure make binding decisions without heavy manual administration. That matters institutionally, but it remains one layer beneath the physical energy system and mainly affects governance costs and participation models. The likely impact is material yet bounded.

**Weak signals (5):**

- (+) [Community microgrids] → routine tariff, capex, and access rules are managed through digital governance stacks (administrative friction falls)
  - (+) [Shared storage/assets] → voting and revenue distribution become automated and auditable (trust barrier lowers)
  - (+) [Municipal utilities] → participatory budgeting for local energy is formalized digitally (citizen role increases)
  - (–) [Manipulation concerns] → identity and voting integrity disputes slow adoption (governance remains fragile)
  - (–) [Regulators] → binding decisions still require conventional legal wrappers (institutional fit remains partial)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Workforce bottlenecks are a major inhibitor of faster energy transition, especially for installers, maintainers, operators, and safety-critical specialists. Scalable learning and portable credentialing directly reduce those bottlenecks and indirectly redistribute opportunity away from a few incumbent training channels. The likely impact is significant and plausibly in the €100M–1B band through faster deployment and reduced delays.

**Weak signals (8):**

- (+) [Installers and technicians] → time to certify for new energy technologies falls sharply (labor pipeline widens)
- (+) [Utilities] → digital credentials are accepted for contractor onboarding and access rights (skills become portable)
- (+) [Rural regions] → remote learning reduces dependence on travel-intensive training centers (geographic access improves)
- (+) [New technologies] → course updates track fast-moving standards for storage, hydrogen, and microgrids (adaptation speeds up)

- (+) [Workforce planning] → utilities forecast capacity using credential-flow data (training becomes infrastructure)
- (–) [Credential quality] → employers demand stronger anti-fraud and practical-testing layers (trust must be built)
- (–) [Labor markets] → large platforms gain leverage over skill verification and reputation (new gatekeepers appear)
- (–) [Unions/professions] → incumbent qualification systems resist rapid modular credentialing (distribution conflict emerges)

## ART 11.090 - Prediction-Market Forecasting Platforms

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

Prediction markets can materially improve investment timing, demand/weather expectations, outage-risk assessment, and policy scenario discipline in energy supply. Their strongest effects are institutional and decision-support based rather than physical. The likely impact is material but bounded unless these forecasts become embedded in operational markets and planning routines at scale.

**Weak signals (5):**

- (+) [Energy planners] → forecasts from internal markets are tracked against official scenarios (collective judgment gets priced)
  - (+) [Utilities and traders] → capital and hedging decisions cite calibrated market probabilities (decision process changes)
  - (+) [Public policy] → infrastructure agencies test prediction markets for permit, cost, or build-time risks (coordination quality improves)
  - (–) [Manipulation controls] → access rules and settlement disputes become central design issues (governance burden rises)
  - (–) [Operators] → real-time operations still rely on conventional forecasting stacks (impact remains bounded)
- Signal density: LOW (linkage moderate; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 10** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART is foundational for a distributed energy system because smart inverters, meters, chargers, storage units, heat systems, sensors, and building controls must interoperate if flexibility and local autonomy are to scale. It changes how the GVN goal is realised by lowering integration cost, reducing vendor lock-in, and making millions of small assets controllable as part of one system. The resulting effect is transformative and plausibly above the >€1B anchor.

**Weak signals (9):**

- (+) [DER procurement] → devices must expose common telemetry/control profiles to qualify (interoperability becomes gatekeeping)
- (+) [Utilities] → integration projects shrink from custom engineering to configuration work (transaction costs collapse)
- (+) [Households/buildings] → customers can switch service providers without replacing hardware (market power rebalances)
- (+) [Aggregators] → mixed-vendor portfolios scale faster than single-OEM stacks (competition broadens)
- (+) [Regulators] → interconnection codes reference standard device identities and update paths (compliance becomes uniform)
- (+) [Cybersecurity teams] → baseline secure-update and revocation rules become universal (security-by-default rises)
- (–) [Incumbent vendors] → proprietary ecosystems resist or mimic open profiles selectively (lock-in conflict sharpens)
- (–) [Legacy fleets] → retrofit burden becomes a visible cost-inequality issue (old hardware is stranded digitally)
- (–) [Market operators] → richer device coordination raises accountability and privacy questions (data governance intensifies)

## ART 12.092 - Interoperable Digital Twin Ecosystems

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Interoperable twins materially improve coordination across utilities, OEMs, EPCs, operators, and regulators by making asset state, assumptions, and interventions portable rather than siloed. That affects planning, maintenance, outage response, and cross-organization accountability, especially in a more complex distributed system. The likely impact is significant and plausibly in the €100M–1B band.

**Weak signals (8):**

- (+) [Grid operators and OEMs] → twin data is exchanged across vendor boundaries without rebuilds (coordination friction drops)
- (+) [Maintenance planning] → intervention rehearsals use shared twin packages, not static drawings (downtime risk falls)
- (+) [Regulators] → compliance evidence is pulled from live twin histories (auditability improves)
- (+) [Insurance/finance] → asset risk models begin consuming twin-based condition data (capital allocation changes)
- (+) [DER portfolios] → planners combine network and building twins for local flexibility decisions (planning granularity deepens)
- (–) [Liability disputes] → disagreements center on whose twin was authoritative (governance must mature)
- (–) [Cloud/platform power] → a few twin ecosystems control schemas and update paths (data power concentrates)
- (–) [Legacy assets] → poor sensorization limits benefits to newer infrastructure first (capability gap appears)



## ART 12.093 - Global Supply Chain Traceability Networks

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Energy transition hardware increasingly depends on contested claims about origin, carbon intensity, labor conditions, and handling, while outages and quality failures demand better root-cause visibility. Traceability networks materially improve procurement trust, certification, recycling, and risk management across fuels, batteries, magnets, solar, and grid equipment. The total effect is significant and plausibly in the €100M–1B band.

**Weak signals (8):**

- (+) [Battery, magnet, and solar procurement] → origin and custody data become tender pass/fail criteria (provenance becomes commercial)
- (+) [Utilities] → root-cause investigations use shared product histories across suppliers (failure analysis speeds up)
- (+) [Green-fuel markets] → carbon-intensity and origin claims are machine-verifiable end to end (buyer trust strengthens)
- (+) [Recycling sector] → end-of-life component passports improve material recovery rates (circularity becomes operable)
- (+) [Public procurement] → socially/environmentally sensitive inputs require traceability evidence (social acceptability hardens)
- (–) [Small suppliers] → compliance costs rise faster than margins (market concentration risk grows)
- (–) [Data disputes] → actors fight over selective disclosure and commercial secrecy (governance tightens)
- (–) [Counterfeit control] → enforcement shifts from customs/manual checks to digital evidence (institutional routines change)

## ART 12.094 - Personal Data Portability & Trust Frameworks

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART matters because flexible tariffs, home energy optimization, mobility-energy coupling, and provider switching increasingly depend on user data moving safely across actors. That materially lowers friction in retail innovation and participation, but it does not by itself change the physical supply architecture. The impact is therefore material but bounded.

**Weak signals (5):**

- (+) [Retail energy switching] → customers can port usage/device histories to new providers easily (competition strengthens)
- (+) [Home energy platforms] → consent dashboards become standard for sharing battery/EV/building data (trust barrier lowers)
- (+) [Demand-response markets] → user permission receipts are machine-verifiable across services (participation becomes portable)
- (–) [Consumer protection] → scams and poor recovery flows slow trust in data wallets (adoption remains uneven)

- (–) [Utilities] → many legacy billing systems cannot consume portable data cleanly (integration remains partial)  
Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 12.095 - Interoperable Digital Currency Payment Networks

**Score: 3** (Impact in GVN 5)

**Justification (3–5 sentences):**

The main energy pathway is smoother settlement for peer-to-peer trading, cross-border balancing, machine-to-machine charging/flexibility, and small-value local energy transactions. That can materially reduce coordination cost, but it remains a financial-enablement layer rather than a direct supply technology. The likely impact is material but bounded.

**Weak signals (5):**

- (+) [Peer-to-peer energy trading] → low-value automated settlements move into routine operation (transaction friction falls)
- (+) [EV charging/flexibility] → machine-to-machine payment flows become viable across providers (automation broadens)
- (+) [Cross-border balancing] → faster settlement rails are tested for small flexible resources (market entry improves)
- (–) [Regulators] → compliance and identity requirements blunt some decentralization gains (governance remains heavy)
- (–) [Utilities] → mainstream billing still dominates most customer relationships (impact remains partial)  
Signal density: LOW (linkage moderate; additional signals would be speculative).

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Energy transitions are often slowed by tariffs, interconnection rules, safety codes, permitting, and compliance logic that must be interpreted manually and differently across actors. Rules-as-code can materially cut that friction, speed updates, lower legal uncertainty, and make new energy-service models easier to scale. The effect is significant and plausibly in the €100M–1B band through faster deployment and lower coordination cost.

**Weak signals (8):**

- (+) [Interconnection processes] → utilities publish executable rule packages alongside guidance text (queue friction falls)
- (+) [Tariff innovation] → new retail/flexibility products are tested against machine-readable constraints quickly (product cycles speed up)
- (+) [Permitting] → automated pre-checks reduce time lost to avoidable application errors (deployment lead times shrink)
- (+) [Small developers] → compliance costs fall because specialist interpretation is partly automated (access broadens)
- (+) [Regulators] → versioned rule changes propagate into market software with less delay (policy responsiveness improves)

- (–) [Legal disputes] → conflicts arise over encoded interpretation vs legislative intent (accountability is contested)
- (–) [Large incumbents] → firms with better policy-engineering teams gain advantage in rule exploitation (capability inequality grows)
- (–) [Cybersecurity teams] → rule engines themselves become critical infrastructure to protect (governance becomes digital)

## ART 12.097 - Open Metaverse Interoperability Protocols

**Score: 0** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART has no strong direct pathway to the energy-supply operating model. At most it might support visualization or training, which is too weak and substitutable to matter meaningfully at GVN level.

**Weak signals (3):**

- (+) [Grid planning/training] → immersive energy-control environments begin depending on open metaverse protocols (would create a niche)
  - (+) [Community engagement] → virtual hearings for energy projects rely on interoperable 3D spaces (would create a niche)
  - (–) [Energy operations] → no core market/control systems depend on metaverse protocols (linkage absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 - Content Authenticity Infrastructure

**Score: 1** (Impact in GVN 5)

**Justification (3–5 sentences):**

Its main relevance is protecting trust in visual evidence, public communication, inspection imagery, and incident documentation around energy assets and projects. That matters, especially in politically contested infrastructure decisions, but it remains secondary to the core supply model. The effect is concrete yet limited.

**Weak signals (4):**

- (+) [Inspection workflows] → authenticated photo/video chains become accepted evidence in maintenance and claims (proof gets harder to fake)
  - (+) [Public project communication] → provenance labels are used to counter manipulated siting content (trust defense improves)
  - (–) [Utilities] → operational control systems remain largely unaffected by authenticity tooling (direct linkage weak)
  - (–) [Public attention] → adoption follows misinformation incidents rather than routine practice (impact stays episodic)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 - Privacy-Preserving Collaboration Protocols

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

Energy systems need joint computation across utilities, regulators, buildings, OEMs, and mobility actors, but data-sharing barriers are high. Privacy-preserving collaboration materially improves planning, fraud detection, flexibility aggregation, and sensitive-system coordination without forcing raw-data centralization. That directly supports both system efficiency and social acceptability, plausibly reaching the €100M–1B band.

**Weak signals (8):**

- (+) [Utilities and regulators] → joint analytics run without central data pooling (coordination friction falls)
- (+) [DER and building operators] → shared flexibility models are computed over protected datasets (small-actor participation improves)
- (+) [Cross-border interconnectors] → sensitive operational data is analyzed collaboratively under cryptographic controls (regional coordination strengthens)
- (+) [Market monitoring] → manipulation detection improves without broad raw-data exposure (trust and oversight improve)
- (+) [Consumer-facing services] → richer optimization is offered without full data surrender (social license improves)
- (–) [Performance costs] → latency and compute overhead become a visible deployment bottleneck (economics remain nontrivial)
- (–) [Platform power] → a few secure-compute providers control collaboration infrastructure (new gatekeepers emerge)
- (–) [Audit disputes] → stakeholders contest privacy guarantees and output limits (governance must mature)

## ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

**Score: 5** (Impact in GVN 5)

**Justification (3–5 sentences):**

This ART materially affects energy supply because new hardware classes—batteries, inverters, hydrogen systems, microgrid stacks, advanced materials—scale only when buyers, insurers, regulators, and operators trust their performance claims. Stronger standards and certification shorten qualification cycles, reduce integration risk, and lower the political friction of adopting challenger technologies. That is a significant €100M–1B lever even though it is not itself a generation or storage technology.

**Weak signals (8):**

- (+) [Utilities and EPCs] → procurement increasingly references certified conformance suites, not bespoke tests (adoption friction falls)
- (+) [New energy hardware] → time from prototype to approved field deployment shrinks materially (innovation reaches market faster)
- (+) [Insurers and financiers] → underwriting relies on standardized machine-readable certificates (risk pricing stabilizes)

- (+) [Smaller vendors] → passing common test suites becomes a route into mainstream tenders (market access broadens)
- (+) [Regulators] → approval pathways align around recognized conformance evidence (governance becomes clearer)
- (–) [Standards politics] → dominant firms try to lock in favorable test regimes (market power fights intensify)
- (–) [Global supply chains] → uneven mutual recognition creates certification bottlenecks across jurisdictions (scaling remains uneven)
- (–) [Legacy equipment] → older assets fail new conformance expectations and lose market value (digital/physical stranding appears)

## GVN 6: Materials ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

Score: 5 (Impact in GVN 6)

Justification: Mature global connectivity would make remote mines, quarries, forests, scrapyards, and decentralized processing sites manageable as part of one live materials system. First-order, it reduces outages, travel delays, and coordination frictions; second-order, it shifts bargaining power toward connected platforms and can also reinforce remote extractive regimes by making old supply geographies easier to run. Third-order, it accelerates local secondary-material markets and remote expertise networks that make decentralized production more credible. In a 5.5M-person society, the combined effects on downtime, logistics, and market visibility plausibly sit in the €100M–1B range, so 5.

Weak signals (8):

- (+) Reliability of supply → remote quarries and recycling parks buy satellite-plus-mesh backup links (reduces outage stoppages)
- (+) Limited expertise → equipment vendors bundle remote diagnostics into materials contracts (moves scarce skills remotely)
- (+) Local economic growth → rural depots join live materials trading platforms (makes local stock visible)
- (+) Sustainability → secondary-material exchanges require always-on inventory feeds (improves reuse matching)
- (+) Adequate quality → field sites begin remote video-assisted process support (cuts lab travel delays)
- (–) Preservation of existing structures → incumbents use connectivity to deepen remote extraction control (can entrench old regime)
- (+) Regulatory alignment → permits start accepting continuous remote monitoring from sites (normalizes distributed oversight)
- (–) Security → material-site shutdowns are traced to telecom failures or cyberattacks (reveals network dependence)

## ART 01.002 - Ultra-Low Latency Networks

Score: 3 (Impact in GVN 6)

Justification: This mainly matters where material handling, sorting, refining, and hazardous-site robotics need stable closed-loop control rather than just bandwidth. Directly it enables remote control of time-critical equipment; institutionally it favors firms that can afford edge-compute zones and vendor-certified networks; over time it can shift some dangerous manual work off-site while creating new cyber-safety exposure. Assuming deployment around major ports, recycling parks, and process plants, the impact is more likely in the €10–100M / multi-million-hour range than sector-wide transformation, so 3.

Weak signals (7):

- (+) Process enhancement → sorter and refinery pilots specify millisecond network guarantees (enables remote closed-loop control)
- (+) Reliability of supply → ports co-locate edge nodes with critical material lines (protects throughput)
- (+) Minimization of adverse effects → hazardous interventions move to remote operations rooms (reduces worker exposure)
- (+) Regulatory alignment → safety cases cite deterministic network performance for approvals (opens remote operations)
- (–) Existing investments → only flagship plants deploy latency-guaranteed zones at first (slows broad diffusion)
- (–) Bargaining power → telecom-cloud bundles tie factories to proprietary edge stacks (raises switching costs)
- (–) Security → jitter or spoofing incidents trigger investigations in automated yards (turns latency into safety issue)

## ART 01.003 - Edge AI for Sensor Data

Score: 5 (Impact in GVN 6)

Justification: Edge AI can make dirty, noisy materials environments machine-readable without needing constant cloud links. First-order, it improves inline quality control, sorting, anomaly detection, and site safety; second-order, it lowers dependence on scarce experts but shifts authority toward model owners and sensor vendors; third-order, it can accelerate circular flows by making secondary materials more trustworthy and tradable. That is large enough to plausibly move €100M–1B through lower waste, better uptime, and higher recovery value, so 5.

Weak signals (8):

- (+) Adequate quality → recyclers deploy on-device AI for real-time grade classification (raises trust in secondary feedstock)
- (+) Cost-effectiveness → quarry and plant operators replace manual rounds with anomaly-detection nodes (cuts inspection labor)
- (+) Minimization of adverse effects → dust, leak, and heat alerts shift from central rooms to local devices (faster hazard response)
- (+) Functionality → OEMs sell equipment with embedded defect-recognition as standard (normalizes machine judgment)

- (+) Sustainability → mixed-waste lines advertise AI-assisted contamination reduction rates (improves circular yields)
- (+) Limited expertise → smaller plants buy managed edge-AI subscriptions instead of in-house data teams (widens adoption)
- (–) Bargaining power → process data and retraining rights become contract disputes (locks value into platform vendors)
- (–) Security → adversarial or drift failures in sorting models trigger recalls or insurance reviews (exposes hidden fragility)

## ART 01.004 - Quantum & High-Precision Sensing

Score: 3 (Impact in GVN 6)

Justification: The strongest route here is better non-destructive measurement of composition, contamination, stress, and underground or hidden material conditions. Operationally that improves prospecting, quality assurance, and predictive maintenance; institutionally it can shift authority from central labs to field-grade instruments; feedback-wise it may also create dependence on a few calibration and certification providers. The impact is real but still concentrated in high-value assets and sensitive processes, so 3 fits better than 5.

Weak signals (7):

- (+) Adequate quality → recycled-metal buyers begin requiring advanced non-destructive assay data (cuts destructive sampling)
- (+) Reliability of supply → prospecting firms market gravity and magnetic precision scans for local deposits and tailings (finds overlooked resources)
- (+) Minimization of adverse effects → regulators accept continuous contaminant sensing in lieu of sparse sampling (tightens environmental control)
- (+) Process enhancement → insurers discount early-drift detection on high-consequence equipment (prices precision monitoring)
- (+) Innovation and adaptability → pilot plants use ultra-precise sensing to tune new recipes faster (speeds scale-up)
- (–) Bargaining power → calibration and service contracts concentrate around a few instrumentation firms (creates measurement dependence)
- (–) Security/dual-use → export controls or tamper cases emerge around sensitive sensing modules (can constrain access)

## ART 01.005 - Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 6)

Justification: Dense cheap sensor networks are a strong fit for the challenger regime because they turn sparse manual checking into continuous awareness of materials, machines, and structures. Directly they improve condition monitoring, stock visibility, corrosion detection, and process stability; institutionally they support insurance, certification, and product-passport regimes; feedback-wise they can also intensify worker monitoring and lock plants into particular data platforms. The likely annual effect is comfortably in the significant-impact range, so 5.

Weak signals (8):



- (+) Reliability of supply → stockyards and silos start using dense sensor patches for live inventory and moisture mapping (reduces surprise shortages)
- (+) Adequate quality → recycled-plastic and metal lines monitor many more points per batch (improves grade consistency)
- (+) Functionality → infrastructure materials ship with embedded health-monitoring networks (extends service life)
- (+) Cost-effectiveness → plants cut manual inspection rounds after sensor coverage audits (shifts labor from routine checks)
- (+) Sustainability → demolition and reuse programs require instrumented structural assessments before disposal (supports salvage over landfill)
- (+) Regulatory alignment → insurers and standards bodies begin accepting continuous condition data (changes evidence norms)
- (–) Bargaining power → integrators demand exclusive access to sensor streams and failure models (captures operational value)
- (–) Security → false positives or spoofed node clusters trigger handling or shutdown errors (tests trust in dense sensing)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

Score: 1 (Impact in GVN 6)

Justification: The main link is indirect: it can make workforce, facility, and inter-firm sensing more acceptable in materials supply chains where IP, labor trust, and legal exposure otherwise slow deployment. That matters, but privacy is not the dominant bottleneck in this GVN compared with certification, process economics, or material performance. The effect is concrete yet limited, so 1. Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → unions or works councils accept sensor deployments only with on-device anonymization (unblocks some monitoring)
- (+) Bargaining power → suppliers agree to share process metrics once raw data stays local (creates narrow collaboration route)
- (+) Regulatory alignment → industrial monitoring guidance begins favoring privacy-by-design architectures (lowers legal friction)
- (–) Existing bottlenecks → materials firms still cite cost and certification before privacy (shows secondary role)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

Score: 1 (Impact in GVN 6)

Justification: This is mostly an assurance layer for long-lived industrial control, contracts, and design data. It matters for critical infrastructure and trade secrecy, but it does not by itself shift material availability, circularity, or process economics very far. The impact is worth watching, but still limited relative to core GVN bottlenecks, so 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → critical-material plants begin upgrading control networks for long-life security (protects high-value operations)
- (+) Regulatory alignment → procurement rules for strategic materials add post-quantum communication clauses (raises assurance baseline)
- (–) Cost-effectiveness → smaller recyclers defer upgrades because cyber spend does not change recovery economics (keeps impact bounded)
- (–) Security → a major “harvest now, decrypt later” scare shifts attention to materials trade data (would strengthen linkage)

## ART 01.008 - Integrated Sensing and Communication (ISAC)

Score: 3 (Impact in GVN 6)

Justification: ISAC could turn warehouses, yards, plants, and transport corridors into always-on coarse sensing environments without separate sensor build-outs. Directly it improves asset tracking, safety, and flow visibility; institutionally it could fold materials monitoring into telecom infrastructure and procurement; feedback-wise it raises new surveillance and cybersecurity issues. That is meaningful, but still more of an enabling layer than a dominant shift in materials production itself, so 3.

Weak signals (7):

- (+) Reliability of supply → ports and depots test wireless nodes that double as tracking infrastructure (lowers sensing capex)
- (+) Cost-effectiveness → site operators cancel standalone radar/camera upgrades in favor of ISAC-capable networks (converges infrastructure)
- (+) Minimization of adverse effects → cluttered yards use radio-based motion alerts where sightlines are poor (improves safety)
- (+) Functionality → OEM dashboards begin exposing logistics-sensing outputs from communication gear (normalizes dual use)
- (+) Regulatory alignment → site-safety cases include network-derived occupancy and movement evidence (broadens accepted proofs)
- (–) Privacy/power → workers contest passive location and activity inference from the network layer (raises labor conflict)
- (–) Security → spoofing or denial incidents show shared comms-sensing dependencies (reveals common-mode risk)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 6)

Justification: These chips matter mainly because they make rich sensing and low-latency control cheaper to embed inside harsh industrial environments. Directly they support always-on inspection, anomaly detection, and robotic control at the point of action; institutionally they reduce dependence on cloud connectivity but may increase dependence on specialized chip vendors and toolchains. The result is a material, but still enabling, effect on quality, uptime, and automation economics, which fits 3.

Weak signals (7):

- (+) Adequate quality → machine-vision vendors for recyclers advertise lower-power inline inspection hardware (brings AI to more lines)
- (+) Cost-effectiveness → plants deploy always-on anomaly detection where heat and power budgets were limiting (expands edge monitoring)
- (+) Reliability of supply → remote material sites standardize on low-power edge controllers for critical assets (improves resilience)
- (+) Limited expertise → packaged industrial modules hide neuromorphic complexity behind standard APIs (widens adoption)
- (+) Sustainability → sensor networks stay active without heavy cooling or oversized power supplies (cuts monitoring overhead)
- (–) Bargaining power → specialized chip/software stacks lock plants into narrow ecosystems (raises switching costs)
- (–) Supply risk → new demand for niche chip materials creates fresh dependence patterns (shifts, not removes, bottlenecks)

## ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

Score: 3 (Impact in GVN 6)

Justification: The biggest materials-GVN effects are indirect but still meaningful: cheaper ultra-efficient electronics for sensing/control, plus new strategic dependencies around carbon, 2D, spintronic, or cryogenic device materials. First-order it lowers power and heat constraints in distributed automation; second-order it can reconfigure critical-material demand and equipment supply chains; third-order it may move bargaining power toward whoever controls next-generation chip materials and fabs. That is enough for a material impact, but not a dominant driver of the GVN, so 3.

Weak signals (7):

- (+) Process enhancement → industrial electronics roadmaps start specifying beyond-CMOS devices for harsh, low-power control (signals practical entry)
- (+) Reliability of supply → material sites adopt longer-life embedded electronics with reduced cooling needs (lowers maintenance burden)
- (+) Sustainability → automation upgrades cite lower energy per monitored asset (improves sensor economics)
- (+) Innovation and adaptability → equipment vendors redesign around denser compute near tools and sensors (tightens cyber-physical control)
- (–) Reliability of supply → critical-mineral lists expand to include new semiconductor feedstocks (creates new supply chokepoints)
- (–) Bargaining power → a few foundries capture the key production know-how (concentrates value)
- (–) Existing structures → legacy integrators delay adoption until qualification risk is absorbed by others (slows diffusion)

## ART 02.011 - Quantum Computing Platforms

Score: 3 (Impact in GVN 6)

Justification: In this GVN, quantum platforms matter most through materials discovery, supply-chain optimization, and difficult process-modeling problems. Operationally that can improve catalyst selection, substitute-material search, and complex planning; institutionally it concentrates capability in a few cloud-accessible compute providers; feedback-wise it may widen the gap between large incumbents and smaller firms unless accessed as a shared service. The effect is material but specialized, so 3.

Weak signals (7):

- (+) Innovation and adaptability → materials firms buy quantum-access subscriptions for catalyst and alloy screening (signals real design use)
- (+) Sustainability → substitution programs begin using quantum-assisted search for rare or toxic inputs (targets cleaner feedstocks)
- (+) Reliability of supply → commodity-risk teams test quantum optimization for multi-source sourcing and inventory (improves planning)
- (+) Adequate quality → pilot plants use quantum-derived recipes in qualification campaigns (moves from theory to production)
- (–) Bargaining power → access concentrates via a few cloud and pharma-style partnerships (limits broad diffusion)
- (+) Collective capability → public materials labs launch shared quantum discovery consortia (socializes scarce capability)
- (–) Existing structures → many plants continue with classical heuristics because validation burdens dominate (keeps impact bounded)

## ART 02.012 - Photonic and Optical Computing

Score: 1 (Impact in GVN 6)

Justification: The likely route here is cheaper high-throughput simulation and AI, plus lower energy use in heavy industrial data systems. That can help, but it is several steps removed from the main materials bottlenecks and competes with other general-purpose computing advances. The linkage is real but limited, so 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Innovation and adaptability → materials-modeling software starts offering photonic-accelerated versions (creates a narrow route)
- (+) Cost-effectiveness → digital-twin providers market major energy savings from optical accelerators (improves economics)
- (–) Existing bottlenecks → plants still cite process qualification, not compute cost, as the main delay (keeps linkage secondary)
- (–) Bargaining power → only hyperscale vendors deploy the capability at first (limits broad sector impact)

## ART 02.013 - Next-Gen Memory & Storage

Score: 1 (Impact in GVN 6)

Justification: Better memory and storage help with digital twins, traceability, and long-lived materials records, but they do not strongly shift how access to materials is realized. The main effect is incremental improvement in data retention and edge performance. That is worth noting, but not more than 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → asset twins for long-life infrastructure begin storing richer state histories locally (improves diagnostics)
- (+) Regulatory alignment → digital product-passport schemes require longer, denser retention of material history (raises storage demand)
- (–) Existing bottlenecks → material firms keep treating storage as cheap back-end plumbing (shows limited strategic importance)
- (–) Bargaining power → history retention becomes bundled into a few industrial cloud stacks (captures small process value)

## ART 02.014 - Molecular Computing

Score: 1 (Impact in GVN 6)

Justification: The only plausible materials route is very localized sensing-and-computation inside chemical or biological production environments. That could matter in some bio-based materials processes, but for the overall GVN it is still peripheral and highly conditional. So it stays at 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Biotechnology and biomimicry → fermentation-material pilots embed molecular logic for local process control (creates first direct route)
- (+) Minimization of adverse effects → hazardous chemistry systems test non-electronic local sensing-and-response modules (opens niche value)
- (+) Innovation and adaptability → material-science funding calls start naming molecular computing for process control (signals emerging overlap)
- (–) Existing structures → no non-lab materials firm budgets the technology as a core capability (keeps linkage weak)

# 3. Artificial Intelligence & Learning Systems

## ART 03.015 - Causal Learning & Reasoning

Score: 3 (Impact in GVN 6)

Justification: Materials systems are full of hidden interactions between recipes, impurities, equipment settings, regulations, and logistics, so causal models can reduce costly trial-and-error. Directly they improve process tuning and substitution decisions; institutionally they help justify interventions to regulators and insurers; feedback-wise they can also harden bad assumptions if

embedded models are treated as objective truth. The likely impact is material but not by itself transformative, so 3.

Weak signals (7):

- (+) Adequate quality → process teams start using counterfactual tools to explain batch failures (improves root-cause analysis)
- (+) Sustainability → material-substitution projects rank interventions by side-effect estimates, not correlations alone (reduces blind trade-offs)
- (+) Cost-effectiveness → plants test causal models before equipment or recipe changes (cuts failed experimentation)
- (+) Regulatory alignment → environmental permits cite model-based intervention logic with auditable assumptions (supports approval)
- (+) Limited expertise → software vendors package “why did yield move?” tools for non-data-scientists (widens use)
- (–) Bargaining power → proprietary causal models become a source of vendor lock-in (captures process judgment)
- (–) Security/accountability → disputes emerge when automated intervention logic misattributes causes (tests governance)

## ART 03.016 - Federated & Privacy-Preserving Learning

Score: 3 (Impact in GVN 6)

Justification: The main value is unlocking cross-firm or cross-site learning without forcing companies to hand over raw process data or IP. That can materially improve recycling quality models, predictive maintenance, and defect detection; institutionally it lowers one inhibitor to collaboration but may still privilege whoever runs the orchestration layer. The impact is meaningful, especially for fragmented SMEs, but not large enough to be a primary operating-model shift, so 3.

Weak signals (7):

- (+) Limited awareness and expertise → SMEs join shared models for sorting and maintenance without sharing raw data (lowers collaboration barrier)
- (+) Adequate quality → secondary-material processors compare local grade data through federated training consortia (improves consistency)
- (+) Reliability of supply → equipment OEMs coordinate fleet learning across client sites (raises uptime)
- (+) Regulatory alignment → data-sharing agreements shift from raw data transfer to model-update participation (changes legal structure)
- (+) Competitiveness → clusters market “shared intelligence, private data” as a sector offering (supports smaller actors)
- (–) Bargaining power → orchestration platforms claim rights over aggregated models (recentralizes value capture)
- (–) Trust/security → members contest whether updates leak proprietary process information (can stall adoption)

## ART 03.017 - Trustworthy AI Systems

Score: 3 (Impact in GVN 6)

Justification: Trustworthy AI matters because materials and construction decisions often carry safety, warranty, and environmental liability. Directly it can unlock more automation in inspection, scheduling, and process control; institutionally it makes regulators, insurers, and buyers more willing to accept AI-mediated evidence; feedback-wise it can also increase documentation burdens and favor large firms that can certify compliance. The likely effect is material but enabling, so 3.

Weak signals (7):

- (+) Regulatory alignment → certification bodies start requiring explainability and audit trails in AI-driven quality systems (raises adoption credibility)
- (+) Reliability of supply → insurers prefer monitored AI stacks with fallback modes for critical material assets (prices assurance)
- (+) Adequate quality → buyers accept AI-assisted grading only when provenance and confidence are attached (rewards trustworthy deployment)
- (+) Limited expertise → packaged “validated AI” modules appear for recycling and process control (widens adoption)
- (–) Cost-effectiveness → compliance overhead favors large incumbents over smaller circular startups (can slow challenger entry)
- (–) Bargaining power → certified model libraries become controlled by a few vendors (captures institutional trust)
- (–) Accountability → incidents reveal ambiguity over who is liable for AI-mediated material decisions (tests governance)

## ART 03.018 - Automated Machine Learning (AutoML)

Score: 3 (Impact in GVN 6)

Justification: AutoML lowers the skills barrier for building models around material quality, yield, maintenance, and logistics. First-order it speeds experimentation and deployment; second-order it lets smaller firms participate in AI adoption; third-order it can proliferate poorly understood models if guardrails are weak. That looks like a clear €10–100M class impact, but not a system keystone, so 3.

Weak signals (7):

- (+) Limited awareness and expertise → mid-sized recyclers deploy models without dedicated ML teams (reduces talent bottleneck)
- (+) Cost-effectiveness → recipe and maintenance models move from months-long projects to standard software workflows (compresses cycle time)
- (+) Adequate quality → AutoML tools become bundled with machine vision and lab systems (normalizes routine modeling)
- (+) Competitiveness → SMEs use off-the-shelf optimization to match larger incumbents on process tuning (widens capability access)
- (+) Reliability of supply → model-refresh cycles become tied to new production data automatically (improves adaptation)
- (–) Accountability → unexplained AutoML failures trigger disputes in warranty or quality cases (shows governance gap)



- (–) Bargaining power → dominant cloud vendors capture the model-building layer for industrial data (concentrates control)

## ART 03.019 - Collaborative Multi-Agent AI

Score: 5 (Impact in GVN 6)

Justification: This matters where many distributed machines, sensors, and digital agents must jointly manage material flows, sorting, maintenance, and hazardous interventions. Operationally it can turn fragmented yards, depots, and plants into coordinated systems; institutionally it favors whoever owns the orchestration layer; feedback-wise it can also amplify failure cascades when many agents share bad assumptions. The total effect on labor, uptime, and distributed circular operations is plausibly in the €100M–1B range, so 5.

Weak signals (8):

- (+) Reliability of supply → fleets of yard robots and software agents begin sharing live task queues (improves throughput)
- (+) Sustainability → distributed collection and sorting routes are optimized jointly across municipalities and recyclers (raises recovery rates)
- (+) Minimization of adverse effects → hazardous-site response shifts from lone machines to coordinated teams (reduces worker exposure)
- (+) Cost-effectiveness → warehouses and depots replace central dispatch with local agent negotiation layers (cuts coordination friction)
- (+) Limited expertise → remote supervisors manage many sites through shared agent dashboards (multiplies scarce operators)
- (–) Bargaining power → orchestration platforms demand data exclusivity and protocol control (captures system rents)
- (–) Security → one compromised node causes multi-robot miscoordination incidents (exposes cascade risk)
- (–) Existing structures → incumbent ERP vendors wrap multi-agent capability into legacy centralized stacks (can blunt decentralizing effect)

## ART 03.020 - Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 6)

Justification: The plausible route is better search over material formulations or supply plans, but that is still an indirect accelerator layered on top of already indirect AI effects. Even in mature form, it is unlikely to be a major driver of this GVN compared with more immediate AI, materials, and manufacturing changes. So 1 is enough.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Innovation and adaptability → materials-design vendors market quantum-AI modules for formulation search (creates first route)
- (+) Reliability of supply → commodity planners test hybrid optimization for sourcing scenarios (shows narrow planning value)
- (–) Cost-effectiveness → sector users still choose classical HPC because validation dominates (keeps impact small)

- (–) Bargaining power → access stays confined to premium compute providers (limits diffusion)

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

Score: 10 (Impact in GVN 6)

Justification: This directly targets one of the GVN's core transformation paths: faster discovery of renewable materials, low-temperature processes, recyclability-friendly chemistries, and substitutes for scarce or toxic inputs. First-order it shortens the time from hypothesis to validated material/process; second-order it shifts R&D advantage toward actors with automated discovery stacks and shared data; third-order it can rapidly destabilize incumbent assets by making existing materials inferior or non-compliant faster than institutions can adapt. Assuming meaningful use in polymers, composites, catalysts, recycling chemistry, and construction materials, this reaches the transformative anchor, so 10.

Weak signals (9):

- (+) Innovation and adaptability → materials labs switch from human-led screening to autonomous experiment loops (compresses discovery cycles)
- (+) Sustainability → discovery programs explicitly target rare-metal substitution and recyclability as primary objectives (aligns with challenger regime)
- (+) Cost-effectiveness → pilot plants test AI-generated recipes within weeks rather than annual cycles (shrinks scale-up delay)
- (+) Adequate quality → autonomous labs begin producing reproducible qualification data packages (moves from curiosity to procurement)
- (+) Regulatory alignment → standards bodies receive many more applications for new bio-based or low-temperature materials (signals pipeline surge)
- (+) Local economic growth → regional labs and SMEs access shared autonomous discovery facilities (broadens innovation base)
- (–) Existing investments → incumbent process industries face sudden obsolescence of installed chemistry and expertise (creates stranded assets)
- (–) Bargaining power → discovery platforms and proprietary datasets become concentrated in a few firms (captures high-value knowledge)
- (–) Security/dual-use → restrictions appear on AI-generated material recipes with hazardous or strategic properties (shows governance stress)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

Score: 3 (Impact in GVN 6)

Justification: AR/VR does not change material chemistry, but it can materially change how scarce know-how reaches dispersed plants, yards, and construction/reuse sites. Directly it improves training, remote support, and design review; institutionally it lowers the expertise bottleneck that currently favors large incumbents; feedback-wise it can also centralize authority in remote experts and software vendors. The scale is meaningful but still enabling, so 3.

Weak signals (7):

- (+) Limited awareness and expertise → recyclers and material plants adopt AR-guided maintenance and changeover workflows (spreads scarce know-how)
- (+) Adequate quality → construction reuse teams use spatial overlays for salvage and grading decisions (improves salvage accuracy)
- (+) Reliability of supply → OEMs sell remote expert-assist subscriptions with immersive first-person views (cuts travel delays)
- (+) Cost-effectiveness → onboarding time for new material processes falls after immersive training rollout (reduces transition friction)
- (+) Regulatory alignment → certification bodies accept recorded immersive training and inspection traces (changes evidence norms)
- (–) Bargaining power → equipment vendors lock service know-how inside proprietary AR layers (reduces operator autonomy)
- (–) Security → remote guidance errors or compromised overlays trigger safety incidents (tests trust in mediated work)

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 0 (Impact in GVN 6)

Justification: Even in mature form, BCI has no clear, meaningful pathway to changing material availability, circularity, or core processing economics. It could marginally help specialized control tasks, but that is too peripheral to the GVN's main bottlenecks. So this stays at 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → material-handling vendors pilot BCI control for exceptional remote operations (would create a first narrow link)
- (+) Minimization of adverse effects → hazardous-site teleoperation studies compare BCI to conventional controls (tests niche safety value)
- (+) Regulatory alignment → industrial safety guidance mentions neural interfaces for machinery control (institutional entry point)
- (–) Existing bottlenecks → no materials operator budgets BCI as a core capability (linkage remains absent)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 3 (Impact in GVN 6)

Justification: This mainly affects labor-constrained, physically harsh parts of the GVN such as sorting, demolition, warehousing, maintenance, and construction handling. Directly it can reduce injury and extend workforce participation; institutionally it changes insurance, labor bargaining, and job design; feedback-wise it may also normalize higher work intensity and postpone automation choices. That is a real, society-scale labor and safety effect, but not a central operating-model shift, so 3.

Weak signals (7):

- (+) Minimization of adverse effects → demolition, recycling, and warehouse operators procure powered exosuits for repetitive handling (cuts strain injuries)

- (+) Reliability of supply → staffing gaps in material yards are partly filled through assistive wearables (reduces labor bottlenecks)
- (+) Cost-effectiveness → insurers offer lower premiums for injury-prone material operations using certified exoskeletons (prices safety gains)
- (+) Local economic growth → older or partially disabled workers remain active in material handling roles (widens labor pool)
- (+) Regulatory alignment → occupational-safety guidance begins specifying approved assistive wearables (normalizes use)
- (–) Bargaining power → employers use wearables to raise expected output per worker (can intensify labor pressure)
- (–) Existing structures → adoption clusters in incumbent heavy operators first, not community circular enterprises (uneven gains)

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 1 (Impact in GVN 6)

Justification: The relevant path is better teleoperation and fine handling in sorting, maintenance, and hazardous material environments. That matters in niches, but it is not one of the dominant constraints on this GVN relative to materials performance, certification, or process cost. So 1 is enough.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Minimization of adverse effects → hazardous cleanup robots add force and texture feedback for remote operators (improves niche control)
- (+) Adequate quality → delicate sorting and disassembly pilots use richer feedback gloves (supports selective recovery)
- (+) Reliability of supply → underwater or confined-space servicing tools advertise haptic guidance for material infrastructure (opens remote maintenance)
- (–) Cost-effectiveness → most material operators still choose simpler cameras and automation over high-end feedback systems (keeps impact limited)

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 1 (Impact in GVN 6)

Justification: The main link is smoother operation of complex tools and better operator support in plants, yards, and construction sites. That can reduce some coordination friction, but it is secondary to larger material, energy, certification, and robotics shifts. The impact is concrete but limited, so 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → industrial interfaces start inferring operator intent to simplify multi-step material workflows (reduces training burden)
- (+) Minimization of adverse effects → context-aware alerts suppress nuisance alarms in dusty, noisy operations (improves human attention)
- (+) Cost-effectiveness → material equipment vendors market “operator-assist AI” rather than full autonomy (signals practical entry)

- (–) Existing bottlenecks → buyers continue to prioritize process hardware and certification over interface intelligence (keeps linkage secondary)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 0 (Impact in GVN 6)

Justification: There is no credible path from BBI to meaningful changes in material access, quality, sustainability, or supply structure within this GVN. Any effect would be extremely indirect and peripheral. So 0 is the disciplined score.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → extreme teleoperation research uses shared-neural coordination in material hazard settings (would create first route)
- (+) Innovation and adaptability → grants appear for BBI-enabled industrial collaboration rather than medical uses (signals overlap)
- (+) Regulatory alignment → industrial ethics guidance mentions BBI for remote work (institutional foothold)
- (–) Existing bottlenecks → no material-sector procurement or standards activity emerges (confirms non-linkage)

## ART 04.028 - Memory Prostheses

Score: 0 (Impact in GVN 6)

Justification: Memory prostheses could change some individual work capabilities, but they do not plausibly change the GVN's material, logistical, or institutional bottlenecks in a meaningful way. The linkage is too remote for more than watchpoints. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → hazardous-material operations research explores implanted memory support for rare procedures (would create a niche route)
- (+) Regulatory alignment → industrial fitness-for-duty standards discuss cognitive implants (institutional foothold)
- (+) Cost-effectiveness → firms begin valuing implant-supported retention in scarce specialist roles (signals narrow labor effect)
- (–) Existing bottlenecks → sector transition plans still focus on training, automation, and certification instead (keeps linkage absent)

# 5. Robotics & Physical Autonomy

## ART 05.029 - Self-Driving Vehicles

Score: 5 (Impact in GVN 6)

Justification: Materials systems are logistics-heavy, so autonomous road transport can materially alter raw-material haulage, waste collection, and site-to-site supply reliability. First-order it lowers

transport costs and schedule volatility; second-order it redistributes value between operators, fleet platforms, and local labor markets; third-order it can either support more local circular collection or entrench long-distance extractive supply chains. The combined magnitude is clearly in the significant-impact range, so 5.

Weak signals (8):

- (+) Reliability of supply → bulk haulers and waste fleets sign driver-out service contracts on fixed routes (reduces scheduling bottlenecks)
- (+) Cost-effectiveness → quarries, ports, and recycling clusters redesign shift patterns around autonomous night transport (raises asset utilization)
- (+) Sustainability → dense reverse-logistics routes for scrap and demolition materials become economically viable (supports circular collection)
- (+) Minimization of adverse effects → high-risk haul segments shift away from fatigued human driving (cuts accident exposure)
- (+) Local economic growth → remote deposits become easier to exploit with thinner local labor footprints (changes regional development pattern)
- (–) Structural unemployment → driver labor disputes appear around waste and materials fleets (signals redistribution shock)
- (–) Preservation of existing structures → autonomy prolongs centralized long-distance logistics rather than localization (can reinforce incumbent model)
- (–) Security → fleet cyber incidents trigger scrutiny of autonomous materials transport (reveals systemic vulnerability)

## ART 05.030 - Drone Swarms & Aerial Robots

Score: 3 (Impact in GVN 6)

Justification: The strongest pathways are faster surveying, stockpile measurement, environmental monitoring, inspection, and targeted interventions around material sites. That saves time and improves oversight, but the effect stays narrower than ground automation or core process change. The likely impact is material yet bounded, which fits 3.

Weak signals (7):

- (+) Reliability of supply → quarries and yards replace periodic surveys with automated aerial stockpile mapping (improves inventory accuracy)
- (+) Minimization of adverse effects → drone swarms handle inspection of unstable structures, tailings, and roofs (reduces worker exposure)
- (+) Sustainability → demolition and forest-material operations use aerial grading and routing for selective recovery (improves usable yield)
- (+) Cost-effectiveness → insurers accept drone-based condition evidence for large material sites (prices inspection savings)
- (+) Regulatory alignment → routine beyond-visual-line-of-sight approvals expand around industrial and waste sites (widens feasible use)
- (–) Bargaining power → service markets consolidate around a few fleet-platform operators (captures data and margins)
- (–) Security/dual-use → site restrictions rise after drone interference or espionage incidents (adds governance burden)

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 6)

Justification: This is one of the clearest labor-and-operating-model disruptions for the GVN because many materials tasks are dirty, hazardous, irregular, and still built around human spaces. Directly, capable general-purpose robots could automate sorting, disassembly, maintenance, reconfiguration, and material handling across dispersed sites; institutionally, they shift value toward robot-platform owners and away from routine labor while making local, smaller-scale operations more viable; third-order, they can accelerate both circular recovery and social backlash through job displacement. If they become broadly usable in built-for-humans environments, the shift is transformative rather than merely incremental, so 10.

Weak signals (9):

- (+) Cost-effectiveness → recycling, warehousing, and construction-material sites move from single-task robots to general-purpose workcells (signals capability crossover)
- (+) Sustainability → disassembly and salvage tasks once considered too labor-intensive become automated service lines (raises recovery rates)
- (+) Reliability of supply → remote experts supervise robot labor across many material sites (decouples throughput from local staffing)
- (+) Minimization of adverse effects → hazardous cleanup, furnace-adjacent work, and confined-space tasks move to humanoid crews (cuts human exposure)
- (+) Reconfigurable production → plants redesign layouts for robot-human mixed operation in existing buildings (uses human-built infrastructure)
- (+) Local economic growth → small regional material hubs automate without full bespoke lines (supports decentralization)
- (–) Structural unemployment → labor conflict intensifies in waste, warehouse, and basic maintenance roles (signals disruption)
- (–) Bargaining power → a few robot vendors control skill libraries and service data (concentrates operational power)
- (–) Security → sabotage or remote hijack scenarios enter industrial contingency planning (turns robotics into critical infrastructure)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 3 (Impact in GVN 6)

Justification: Soft systems matter where materials are irregular, fragile, dirty, or safety-sensitive, especially in sorting, disassembly, handling, and inspections in cluttered spaces. That can materially improve selective recovery and damage rates, but it does not dominate the GVN the way general-purpose robotics or circular manufacturing would. So 3 is the right scale.

Weak signals (7):

- (+) Sustainability → recyclers adopt soft grippers for mixed and fragile material streams (raises selective recovery)
- (+) Adequate quality → delicate composite, textile, and bio-based materials see lower handling damage (improves resale value)
- (+) Minimization of adverse effects → compliant machines take over crush-risk and awkward-reach tasks (improves worker safety)



- (+) Cost-effectiveness → handling systems begin competing on reduced breakage, not just speed (changes equipment value logic)
- (+) Innovation and adaptability → soft end-effectors become standard options in reconfigurable cells (broadens deployment)
- (–) Existing structures → high-throughput incumbents keep rigid automation for uniform bulk flows (limits broad effect)
- (–) Maintenance risk → material-site operators report wear and cleaning challenges in harsh environments (tests economics)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 5 (Impact in GVN 6)

Justification: This ART has a broad route into remote prospecting, underwater infrastructure, hazardous inspection, waste-site work, and long-duration monitoring around material assets. First-order it reduces human exposure and travel; second-order it shifts capability toward operators who can manage autonomous fleets and mission data; third-order it can open previously marginal resources or make environmental oversight much harder to evade. The total impact is large enough for 5.

Weak signals (8):

- (+) Reliability of supply → underwater, remote, and hazardous material assets move to persistent autonomous inspection (reduces surprise failures)
- (+) Cost-effectiveness → site operators replace episodic specialist crews with resident robotic systems (cuts mobilization delays)
- (+) Minimization of adverse effects → contaminated or unstable environments are monitored and serviced without human entry (improves safety)
- (+) Sustainability → abandoned assets and waste sites get continuous monitoring for leaks and deterioration (tightens environmental control)
- (+) Local economic growth → smaller jurisdictions access advanced monitoring through robot-as-a-service models (widens capability access)
- (–) Preservation of existing structures → harder-to-reach extractive assets become economical to keep operating (can delay transition)
- (–) Bargaining power → autonomy vendors bundle maps, maintenance models, and mission control into closed services (captures rents)
- (–) Security → remote asset tampering or dual-use incidents drive new restrictions (raises governance cost)

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 6)

Justification: This matters because many material sites are messy, variable, and expensive to automate one machine at a time. First-order, autonomy-support infrastructure lowers the sensing and coordination burden for every robot in a yard, plant, depot, or reuse center; second-order, it favors operators with the capital to redesign facilities and may exclude smaller entrants unless shared zones emerge; third-order, it can make dense circular or localized material handling far more economical. That makes it a significant operating-model enabler, so 5.

Weak signals (8):

- (+) Cost-effectiveness → new recycling parks include robot-readable surfaces, docking, and traffic rules from day one (lowers automation complexity)
- (+) Reliability of supply → ports and bulk depots retrofit localization beacons and coordination posts (raises throughput predictability)
- (+) Sustainability → municipal reuse centers redesign layouts for autonomous sorting and movement (makes circular labor scalable)
- (+) Limited expertise → simpler robots perform reliably once environments carry more intelligence (widens supplier base)
- (+) Regulatory alignment → industrial building guidance starts specifying autonomy-ready infrastructure zones (normalizes retrofits)
- (–) Existing investments → older plants delay adoption because retrofit capex is too high (creates dual-speed sector)
- (–) Bargaining power → site standards are written around a few dominant robot ecosystems (locks in vendors)
- (–) Security → shared coordination infrastructure becomes a new critical failure point (creates common-mode risk)

## **ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics**

Score: 1 (Impact in GVN 6)

Justification: The relevant value is longer-endurance robots at remote material sites, but line-of-sight and safety constraints keep this a niche infrastructure layer. It could matter for certain fixed corridors or hazardous zones, yet it is not a primary determinant of the GVN's broader transition. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → remote stockyard or perimeter robots test beam-powered persistent patrols (signals niche endurance value)
- (+) Minimization of adverse effects → contaminated zones adopt beamed-power robots to avoid battery swaps (reduces human servicing)
- (+) Cost-effectiveness → fixed industrial corridors compare beaming with charger fleets and manual servicing (tests economics)
- (–) Regulatory alignment → safety restrictions keep deployments confined to tightly controlled sites (limits scale)

## **ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

Score: 1 (Impact in GVN 6)

Justification: This is mainly a niche mobility/manipulation improvement for inspection and handling on smooth vertical or delicate surfaces. Useful in some plants, warehouses, and construction-maintenance contexts, but not broad enough to shift the materials GVN substantially. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Minimization of adverse effects → vertical tank, façade, and smooth-surface inspections shift to dry-adhesion robots (reduces work-at-height risk)
- (+) Adequate quality → delicate sheet and panel handling pilots adopt residue-free gripping (protects high-finish materials)
- (+) Cost-effectiveness → plants replace temporary fixtures or vacuum gear for repeated niche tasks (shows local value)
- (–) Existing bottlenecks → adoption stays confined to inspection specialists rather than mainstream material handling (keeps impact small)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 10 (Impact in GVN 6)

Justification: This sits very close to the challenger regime because it reduces waste, tooling dependence, and assembly complexity while enabling new material/function combinations. First-order it changes how complex parts and structures are made; second-order it shifts value from mass-production scale to design files, feedstock quality, and local fabrication capacity; third-order it can shrink logistics, boost repairability, and strand some conventional tooling assets. Assuming certification expands into real industrial and construction components, this is transformative enough for 10.

Weak signals (9):

- (+) Cost-effectiveness → manufacturers cancel tooling for low-volume complex parts in favor of hybrid print workflows (signals economic crossover)
- (+) Sustainability → printed designs explicitly target material minimization and repair over overbuilding (aligns with challenger values)
- (+) Functionality → parts with embedded channels, sensors, and conductive paths enter routine industrial procurement (moves beyond prototyping)
- (+) Local economic growth → regional print hubs win work once reserved for distant specialized suppliers (supports localization)
- (+) Adequate quality → certification bodies publish methods for multi-material bond and lifecycle testing (opens wider adoption)
- (+) Reliability of supply → spare-part inventories shift from stockholding to qualified print files and local feedstocks (changes resilience model)
- (–) Existing investments → conventional tooling and assembly assets face accelerated obsolescence (creates stranded capital)
- (–) Bargaining power → value concentrates in material-file ecosystems and qualified feedstock suppliers (shifts industry control)
- (–) Security → sabotage or counterfeiting of design files becomes a materials-quality risk (adds digital integrity burden)

### ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 10 (Impact in GVN 6)

Justification: This changes how material systems are run by turning design, production, maintenance, and quality into a more continuously modeled loop rather than a sequence of

handoffs. Directly it cuts scrap, downtime, and risky scale-up; institutionally it embeds expert knowledge into software and helps novel materials pass through qualification faster; feedback-wise it also concentrates power in model owners and can hide bias behind simulation authority. Across major material flows, that is a transformative shift in operating model, so 10.

Weak signals (9):

- (+) Adequate quality → new material introductions require twin-based qualification before physical ramp-up (changes evidence pathway)
- (+) Cost-effectiveness → plants tie recipe changes and maintenance plans to live simulated outcomes (cuts expensive trial-and-error)
- (+) Reliability of supply → industrial clusters begin sharing model-driven outage and bottleneck forecasts (improves coordination)
- (+) Sustainability → twins optimize energy, waste, and recycled-content trade-offs in real time (makes greener operation measurable)
- (+) Limited expertise → remote experts intervene through model-based dashboards rather than site presence (spreads scarce know-how)
- (+) Regulatory alignment → insurers and regulators accept twin traces as part of compliance and incident review (institutionalizes use)
- (–) Bargaining power → vendors who own the twin schema and physics stack capture strategic control (locks in ecosystems)
- (–) Existing structures → poorly instrumented legacy plants become second-class assets (deepens dual-speed transition)
- (–) Security → manipulated or stale twins cause bad operational decisions at scale (creates new common-mode risk)

## ART 06.039 - Reconfigurable & Agile Factories

Score: 10 (Impact in GVN 6)

Justification: This directly attacks the dominant regime's dependence on large batches, long changeovers, and capital-heavy dedicated lines. First-order it enables local, smaller, faster shifts between materials and products; second-order it lowers the threshold for new entrants and supports volatile demand or circular inputs; third-order it can destabilize incumbent scale economics and move power toward modular-system and recipe owners. Because it changes how the GVN goal is realized, 10 fits.

Weak signals (9):

- (+) Cost-effectiveness → firms start valuing low-changeover time over pure line speed in capex decisions (signals regime shift)
- (+) Reliability of supply → regional plants switch between virgin and recycled inputs without major rebuilds (improves resilience)
- (+) Sustainability → variable secondary feedstocks become commercially workable in modular cells (supports circular operations)
- (+) Local economic growth → smaller jurisdictions attract production with modular, fast-start facilities (supports localization)
- (+) Limited expertise → reusable digital recipes reduce dependence on locally scarce specialists (broadens operability)
- (+) Innovation and adaptability → product teams shorten design-to-production loops through modular retooling (compresses iteration)

- (–) Existing investments → fixed single-purpose lines lose strategic value faster than expected (strands capital)
- (–) Bargaining power → module vendors and orchestration software capture more of the margin (shifts control)
- (–) Security → recipe tampering or misconfiguration creates rapid, multi-cell quality failures (raises cyber/process risk)

## ART 06.040 - Circular & Sustainable Manufacturing

Score: 20 (Impact in GVN 6)

Justification: This is the clearest keystone match to the GVN's challenger regime because it directly reorganizes material access away from extraction-heavy, wasteful, globally stretched linear chains and toward recirculation, requalification, and lower-energy transformation. First-order it turns scrap, waste, and end-of-life products into primary inputs; second-order it rewrites procurement, ownership, sorting, certification, and local industrial structure; third-order it disrupts incumbent raw-material demand, labor patterns, and capital allocation while making product design, recovery, and material data mutually reinforcing. Without something like this, most of the other challenger elements remain partial or niche. That makes it a true 20 rather than merely a high 10.

Weak signals (12):

- (+) Sustainability → large buyers set rising recycled-content and take-back requirements in core materials contracts (pulls circular demand forward)
- (+) Cost-effectiveness → recovered feedstock begins clearing tenders against virgin inputs without subsidy (signals economic crossover)
- (+) Reliability of supply → plants diversify from single-source virgin supply to mixed recovered streams (improves resilience)
- (+) Adequate quality → requalified secondary materials gain routine acceptance in high-value components (breaks trust barrier)
- (+) Local economic growth → municipal and regional material loops form around demolition, repair, and remanufacture hubs (relocalizes value creation)
- (+) Minimization of adverse effects → disposal and transport volumes fall as more material is processed locally (cuts externalities)
- (+) Functionality → product design teams optimize for disassembly, reuse, and traceable composition from the start (locks in circular design logic)
- (+) Regulatory alignment → building codes, public procurement, or EPR rules privilege reuse and material recovery (changes incentive structure)
- (+) Innovation and adaptability → AI/robotic sorting and low-temperature reprocessing lines move from pilots to standard plant packages (industrializes the model)
- (–) Existing investments → incumbent extractive and high-heat assets face accelerated write-down risk (reveals regime conflict)
- (–) Bargaining power → data-rich circular platforms or sorter operators capture disproportionate value from distributed inputs (creates new gatekeepers)
- (–) Security/quality → fraud over recycled content, contamination, or passport data becomes a major enforcement issue (tests system credibility)

## ART 06.041 - Bio-fabrication technologies

Score: 1 (Impact in GVN 6)

Justification: The materials linkage is mostly spillover from tissue-engineering tools into niche bio-derived materials or specialty substrates. That is real, but it is not the main route by which this GVN changes. So the impact stays limited at 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Biotechnology and biomimicry → biofabrication platforms start producing non-medical structural or coating materials (creates first direct route)
- (+) Innovation and adaptability → materials labs share equipment with tissue-engineering facilities for soft biomaterial prototyping (signals overlap)
- (+) Adequate quality → specialty bio-derived material suppliers market bioreactor-made consistency as a selling point (shows niche value)
- (–) Existing bottlenecks → mainstream manufacturing and construction buyers see the field as medical, not material infrastructure (keeps linkage weak)

## ART 06.042 - 4D Printed & Programmable Materials

Score: 5 (Impact in GVN 6)

Justification: These materials reduce the need for assemblies, manual adjustment, and overdesign by embedding response into the material itself. Directly that improves adaptability and lifecycle performance; institutionally it shifts value toward design libraries, trigger protocols, and qualification methods; feedback-wise it can also complicate recycling and inspection if behavior is poorly documented. The impact is significant but not as system-wide as circular manufacturing or agile factories, so 5.

Weak signals (8):

- (+) Functionality → suppliers begin selling components whose shape or permeability changes in service (moves from novelty to product logic)
- (+) Cost-effectiveness → assemblies are redesigned into single programmable parts with fewer fasteners and maintenance steps (cuts complexity)
- (+) Reliability of supply → compact transport and self-deploying structures reduce logistics and installation constraints (improves access in remote sites)
- (+) Sustainability → adaptive parts extend service life instead of requiring manual retrofits or replacement (reduces material throughput)
- (+) Adequate quality → standards bodies publish fatigue and trigger-response test methods for programmable materials (supports bankability)
- (–) Recycling bottleneck → end-of-life processors struggle with unknown triggers and mixed material formulations (creates new sorting challenge)
- (–) Bargaining power → design-pattern and materials-IP owners capture high-value positions (concentrates control)
- (–) Security → malicious or accidental triggering becomes a new failure and liability mode (adds governance burden)



## ART 06.043 - Volumetric Additive Manufacturing

Score: 5 (Impact in GVN 6)

Justification: The key value is much faster production of complex small-batch parts, molds, tooling, and components with less assembly and fewer geometric constraints. That improves resilience and iteration speed; institutionally it favors local qualified print capacity and digital inventory over stocked physical inventory; feedback-wise it may disrupt incumbent spare-part, tooling, and logistics models. Assuming certification reaches practical industrial parts rather than remaining lab-bound, 5 is justified.

Weak signals (8):

- (+) Cost-effectiveness → tooling and spare parts shift from stocked inventories to near-instant local print service (compresses lead times)
- (+) Reliability of supply → maintenance teams use layerless printing for emergency parts and fixtures (improves outage recovery)
- (+) Adequate quality → smoother internal channels and fewer support-related defects become routine procurement claims (moves beyond prototype use)
- (+) Local economic growth → compact print units appear in regional maintenance and fabrication hubs (supports localization)
- (+) Innovation and adaptability → product teams iterate geometries inside production windows rather than separate prototyping cycles (speeds change)
- (–) Existing investments → conventional small-batch machining and tooling capacity is repriced downward (creates displacement)
- (–) Bargaining power → value shifts toward material chemistry suppliers and qualified print-software stacks (concentrates control)
- (–) Security → print-file integrity and counterfeit concerns rise for critical spare parts (adds digital trust burden)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 6)

Justification: In this GVN, metamaterials matter mainly as a high-value class of advanced functional materials and as enablers of better sensing/connectivity inside industrial environments. That changes some material demand, product performance, and infrastructure design, but it remains concentrated in specific sectors rather than reshaping the whole materials regime. So 3 fits.

Weak signals (7):

- (+) Functionality → construction and industrial products start specifying wave-control surfaces as embedded material features (signals productization)
- (+) Competitiveness → suppliers market thinner, lighter electromagnetic-control materials as substitutes for bulkier assemblies (shifts value to structure)
- (+) Reliability of supply → communications and sensing infrastructure at material sites adopts reconfigurable surfaces (improves site performance)



- (+) Innovation and adaptability → material labs and OEMs co-develop software-tunable surface products (creates new design workflow)
- (+) Adequate quality → standards emerge for weathering and performance persistence of exposed metamaterial surfaces (supports deployment)
- (–) Bargaining power → IP-heavy surface libraries and specialized fabrication concentrate power (limits broad capture)
- (–) Existing structures → adoption stays limited to premium or defense-adjacent applications for years (caps near-term breadth)

## ART 07.045 - Room-Temperature Superconductors

Score: 5 (Impact in GVN 6)

Justification: If truly mature, ambient superconductors would materially change power delivery, magnetic separation, sensing, and high-current industrial equipment. First-order they lower energy losses and can enable new compact process systems; second-order they create a new strategic materials stack and reshape infrastructure investment; third-order they may make some current energy- and heat-intensive material architectures obsolete. That is a major impact, but not uniquely a materials-GVN keystone, so 5 rather than 10.

Weak signals (8):

- (+) Cost-effectiveness → energy-intensive material plants start modeling conductor replacement against process-heat savings (signals industrial crossover)
- (+) Reliability of supply → magnetic separation, transport, and sensing equipment designs are rewritten around superconducting components (changes equipment baseline)
- (+) Sustainability → decarbonization roadmaps for metals and chemicals start counting transmission and motor-loss reductions (raises sector relevance)
- (+) Functionality → compact high-field tools enter routine material-processing proposals (expands technical option set)
- (+) Regulatory alignment → utilities and industrial codes begin addressing ambient superconducting installations (institutional normalization)
- (–) Existing investments → conventional grid and motor assets face early obsolescence pressure (creates capital conflict)
- (–) Bargaining power → supply tightens around a few conductor formulations and producers (creates new dependency)
- (–) Security/safety → quench, field, or shielding incidents trigger new industrial safeguards (reveals non-trivial operating risks)

## ART 07.046 - Self-Healing & Smart Polymers

Score: 5 (Impact in GVN 6)

Justification: This directly supports longer-lived, lower-maintenance materials in manufacturing and construction, which maps well to the GVN's sustainability and adverse-effects goals. Directly it lowers failure and replacement rates; institutionally it changes warranty, inspection, and lifecycle costing; feedback-wise it can complicate recycling or create hidden performance assumptions if healing is oversold. The overall effect is significant, so 5.

Weak signals (8):

- (+) Reliability of supply → buyers begin valuing lifetime extension over lowest upfront polymer cost (changes procurement logic)
- (+) Minimization of adverse effects → coatings, seals, and composites advertise autonomous crack-sealing in harsh environments (reduces failure exposure)
- (+) Sustainability → asset managers defer replacement cycles after certified healing performance is demonstrated (cuts material throughput)
- (+) Adequate quality → standards publish repeat-healing and residual-strength test methods (supports bankability)
- (+) Functionality → materials are sold with tunable stiffness or permeability profiles for different operating states (adds performance flexibility)
- (–) Recycling bottleneck → waste processors report difficulty separating or reprocessing novel healing chemistries (creates downstream friction)
- (–) Bargaining power → specialty resin and additive suppliers capture much of the value uplift (shifts margin upstream)
- (–) Accountability → warranty disputes emerge over incomplete healing under real conditions (tests trust claims)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 5 (Impact in GVN 6)

Justification: This ART is closely tied to lower-energy processing, corrosion control, cleaner chemistry, and better surface performance, all central to the GVN's cost, sustainability, and quality goals. First-order it can reduce heat, waste, and downtime; second-order it shifts value toward those controlling catalyst/coating IP and lifecycle services; third-order it may preserve some incumbent industries by making them cleaner and more efficient rather than displaced. The total effect is significant, so 5.

Weak signals (8):

- (+) Cost-effectiveness → plants justify retrofits on reduced energy per ton and longer maintenance intervals (shows operational value)
- (+) Minimization of adverse effects → anti-fouling, corrosion, and low-friction coatings are written into high-risk asset strategies (cuts leaks and wear)
- (+) Sustainability → low-temperature catalytic routes begin replacing harsher legacy chemistry in selected material processes (aligns with challenger regime)
- (+) Adequate quality → recovered materials achieve more stable outputs through improved catalytic or surface control (improves process consistency)
- (+) Reliability of supply → critical components last longer in abrasive or corrosive material flows (reduces outage risk)
- (–) Bargaining power → coating and catalyst service contracts become a high-control aftermarket (captures value over time)
- (–) Supply risk → some nano-formulations trigger dependence on scarce elements or complex precursors (creates new bottlenecks)
- (–) Regulatory alignment → environmental and worker-safety scrutiny rises around nanoparticle exposure and disposal (adds compliance cost)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 5 (Impact in GVN 6)

Justification: Better metals directly improve durability, temperature tolerance, corrosion resistance, and equipment lifespan across many material and construction systems. Operationally that reduces downtime and overbuilding; institutionally it shifts certification, sourcing, and component qualification; feedback-wise it can intensify dependence on costly or strategically sensitive alloying elements. The effect is broad and significant, so 5.

Weak signals (8):

- (+) Reliability of supply → operators replace failure-prone components with longer-life advanced alloys in harsh environments (cuts outage cycles)
- (+) Cost-effectiveness → total-cost models begin favoring expensive alloys because replacement labor dominates (changes investment logic)
- (+) Adequate quality → standards and buyers accept HEA-based parts in critical assemblies (crosses qualification barrier)
- (+) Sustainability → longer service intervals reduce material replacement and emergency logistics (lowers lifecycle burden)
- (+) Functionality → new temperature and corrosion envelopes enable more compact or efficient process equipment (raises system performance)
- (–) Supply risk → alloy recipes pull in price-sensitive or geopolitically concentrated elements (creates new procurement exposure)
- (–) Bargaining power → specialty metallurgy and powder suppliers gain disproportionate leverage (moves value upstream)
- (–) Existing structures → conventional metal-processing capacity is repriced as premium alloys penetrate key niches (disrupts incumbents)

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 5 (Impact in GVN 6)

Justification: This is important mainly because it can preserve or reconfigure high-emissions incumbent material industries such as cement, lime, steel, and chemicals under tightening climate constraints. First-order it lowers the emissions barrier to continued production and creates concentrated CO<sub>2</sub> streams for downstream chemistry; second-order it affects permits, industrial siting, and carbon-accounting regimes; third-order it can either enable cleaner incumbents or delay deeper material substitution. The total impact is significant, so 5.

Weak signals (8):

- (+) Regulatory alignment → cement, lime, and chemical projects advance only with integrated capture-material plans (links output to decarbonization)
- (+) Reliability of supply → carbon-constrained plants avoid closure through deployable capture modules (preserves domestic material capacity)
- (+) Sustainability → captured CO<sub>2</sub> starts being contracted as a feedstock for materials and fuels (creates new carbon loop)
- (+) Cost-effectiveness → capture-media replacement and regeneration costs fall enough to enter routine capex decisions (signals industrial practicality)

- (+) Innovation and adaptability → modular sorbent cartridges become a service layer rather than bespoke chemistry (widens adoption)
- (–) Preservation of existing structures → cleaner capture lets some high-impact legacy processes persist longer (can slow deeper transition)
- (–) Bargaining power → sorbent suppliers and carbon-accounting platforms capture critical positions (creates new gatekeepers)
- (–) Security/quality → disputes emerge over capture performance claims and carbon accounting integrity (tests trust architecture)

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

Score: 10 (Impact in GVN 6)

Justification: This fits the GVN directly because the challenger regime explicitly points toward nanocarbons as routes to stronger, lighter, more functional materials and potential substitution for scarce inputs. First-order it changes performance, weight, conductivity, and embedded sensing; second-order it can reconfigure supply chains away from some rare metals and toward advanced carbon-processing ecosystems; third-order it may disrupt incumbent materials sectors and create new health, certification, and IP conflicts. Given the breadth of manufacturing and construction applications, this is transformative enough for 10.

Weak signals (9):

- (+) Functionality → composites with embedded strain or damage sensing move from premium pilots to standard procurement (shows multifunctionality becoming routine)
- (+) Cost-effectiveness → lightweight-strength trade-offs begin beating conventional metal solutions at system level (signals economic crossover)
- (+) Reliability of supply → substitution programs explicitly target rare or volatile material inputs with nanocarbon composites (reduces strategic dependence)
- (+) Adequate quality → construction and industrial standards start addressing dispersion quality and health-safe handling (opens mainstream qualification)
- (+) Sustainability → longer-life, lower-weight structures are sold on lifecycle energy and maintenance gains (widens adoption logic)
- (+) Innovation and adaptability → local manufacturing ecosystems form around nanocarbon-enhanced resins and laminates (supports new clusters)
- (–) Occupational health → nanoparticle handling controls and worker concerns intensify during scale-up (adds friction)
- (–) Bargaining power → IP and feedstock purification capacity concentrate in a few firms (captures high-value positions)
- (–) Existing investments → incumbent metal and composite suppliers face faster displacement than expected (creates regime conflict)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 5 (Impact in GVN 6)

Justification: Thermal management is a major hidden cost both in buildings and in materials processing, so better passive or semi-passive heat control has broad relevance. Directly it reduces

energy demand, overheating, and process variability; institutionally it changes building/product standards and maintenance practices; feedback-wise it may shift value from active equipment makers toward materials suppliers. The total impact is significant, so 5.

Weak signals (8):

- (+) Cost-effectiveness → material plants and building operators adopt thermal-storage and thermal-switch materials to cut peak loads (reduces energy costs)
- (+) Sustainability → insulation, coating, and thermal-interface specs shift toward lifecycle heat-control performance (aligns with lower-energy regime)
- (+) Reliability of supply → temperature-sensitive production lines show fewer trips after smart thermal retrofit (improves uptime)
- (+) Functionality → products and structures are sold with passive temperature-management features as standard (changes design baseline)
- (+) Regulatory alignment → building and industrial energy codes recognize dynamic thermal materials (supports scaled deployment)
- (–) Recycling bottleneck → advanced multi-layer thermal materials create end-of-life separation problems (moves burden downstream)
- (–) Bargaining power → specialty encapsulation and formulation suppliers capture margin and service roles (concentrates value)
- (–) Quality drift → long-cycle fatigue and moisture ingress become warranty disputes (tests real-world persistence)

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

Score: 5 (Impact in GVN 6)

Justification: This matters because motors, actuators, separators, robotics, wind equipment, and many manufacturing systems depend on magnetic materials exposed to concentrated supply chains. First-order it reduces strategic material risk and can widen adoption of automation and electrification; second-order it shifts demand away from geopolitically sensitive inputs and toward new alloy ecosystems; third-order it may reprice both existing mines and magnet-manufacturing capabilities. That is significant enough for 5.

Weak signals (8):

- (+) Reliability of supply → OEMs redesign motors and separators around rare-earth-free magnetic grades (cuts geopolitical exposure)
- (+) Cost-effectiveness → buyers accept slightly larger or different motor geometries in exchange for material security (signals system-level optimization)
- (+) Sustainability → equipment suppliers market reduced dependency on environmentally problematic inputs (supports responsible sourcing)
- (+) Local economic growth → magnet manufacturing or finishing returns closer to end-use markets (supports regional industrialization)
- (+) Regulatory alignment → public procurement favors lower-criticality magnet supply chains in strategic equipment (changes incentives)
- (–) Existing structures → rare-earth-dependent equipment producers resist redesign due to requalification costs (slows transition)
- (–) Bargaining power → new substitute-material suppliers or IP holders gain concentrated leverage (creates replacement dependency)

- (–) Quality/performance → demagnetization and temperature-profile disputes shape early market trust (tests real-world adequacy)

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

Score: 1 (Impact in GVN 6)

Justification: Better desalination can matter for water-stressed material processing and some localized production models, but water is not the dominant system bottleneck in this GVN at large. The route is real yet narrow and context-dependent. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → water-constrained quarries, chemical plants, or mineral processors pilot low-energy desal units (creates direct local route)
- (+) Cost-effectiveness → industrial water-reuse contracts begin favoring nano-membrane systems over trucking or imports (signals niche crossover)
- (+) Sustainability → local material projects in dry regions cite membrane-enabled water independence (supports localized production)
- (–) Existing bottlenecks → most material operators still see energy, certification, and feedstock as larger constraints than water (keeps overall impact limited)

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 3 (Impact in GVN 6)

Justification: These devices matter because they can make electrified industrial power systems smaller, cooler, and more efficient. Operationally that supports process electrification, robotics, high-power chargers, and distributed control; institutionally it changes equipment procurement and service models; feedback-wise it may deepen dependence on a narrow advanced-semiconductor supply base. The net magnitude is material but still enabling, so 3.

Weak signals (7):

- (+) Cost-effectiveness → converters and drives for material plants shrink cooling and passive hardware budgets (improves electrification economics)
- (+) Reliability of supply → high-voltage industrial equipment advertises longer life and lower thermal stress with UWBG modules (raises uptime)
- (+) Sustainability → electrification retrofits become feasible in space- and heat-constrained facilities (widens low-carbon options)
- (+) Functionality → mobile material equipment and high-power chargers adopt lighter, quieter power electronics (improves deployment flexibility)
- (+) Innovation and adaptability → OEM roadmaps start treating high-temperature power electronics as default for harsh sites (signals normalization)
- (–) Supply risk → wafer and packaging constraints create a new advanced-component dependency (replaces one bottleneck with another)
- (–) Bargaining power → a few device makers dominate module qualification and long-term service (concentrates leverage)



## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 3 (Impact in GVN 6)

Justification: The link here is mostly through safer, denser hydrogen logistics for steel, chemicals, remote sites, or backup energy systems. That can ease adoption of hydrogen in materials processing, but it is one support layer among several and not the central driver of the GVN. So 3 is appropriate.

Weak signals (7):

- (+) Reliability of supply → industrial hydrogen users trial cartridge-like solid storage near material sites (simplifies on-site buffering)
- (+) Minimization of adverse effects → safety cases favor lower-pressure solid storage over gas cylinders in dense facilities (reduces handling risk)
- (+) Cost-effectiveness → remote material operations compare solid storage with trucked fuels and high-pressure systems (tests practical crossover)
- (+) Sustainability → hydrogen-fed process pilots in metals and chemicals cite storage simplicity as an adoption enabler (widens feasible use)
- (+) Regulatory alignment → industrial gas codes begin covering swap-in solid hydrogen modules (supports routine deployment)
- (–) Supply risk → storage chemistries introduce new dependence on alloying or porous media inputs (creates fresh material exposure)
- (–) Existing structures → many operators still prefer pipeline or centralized gas solutions where scale is large (limits breadth)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

Score: 5 (Impact in GVN 6)

Justification: If mature and available, fusion would mainly affect this GVN through abundant low-carbon power and possibly high-grade heat for energy-intensive material industries. That can change cost structures, industrial siting, and carbon constraints; institutionally it shifts power to large capital projects and regulated operators; feedback-wise it may preserve some centralized heavy-industry logic rather than localize everything. The likely impact is significant, but not uniquely a materials-system keystone, so 5.

Weak signals (8):

- (+) Cost-effectiveness → energy-intensive material plants begin scoping co-location with fusion sites (signals industrial fit)
- (+) Reliability of supply → steel, chemicals, and mineral processing roadmaps count on steady fusion-backed power/heat (supports baseload material production)
- (+) Sustainability → decarbonization strategies for hard-to-abate materials include fusion in domestic capacity planning (links power to material security)
- (+) Regulatory alignment → industrial heat and power rules start addressing fusion off-take to process industries (institutionalizes pathway)
- (+) Local economic growth → regions market fusion-adjacent material clusters to attract new process investment (reshapes industrial geography)



- (–) Preservation of existing structures → centralized heavy industry gains a new lease on life (can slow distributed alternatives)
- (–) Existing investments → utilities and industrial firms face major capital-allocation conflicts around legacy energy assets (creates path dependence battles)
- (–) Security/safety → reactor downtime or licensing shocks become supply-chain risks for co-located material plants (reveals concentration risk)

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 5 (Impact in GVN 6)

Justification: SMRs have a direct route into domestic material security because they can provide firm power and heat to industrial clusters with less dependence on fuel transport or weather. First-order they stabilize energy-intensive production; second-order they alter siting, permitting, and industrial bargaining; third-order they can preserve incumbent process industries while reducing emissions. That is significant enough for 5.

Weak signals (8):

- (+) Reliability of supply → materials clusters seek firm nuclear heat/power supply contracts from modular projects (signals industrial coupling)
- (+) Cost-effectiveness → chemical, mineral, or metals operators compare SMRs with grid upgrades and fossil backup (tests crossover logic)
- (+) Sustainability → decarbonization plans for hard-to-electrify plants include SMR heat as a serious option (widens feasible pathways)
- (+) Local economic growth → remote or grid-constrained industrial regions pitch SMRs as anchor infrastructure (reshapes site competition)
- (+) Regulatory alignment → licensing guidance starts addressing industrial cogeneration and process-heat use (opens practical deployment)
- (–) Existing investments → centralized, high-capex energy models can crowd out smaller flexible alternatives (may reinforce old structures)
- (–) Bargaining power → nuclear vendors and regulators gain strong gatekeeping roles in industrial energy strategy (concentrates control)
- (–) Security → nuclear security and waste politics affect material-cluster siting and social acceptance (adds governance friction)

## ART 08.058 - Thin-film solar cells

Score: 3 (Impact in GVN 6)

Justification: Thin-film solar mainly matters here as a distributed energy layer that can be integrated into warehouses, depots, yards, vehicles, and some products. That improves resilience and local energy harvesting, but it does not by itself determine the shift in materials production. The effect is material and practical, yet bounded, so 3.

Weak signals (7):

- (+) Cost-effectiveness → warehouses, material depots, and temporary structures adopt solar skins where rigid panels were awkward (widens on-site generation)
- (+) Reliability of supply → remote monitoring and small processing assets use integrated thin-film power instead of grid extensions (supports decentralized operations)

- (+) Sustainability → construction products start bundling power generation into envelopes and surfaces (changes building-material value)
- (+) Local economic growth → regional installers and fabricators gain work in retrofit-integrated solar materials (supports local capability)
- (+) Functionality → transport containers, barriers, or covers add energy-generating surfaces as standard options (blends material and power roles)
- (–) Recycling bottleneck → composite encapsulation and recovery issues trigger end-of-life concerns (moves burden downstream)
- (–) Existing structures → low-cost grid power in some regions keeps integrated solar secondary for many industrial users (limits breadth)

## ART 08.059 - Bionic Leaf Technology

Score: 3 (Impact in GVN 6)

Justification: The route here is decentralized production of hydrogen-rich or carbon-based feedstocks directly from sunlight, water, and carbon sources. That could matter for chemical precursors and local material chemistry, but it still competes with several other power-to-molecule routes and depends on practical process integration. So the impact is material but not dominant, which fits 3.

Weak signals (7):

- (+) Sustainability → pilot sites co-produce low-carbon chemical intermediates near material users rather than importing them (signals local molecule production)
- (+) Cost-effectiveness → specialty material firms compare bionic-leaf panels with electrolyzer-plus-reactor stacks (tests process simplification value)
- (+) Reliability of supply → remote or islanded material sites trial local molecule generation for niche inputs (improves autonomy)
- (+) Innovation and adaptability → catalyst and panel vendors begin marketing materials-specific output recipes (moves beyond energy demo)
- (+) Regulatory alignment → product-certification schemes start recognizing panel-origin chemical feedstocks (supports tradability)
- (–) Existing structures → incumbents keep preferring centralized large-scale chemical supply chains (limits broader displacement)
- (–) Quality/control → consistency and separation concerns shape buyer reluctance for serious material inputs (tests industrial adequacy)

## ART 08.060 - Grid-Scale Energy Storage

Score: 5 (Impact in GVN 6)

Justification: Electrified material processing and recycling need reliable power, not just cheap average power, so long-duration storage has a strong indirect route into this GVN. First-order it reduces outage risk and demand spikes; second-order it changes industrial siting, contracting, and grid dependence; third-order it can enable more local, flexible, low-temperature processing models while also strengthening incumbent utilities. The impact is significant, so 5.

Weak signals (8):

- (+) Reliability of supply → material plants sign storage-backed power contracts instead of relying on curtailment or diesel backup (improves uptime)
- (+) Cost-effectiveness → electrified heat and recycling projects proceed once multi-day storage is available locally (changes investment threshold)
- (+) Sustainability → variable renewable power becomes usable for more material operations without overbuilding fossil backup (widens clean-energy use)
- (+) Local economic growth → industrial micro-hubs pair storage with local generation to support new processing capacity (supports decentralization)
- (+) Minimization of adverse effects → grid events cause fewer emergency shutdowns and flaring episodes in process industries (reduces disruption)
- (–) Bargaining power → utilities and storage operators capture new leverage over industrial flexibility and access terms (reshapes contracts)
- (–) Existing structures → capital-heavy storage deployment can favor established industrial zones over new local entrants (uneven benefits)
- (–) Safety/governance → fire, gas, or outage incidents at storage sites drive stricter industrial integration rules (adds compliance cost)

## ART 08.061 - Solid-State Batteries

Score: 3 (Impact in GVN 6)

Justification: The main effects are safer higher-density storage for mobile machinery, robots, sensors, and some distributed energy systems that support materials operations. That improves uptime and logistics, but it is still a support technology rather than a fundamental reorganization of material access. So 3 is the disciplined score.

Weak signals (7):

- (+) Reliability of supply → material-handling vehicles and robots adopt longer-running, safer packs (reduces downtime)
- (+) Minimization of adverse effects → insurers or site managers prefer solid-state storage in confined or fire-sensitive facilities (changes equipment choice)
- (+) Cost-effectiveness → higher uptime and lower cooling burden shift TCO in mobile equipment tenders (improves electrification economics)
- (+) Sustainability → remote sensor and machine fleets reduce pack replacement frequency (cuts maintenance overhead)
- (+) Functionality → compact electric tools and autonomous equipment enter more material-site workflows (widens electrified use)
- (–) Supply risk → new electrolyte and interface materials create fresh dependencies (replaces one constraint with another)
- (–) Existing structures → grid and process bottlenecks still dominate for many heavy material operations (keeps impact bounded)

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 10 (Impact in GVN 6)

Justification: This is one of the strongest direct energy-to-material pathways because many material industries need molecules and high-temperature reducing agents, not just electricity. First-order it can decarbonize steel, chemicals, fertilizers, and other feedstocks; second-order it reshapes industrial geography around cheap clean power, water, storage, and certification; third-order it can

strand fossil-linked assets while creating new trade and infrastructure dependencies. That is a transformative change in how parts of the GVN operate, so 10.

Weak signals (9):

- (+) Sustainability → steel, chemical, and fertilizer projects shift from pilot language to bankable hydrogen off-take contracts (signals industrial crossover)
- (+) Reliability of supply → material producers diversify from fossil feedstocks into local or regional power-to-X supply (changes resilience logic)
- (+) Cost-effectiveness → dispatch-flexible electrolyzers become part of industrial energy optimization rather than standalone demos (integrates into operations)
- (+) Regulatory alignment → buyers start requiring certified low-carbon molecular feedstocks and origin data (creates tradable green premium)
- (+) Local economic growth → regions with cheap clean power attract new conversion and materials capacity (reshapes industrial map)
- (+) Innovation and adaptability → modular synthesis units produce different molecules based on local constraints (supports flexible supply)
- (–) Existing investments → fossil-linked infrastructure and expertise face accelerated obsolescence (creates transition conflict)
- (–) Bargaining power → electrolyzer, catalyst, and certification platforms become new choke points (shifts strategic control)
- (–) Safety/governance → hydrogen handling incidents or water conflicts trigger stricter siting and social license battles (tests scale path)

## ART 08.063 - High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 6)

Justification: Better wind mainly affects this GVN through cheaper clean electricity and through demand for advanced materials in energy equipment. That matters for electrified processing, but the pathway is indirect and shared with other power technologies. So 3 is appropriate.

Weak signals (7):

- (+) Cost-effectiveness → energy-intensive material plants contract more directly with wind-backed supply as performance improves (lowers power cost exposure)
- (+) Reliability of supply → storage-plus-wind packages enter industrial power strategies for remote or coastal material sites (improves resilience)
- (+) Sustainability → lower-carbon electricity makes electric or low-temperature material routes more bankable (supports challenger processes)
- (+) Functionality → advanced blades, coatings, and monitoring feed back demand into the materials sector itself (creates reciprocal pull)
- (+) Local economic growth → regions with strong wind resources attract process industries or green material projects (reshapes siting)
- (–) Bargaining power → grid access and balancing still sit with a few utilities or large developers (limits distributed gains)
- (–) Existing structures → intermittency and permitting still cap direct transformation in many material uses (keeps impact moderate)

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 6)

Justification: The plausible materials route is power delivery to remote sites, temporary operations, or hard-to-connect sensors and machines. That is interesting, but still niche compared with terrestrial energy and storage options. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → remote material monitoring or temporary processing sites test cable-free power delivery (creates narrow field use)
- (+) Cost-effectiveness → isolated operations compare beamed power against fuel logistics and line extension (tests remote-value case)
- (+) Minimization of adverse effects → hazardous locations use power transfer to reduce human servicing of generators (improves niche safety)
- (–) Regulatory alignment → beam-safety and spectrum constraints keep industrial use highly bounded (limits scale)

## ART 08.065 - Advanced geothermal technology

Score: 5 (Impact in GVN 6)

Justification: Advanced geothermal fits this GVN well because it offers steady heat and power close to industrial demand, which is especially valuable for materials processing. First-order it lowers fuel-risk and outage exposure; second-order it can reshape industrial siting and permit local clusters; third-order it may allow cleaner incumbents or new low-carbon processing hubs to emerge. The likely effect is significant, so 5.

Weak signals (8):

- (+) Reliability of supply → material plants and industrial parks pursue co-location with deep-heat projects (signals heat-market fit)
- (+) Cost-effectiveness → process-heat users compare geothermal baseload with gas and major grid upgrades (tests industrial crossover)
- (+) Sustainability → low-carbon heat becomes a central part of domestic materials-security strategies (links energy and material policy)
- (+) Local economic growth → regions market geothermal-backed manufacturing and recycling parks (supports localization)
- (+) Regulatory alignment → permitting frameworks start explicitly covering industrial off-take from geothermal fields (supports deployment)
- (–) Existing structures → subsurface rights and drilling expertise concentrate benefits in certain regions only (creates spatial unevenness)
- (–) Bargaining power → deep-well and reservoir service providers capture scarce strategic positions (limits competition)
- (–) Risk/governance → induced seismicity or well-integrity controversies reshape social license near material clusters (adds adoption friction)

## ART 08.066 - Resilient microgrids

Score: 5 (Impact in GVN 6)

Justification: Microgrids align with the GVN's push toward decentralized, resilient processing by making local material sites less vulnerable to central-grid interruptions. Directly they improve uptime and power quality; institutionally they encourage local industrial coordination and new ownership models; feedback-wise they can also create islands of resilience that favor better-capitalized operators first. The impact is significant, especially for distributed circular operations, so 5.

Weak signals (8):

- (+) Reliability of supply → recycling parks, foundries, and construction-material sites install islandable power systems (reduces interruption risk)
- (+) Cost-effectiveness → small and mid-sized process sites justify microgrids against downtime and power-quality losses (changes investment logic)
- (+) Sustainability → local renewables and storage become usable for more material operations once islanding is available (supports decentralization)
- (+) Local economic growth → regional clusters coordinate shared energy assets around material production and recovery (builds local resilience)
- (+) Minimization of adverse effects → power failures cause fewer environmental releases or scrap events in sensitive processes (improves robustness)
- (–) Bargaining power → facility owners with capital gain resilience advantages over smaller competitors (can widen inequality)
- (–) Regulatory alignment → interconnection and tariff disputes slow wider replication (shows institutional friction)
- (–) Security → microgrid control layers become new cyber-critical infrastructure for material sites (adds governance burden)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

Score: 5 (Impact in GVN 6)

Justification: The key route is enabling organisms and biomaterials tailored for fibers, polymers, catalysts, enzymes, forestry inputs, and low-temperature processing. Directly it improves the precision of biological material design; institutionally it intensifies IP, biosafety, and certification battles; feedback-wise it can shift value away from extractive raw materials toward designed living feedstocks. That is significant enough for 5.

Weak signals (8):

- (+) Biotechnology and biomimicry → material firms fund edited microbes, plants, or fungi for fibers, binders, or additives (signals direct materials use)
- (+) Sustainability → substitution programs target toxic or rare inputs with gene-edited bio-based alternatives (aligns with challenger regime)
- (+) Cost-effectiveness → fermentation or cultivation yields improve enough to enter industrial sourcing discussions (moves beyond lab interest)



- (+) Adequate quality → edited bio-based materials begin passing consistency and impurity thresholds needed for procurement (crosses qualification barrier)
- (+) Regulatory alignment → biosafety and product rules start distinguishing industrial-material edits from food or medical uses (opens pathway)
- (–) Bargaining power → patents on edited strains and traits concentrate control over feedstock supply (captures strategic value)
- (–) Existing structures → conventional materials sectors lobby for restrictive rules or slower approval (reveals regime resistance)
- (–) Security/dual-use → containment breaches or biosecurity scares affect public acceptance of industrial use (adds governance cost)

## ART 09.068 - mRNA Therapies & Vaccines

Score: 0 (Impact in GVN 6)

Justification: This ART does not have a meaningful direct pathway to material access, material performance, or supply-system reorganization in this GVN. Spillovers in manufacturing method or cold-chain infrastructure are too weak to count as meaningful here. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Innovation and adaptability → mRNA process equipment starts being repurposed for non-medical material enzymes or bio-additives (would create a first route)
- (+) Cost-effectiveness → material-biotech startups cite mRNA manufacturing spillovers in industrial production tools (signals overlap)
- (+) Regulatory alignment → industrial biotechnology rules borrow directly from mRNA production frameworks (institutional foothold)
- (–) Existing bottlenecks → material firms keep treating mRNA as a health-only platform (confirms non-linkage)

## ART 09.069 - Cellular Agriculture & Cultured Meat

Score: 1 (Impact in GVN 6)

Justification: The strongest materials link is indirect: bioreactor scale-up, protein biomass, and some process platforms can spill into bio-based inputs and specialty materials. That is worth watching, but it is peripheral to the main materials GVN. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Biotechnology and biomimicry → cultured-protein or biomass platforms start selling non-food binders, films, or additives (creates direct route)
- (+) Cost-effectiveness → fermentation infrastructure developed for food is repurposed for industrial biomaterial production (shows asset crossover)
- (+) Sustainability → material firms source functional proteins or cell-derived ingredients from food-adjacent plants (signals spillover use)
- (–) Existing bottlenecks → most investment and regulation stay locked to food markets rather than materials (keeps impact limited)



## ART 09.070 - Organoids & Tissue Engineering

Score: 0 (Impact in GVN 6)

Justification: For this GVN, organoids and tissue engineering are too far from core material access and processing questions. They may help some testing niches, but not enough to amount to a meaningful impact on the operating model. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Minimization of adverse effects → new material-toxicity testing starts using organoid models instead of animal or crude surrogate methods (would create a niche link)
- (+) Regulatory alignment → safety approval for novel materials references organoid-based evidence (institutional foothold)
- (+) Innovation and adaptability → materials labs co-develop testing pipelines with tissue-engineering groups (signals limited overlap)
- (–) Existing bottlenecks → mainstream material firms do not treat organoids as part of supply strategy (confirms non-linkage)

## ART 09.071 - Synthetic Biology & Designer Microbes

Score: 10 (Impact in GVN 6)

Justification: This is one of the most direct matches to the challenger regime because it enables materials and chemical intermediates to be made through biological routes at lower temperatures and often with different feedstocks and plant scales. First-order it can produce polymers, binders, fibers, enzymes, pigments, and specialty chemistries under milder conditions; second-order it shifts power toward strain owners, fermentation infrastructure, and biomass/feedstock supply networks; third-order it can disrupt extractive industries, enable localization, and create biosafety and IP conflicts. That is transformative enough for 10.

Weak signals (9):

- (+) Biotechnology and biomimicry → industrial microbes move from enzyme niches into direct production of material precursors and structural biopolymers (signals core-route emergence)
- (+) Sustainability → projects explicitly replace heat-intensive petrochemical or mining-derived inputs with fermentation routes (aligns with GVN challenger values)
- (+) Cost-effectiveness → room-temperature or low-temperature bio-routes start competing with legacy chemistry on delivered cost (crosses economic threshold)
- (+) Local economic growth → smaller regional bioprocessing plants appear near waste, biomass, or captured-carbon streams (supports decentralized production)
- (+) Reliability of supply → manufacturers add bio-derived alternatives to hedge volatile or geopolitically concentrated material inputs (improves resilience)
- (+) Adequate quality → certification systems accept bio-produced materials with consistent impurity and performance profiles (opens procurement)
- (–) Bargaining power → IP over strains, chassis, and nutrient recipes concentrates value in a few platforms (creates new gatekeepers)
- (–) Existing structures → incumbents push for restrictive standards or public concern over biological production (signals regime resistance)

- (–) Security/dual-use → containment, traceability, or misuse concerns drive biosurveillance requirements for industrial facilities (adds governance burden)

## ART 09.072 - Microbiome Engineering

Score: 3 (Impact in GVN 6)

Justification: The strongest path is steering microbial communities for bioleaching, waste treatment, contamination control, soil/forest feedstock quality, and some low-intensity material transformations. That can materially improve resource recovery and environmental performance, but it is still more specialized than synthetic biology as a broad materials-production platform. So 3 fits.

Weak signals (7):

- (+) Sustainability → tailings, soils, or waste streams are managed through microbiome interventions for recovery or stabilization (shows practical use)
- (+) Reliability of supply → bioleaching or bioremediation improves access to lower-grade or contaminated resources (extends usable feedstocks)
- (+) Minimization of adverse effects → microbial community management replaces harsher broad-spectrum chemical treatments (reduces environmental burden)
- (+) Cost-effectiveness → operators begin paying for microbiome management as a service around waste and resource sites (signals economic entry)
- (+) Regulatory alignment → environmental permits reference managed microbial pathways and monitoring protocols (institutionalizes use)
- (–) Security/ecology → unintended spread or ecosystem effects trigger tighter oversight (raises social-license risk)
- (–) Existing structures → variability across sites keeps many buyers cautious about depending on living systems (caps breadth)

## ART 09.073 - Precision Medicine & Genomic Diagnostics

Score: 0 (Impact in GVN 6)

Justification: This ART has no meaningful direct route into material access, supply reliability, or process transformation in this GVN. Workforce-health spillovers are too generic and weak to count. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Minimization of adverse effects → worker-exposure monitoring in hazardous material sectors starts using genomic diagnostics (would create a narrow labor-health route)
- (+) Regulatory alignment → occupational health rules in materials industries begin referencing genomic risk tools (institutional foothold)
- (+) Cost-effectiveness → firms use genomic diagnostics to manage scarce specialist labor retention in hazardous jobs (signals indirect overlap)
- (–) Existing bottlenecks → core material strategy remains unaffected by precision-medicine capabilities (confirms non-linkage)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

Score: 1 (Impact in GVN 6)

Justification: The best route is faster, more realistic testing of toxicity, exposure, and biological interactions for novel materials and coatings. That can ease some approval and safety bottlenecks, but it is still a supporting tool rather than a major driver of material-system change. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Minimization of adverse effects → new coatings and additives begin using organ-on-chip assays for safety screening (creates a direct testing route)
- (+) Regulatory alignment → material safety dossiers start including chip-based biological evidence (institutional entry point)
- (+) Innovation and adaptability → faster biological screening shortens iteration on novel material chemistries (supports R&D speed)
- (–) Existing bottlenecks → scaling, certification, and cost still dominate more than biological assay speed (keeps impact limited)

## ART 09.075 - Biological Aging & Longevity Barriers

Score: 0 (Impact in GVN 6)

Justification: While longevity therapies could alter labor markets in the long run, they do not plausibly change the material system in a targeted or meaningful way for this GVN. The linkage is too broad and diffuse. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → hazardous material sectors start treating longevity interventions as retention tools for rare experts (would create a narrow labor route)
- (+) Cost-effectiveness → firms model longer specialist careers against retraining needs in transition-intensive sectors (signals indirect overlap)
- (+) Regulatory alignment → occupational health frameworks in heavy industry mention longevity interventions (institutional foothold)
- (–) Existing bottlenecks → material strategy still centers on process, feedstocks, and regulation, not worker age-extension (confirms non-linkage)

## ART 09.076 - Engineered Living Materials

Score: 10 (Impact in GVN 6)

Justification: This ART directly matches the challenger regime's push toward biologically mediated, lower-energy, more regenerative material systems. First-order it enables self-healing, moisture-managing, carbon-sequestering, or adaptive construction and manufacturing materials; second-order it shifts supply chains toward bioprocess control, nutrient/activation regimes, and new testing/certification systems; third-order it can displace inert high-energy materials in some uses while creating biosafety and maintenance-governance issues. That is transformative enough for 10.

Weak signals (9):

- (+) Sustainability → construction and infrastructure pilots specify living materials for self-repair or carbon-mineralizing functions (signals direct substitution path)
- (+) Cost-effectiveness → lifecycle models begin favoring regenerative materials over repeated repair and replacement (changes investment logic)
- (+) Reliability of supply → structures use in-place self-healing to reduce emergency maintenance dependence (improves resilience)
- (+) Functionality → materials are sold with active moisture, crack, or surface-response capabilities rather than passive properties alone (changes product logic)
- (+) Adequate quality → certification programs emerge for living-material behavior under real temperature and humidity cycles (opens procurement)
- (+) Local economic growth → regional bioprocessing and fabrication hubs form around locally sourced living-material inputs (supports localization)
- (–) Regulatory alignment → biosecurity, sterility, and accountability rules slow acceptance in mainstream construction (signals institutional friction)
- (–) Bargaining power → activator recipes, starter cultures, and monitoring platforms become proprietary choke points (concentrates control)
- (–) Public trust/security → failures or unintended biological persistence trigger social-license conflicts (tests deployment legitimacy)

## ART 09.077 - Gene Drive Pest Control

Score: 1 (Impact in GVN 6)

Justification: The plausible link is protection of forestry, biomass, or agricultural feedstocks used in material chains. That could matter in specific regions or sectors, but it is too indirect and governance-heavy to count as a major GVN driver. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → forestry and biomass sectors begin evaluating gene drives against feedstock pests (creates direct but narrow route)
- (+) Sustainability → pressure rises for pest control that avoids repeated chemical treatment of material crops (supports alternative interest)
- (+) Regulatory alignment → environmental authorities discuss gene-drive use for strategic bio-based feedstocks (institutional foothold)
- (–) Security/ecology → reversibility and ecosystem-risk concerns dominate early debate (keeps practical impact limited)

## ART 09.078 - Artificial Wombs & Synthetic Embryos

Score: 0 (Impact in GVN 6)

Justification: There is no meaningful route from this ART to broad material availability or supply-system transformation in this GVN. Any overlap would be extremely indirect. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Biotechnology and biomimicry → developmental-biology platforms start being repurposed for industrial biomaterial cultivation (would create a first route)

- (+) Innovation and adaptability → non-medical material labs borrow synthetic-embryo process controls for niche biofabrication (signals overlap)
- (+) Regulatory alignment → industrial biotechnology guidance references artificial-womb bioreactor methods (institutional foothold)
- (–) Existing bottlenecks → materials-sector budgets and standards remain disconnected from the field (confirms non-linkage)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

Score: 3 (Impact in GVN 6)

Justification: The main pathways are remote connectivity plus continuous Earth observation for exploration, forestry, logistics, environmental compliance, and disruption response. That materially helps supply visibility and remote operations, but it remains an enabling layer rather than a core material-production transformation. So 3 fits.

Weak signals (7):

- (+) Reliability of supply → remote extraction, forestry, and recycling sites standardize on constellation-backed connectivity (reduces communications fragility)
- (+) Sustainability → Earth-observation feeds become routine for stockpile, land-use, and environmental compliance monitoring (improves oversight)
- (+) Cost-effectiveness → operators use frequent satellite observations to replace some ground surveys and travel (cuts coordination burden)
- (+) Local economic growth → peripheral regions become more investable for monitored, connected material operations (widens geographic options)
- (+) Regulatory alignment → permits and insurance increasingly accept satellite-derived evidence for site status (normalizes remote verification)
- (–) Bargaining power → a few constellation operators control critical communications and sensing pipelines (concentrates dependence)
- (–) Security → orbital outages, jamming, or data restrictions become material-supply risks (adds geopolitical fragility)

### ART 10.080 - Space Resource Utilization (SRU)

Score: 3 (Impact in GVN 6)

Justification: If Earth-return SRU matures, the materials-GVN relevance is mostly around rare, high-value metals and the bargaining power of terrestrial suppliers. Directly it does little for bulk construction materials, but institutionally it could alter critical-material strategy, provenance, and geopolitical dependence. That is meaningful yet still narrower than the core GVN, so 3.

Weak signals (7):

- (+) Reliability of supply → strategic-material planning begins including off-Earth concentrate as a hedge against terrestrial concentration (signals policy relevance)
- (+) Cost-effectiveness → high-value metals are priced against expected SRU returns in long-term contracts (shows market anticipation)

- (+) Sustainability → supply-security narratives cite lower terrestrial mining pressure for specific scarce metals (supports niche acceptance)
- (+) Regulatory alignment → customs, ownership, and assay rules are drafted for returned extraterrestrial material (creates institutional pathway)
- (+) Adequate quality → buyers define purity and chain-of-custody requirements for SRU-origin metal inputs (moves toward procurement reality)
- (–) Bargaining power → access is likely concentrated in a few mission operators and financiers (limits broad benefit capture)
- (–) Existing structures → bulk material systems remain largely untouched, keeping overall breadth moderate (caps score)

## ART 10.081 - Closed-Loop Life Support System

Score: 0 (Impact in GVN 6)

Justification: Closed-loop life support may offer conceptual spillovers for circular process design, but that is too indirect to count as a meaningful impact on this GVN. The Earth-side materials system does not depend on this technology. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Sustainability → terrestrial industrial ecologists directly transfer life-support loop designs into material parks (would create a first route)
- (+) Innovation and adaptability → circular-manufacturing vendors market spinouts from habitat life-support systems (signals overlap)
- (+) Cost-effectiveness → small closed-loop utility modules derived from space tech enter remote material sites (niche crossover)
- (–) Existing bottlenecks → material firms do not treat life-support systems as part of their transition toolkit (confirms non-linkage)

## ART 10.082 - High-Altitude Platforms & Balloons

Score: 1 (Impact in GVN 6)

Justification: The relevant route is temporary sensing and connectivity over remote or disrupted material geographies. That has some value in emergencies and sparse areas, but it is not a major determinant of how materials are produced, moved, or recycled overall. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → remote forestry, mining, or disaster-debris operations use HAPs for temporary connectivity and mapping (creates niche value)
- (+) Minimization of adverse effects → environmental monitoring over large waste or extraction areas shifts to persistent aerial platforms (improves oversight)
- (+) Cost-effectiveness → operators use HAPs where satellites are too coarse and towers too slow to deploy (signals narrow fit)
- (–) Existing structures → long-term materials operations still prefer terrestrial or orbital infrastructure (keeps impact limited)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

Score: 3 (Impact in GVN 6)

Justification: The meaningful route is shared provenance, custody, automated settlement, and programmable claims across fragmented material chains. That can reduce reconciliation and fraud, especially in circular and cross-border flows; institutionally it shifts trust from bilateral relationships to protocol and platform operators; feedback-wise it can also add complexity and speculative behavior. The impact is real but not foundational enough for more than 3.

Weak signals (7):

- (+) Reliability of supply → recycled and critical-material trades begin using tamper-evident custody records (improves traceability across many actors)
- (+) Sustainability → claims about recycled content or origin are settled through shared digital proofs rather than PDFs (reduces dispute friction)
- (+) Cost-effectiveness → contract execution for secondary materials becomes more automated and faster (cuts admin overhead)
- (+) Regulatory alignment → customs, EPR, or compliance pilots accept protocol-based provenance proofs (institutionalizes use)
- (+) Local economic growth → smaller recyclers join wider markets once trust requirements are easier to satisfy (widens participation)
- (–) Bargaining power → protocol, wallet, or token infrastructure captures rents and standards control (creates new gatekeepers)
- (–) Volatility/security → fraud, bridge failures, or speculative tokens damage trust in material-chain use cases (slows adoption)

### ART 11.084 - Platform Cooperatives & Fair Work

Score: 1 (Impact in GVN 6)

Justification: The clearest route is organizing distributed repair, salvage, waste collection, or local fabrication labor on fairer digital terms. That may matter at the margin, but it does not strongly shift the material system's main technological and regulatory bottlenecks. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Local economic growth → worker-owned platforms begin organizing repair, salvage, and material-recovery labor (creates a social-organization route)
- (+) Sustainability → co-op marketplaces make local reuse and small-batch fabrication easier to coordinate (supports circular participation)
- (+) Bargaining power → municipalities favor co-op platforms in waste and reuse procurement (tests institutional support)
- (–) Existing structures → large incumbent logistics and recycling operators still dominate high-volume flows (keeps impact limited)



## ART 11.085 - Open Data Sharing Marketplaces

Score: 3 (Impact in GVN 6)

Justification: Materials systems suffer from fragmented data on quality, availability, demand, and process performance, so marketplaces for governed sharing can materially reduce information bottlenecks. Operationally they improve matching and learning; institutionally they lower barriers for smaller actors while creating new platform control points; feedback-wise they can also raise re-identification and trade-secret disputes. The likely scale is material but enabling, so 3.

Weak signals (7):

- (+) Reliability of supply → marketplaces begin listing real-time secondary-material availability with machine-readable quality fields (improves matching)
- (+) Adequate quality → buyers pay for verified process or composition datasets to reduce procurement uncertainty (prices better information)
- (+) Cost-effectiveness → firms stop building bespoke bilateral data integrations for common material queries (cuts coordination friction)
- (+) Local economic growth → smaller recyclers and labs monetize niche data they could not previously market (widens participation)
- (+) Regulatory alignment → compliance and passport data access is brokered through standardized licenses and APIs (institutionalizes exchange)
- (–) Bargaining power → marketplace operators control discovery, standards, and fees for data-rich material ecosystems (creates new gatekeepers)
- (–) Trust/security → disputes over provenance, misuse, or reverse engineering slow cross-firm participation (keeps adoption bounded)

## ART 11.086 - Secure & Resilient Social Platforms

Score: 1 (Impact in GVN 6)

Justification: The strongest link is more robust coordination among distributed workers, communities, and multi-party projects during disruptions or contested conditions. That matters in edge cases, but it is not a primary lever on material access or production. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → emergency material-distribution and repair communities migrate to resilient platforms during outages (shows niche coordination value)
- (+) Local economic growth → reuse and maker networks prefer interoperable community platforms over centralized apps (supports small-scale collaboration)
- (+) Security → sensitive industrial communities adopt stronger privacy and redundancy for coordination (signals narrow uptake)
- (–) Existing bottlenecks → mainstream material procurement and production remain on formal enterprise systems (keeps impact limited)

## ART 11.087 - Collective Open Innovation Networks

Score: 5 (Impact in GVN 6)

Justification: This aligns strongly with a GVN that needs rapid exploration of new materials,

recycling methods, and decentralized process models while knowledge is scattered. First-order it reduces team-assembly and experimentation friction; second-order it broadens participation beyond incumbent R&D hierarchies; third-order it can shift value toward whoever controls challenge platforms, validation rules, and shared infrastructure. The likely impact on innovation speed and diversity is significant, so 5.

Weak signals (8):

- (+) Innovation and adaptability → material challenges move from closed R&D programs to open, versioned multi-actor platforms (widens problem-solving base)
- (+) Sustainability → consortia post substitution and circularity problems publicly with shared test criteria (targets challenger priorities)
- (+) Cost-effectiveness → firms use distributed challenge networks before funding full internal programs (cuts failed search costs)
- (+) Adequate quality → benchmark datasets and validation traces become standard outputs of collaborative materials work (improves comparability)
- (+) Local economic growth → SMEs, labs, and regional actors win material innovation work without long procurement cycles (widens access)
- (–) Bargaining power → platform owners define reputation, IP terms, and visibility (captures value from open collaboration)
- (–) Existing structures → incumbent firms participate selectively while keeping high-value data private (limits openness)
- (–) Security/IP → disputes rise over reuse of shared results and sensitive process inputs (tests governance)

## ART 11.088 - Scalable Decentralized Governance

Score: 1 (Impact in GVN 6)

Justification: This can support multi-party management of shared assets or local material commons, but it is not a main bottleneck for manufacturing and construction materials at large. The effect is possible yet peripheral. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Local economic growth → shared repair, reuse, or maker assets begin using on-platform governance for pooled decisions (creates a narrow institutional route)
- (+) Bargaining power → circular cooperatives test coded governance over shared equipment and budgets (signals limited fit)
- (+) Regulatory alignment → public pilots allow machine-readable governance for community material infrastructures (institutional foothold)
- (–) Existing structures → mainstream supply chains still rely on conventional corporate and contractual governance (keeps impact limited)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

Score: 5 (Impact in GVN 6)

Justification: Skills are an explicit inhibitor in the GVN, so scalable learning and portable credentials have unusually strong second-order importance here. Directly they accelerate retraining

into recycling, advanced materials, bio-based production, and decentralized manufacturing; institutionally they lower entry barriers and make capabilities more legible across firms; feedback-wise they may also concentrate training standards in a few platforms. Because labor transition and expertise diffusion are make-or-break for the challenger regime, 5 is justified.

Weak signals (8):

- (+) Limited awareness and expertise → material-transition roles are filled through microcredentials rather than legacy degrees alone (signals skills-market shift)
- (+) Local economic growth → regional hubs use digital credentialing to stand up new recycling and advanced-material workforces quickly (supports localization)
- (+) Cost-effectiveness → firms shorten onboarding for new processes using networked training plus verified competency proofs (cuts transition costs)
- (+) Reliability of supply → scarce maintenance and quality roles become easier to source across sites through portable credentials (improves staffing resilience)
- (+) Regulatory alignment → inspectors, buyers, or insurers recognize digital skill proofs for specific material operations (institutional acceptance)
- (–) Bargaining power → large platforms define what counts as valid skill in emerging material domains (captures educational control)
- (–) Existing structures → incumbent training systems and unions contest fast credential routes (reveals transition friction)
- (–) Quality risk → poor credential inflation or weak assessment harms trust in new workforce pipelines (tests credibility)

## ART 11.090 - Prediction-Market Forecasting Platforms

Score: 1 (Impact in GVN 6)

Justification: Better forecasting can help demand, price, and disruption planning, but this remains a decision-support layer rather than a major driver of how materials are produced or recovered. The effect is worth watching but limited. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → material buyers start using market-based forecasts for disruption and price planning (creates a narrow planning route)
- (+) Cost-effectiveness → forecast platforms are plugged into inventory and procurement systems for key materials (signals limited operational use)
- (+) Regulatory alignment → public agencies test prediction markets for critical-material policy decisions (institutional foothold)
- (–) Existing bottlenecks → firms still treat hard process and certification constraints as more binding than forecast quality (keeps impact limited)

## 12. Protocols, Standards & Socio-Technical Infrastructure

## ART 12.091 - Universal IoT Interoperability Standards

Score: 5 (Impact in GVN 6)

Justification: This is a strong enabler because sensorization of materials flows only becomes economical at scale when devices from many vendors can work together cheaply and securely. Directly it reduces integration time and maintenance friction; institutionally it makes product passports, distributed monitoring, and multi-party automation more feasible; feedback-wise it can also create standard-setting power struggles. The total effect is significant enough for 5.

Weak signals (8):

- (+) Cost-effectiveness → material operators stop funding custom gateways for each sensor vendor (reduces integration drag)
- (+) Reliability of supply → mixed fleets of trackers, meters, and condition sensors are deployed across yards and plants as one system (improves visibility)
- (+) Sustainability → circular programs attach interoperable device identities to bins, parts, and recovered streams (supports scalable tracking)
- (+) Adequate quality → common schemas let buyers compare condition and composition data across suppliers (improves trust)
- (+) Regulatory alignment → product-passport and industrial-monitoring rules reference open device profiles (institutionalizes standards)
- (–) Bargaining power → dominant firms fight to shape “open” standards around their installed base (reveals governance conflict)
- (–) Security → widely used standard stacks become attractive common attack surfaces (adds cyber coordination burden)
- (–) Existing structures → legacy assets remain expensive to migrate, slowing full-system benefits (keeps dual-speed transition)

## ART 12.092 - Interoperable Digital Twin Ecosystems

Score: 5 (Impact in GVN 6)

Justification: Interoperable twins matter because material assets live across long lifecycles, many owners, and multiple software stacks. First-order they reduce duplicate modeling and speed diagnosis; second-order they make design-production-recovery information more portable across organizations; third-order they can shift power toward whoever controls twin schemas, identities, and permitted use. The impact is significant, especially for circular and distributed systems, so 5.

Weak signals (8):

- (+) Reliability of supply → twins of equipment, inventories, and infrastructure begin surviving contractor and owner changes (improves continuity)
- (+) Adequate quality → design, process, and end-of-life data travel together instead of being rebuilt in each software silo (supports lifecycle consistency)
- (+) Sustainability → reuse and recycling decisions draw on interoperable asset histories rather than fresh manual inspection alone (improves recovery decisions)
- (+) Cost-effectiveness → plants cut integration budgets when twins move between vendors without custom rebuilds (reduces friction)
- (+) Regulatory alignment → compliance and maintenance records are linked into portable twin packages (normalizes shared evidence)

- (–) Bargaining power → schema owners and major cloud platforms compete to control interoperability baselines (creates new gatekeepers)
- (–) Security → twin identity and permission failures become high-impact operational issues (raises trust requirements)
- (–) Existing structures → poorly instrumented legacy assets lag behind newer twin-rich equipment (deepens transition divide)

## ART 12.093 - Global Supply Chain Traceability Networks

Score: 10 (Impact in GVN 6)

Justification: This directly addresses several GVN values at once: supply reliability, sustainability, adverse-effects control, and material quality. First-order it makes provenance, composition, handling, and custody visible; second-order it changes financing, procurement, compliance, and bargaining across global and circular flows; third-order it can either empower smaller trusted suppliers or let dominant buyers impose costly data demands. Because traceable origin and composition are central to scaling recycled, bio-based, and responsible materials, the impact is transformative enough for 10.

Weak signals (9):

- (+) Reliability of supply → buyers demand live provenance and custody visibility for critical and recycled materials (changes baseline procurement)
- (+) Sustainability → recycled-content and responsible-sourcing claims shift from static certificates to event-linked trace histories (raises claim credibility)
- (+) Adequate quality → composition, handling, and transformation records become prerequisites for high-value secondary materials (improves bankability)
- (+) Cost-effectiveness → root-cause analysis of contamination or failure increasingly relies on shared trace networks rather than manual audits (cuts dispute costs)
- (+) Regulatory alignment → customs, EPR, and product-passport regimes converge on interoperable traceability data fields (institutional lock-in)
- (+) Local economic growth → smaller suppliers gain market access once they can prove origin and quality digitally (widens participation)
- (–) Bargaining power → major buyers and platform operators dictate data burdens and fee structures (can squeeze smaller actors)
- (–) Existing structures → opaque intermediaries and informal supply chains lose position as proof requirements tighten (signals regime disruption)
- (–) Security/fraud → counterfeit tags, forged events, or data withholding become strategic enforcement problems (tests system integrity)

## ART 12.094 - Personal Data Portability & Trust Frameworks

Score: 0 (Impact in GVN 6)

Justification: This framework is primarily about individual personal data rather than material provenance, industrial assets, or process coordination. It has no meaningful direct path to the core GVN. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → workers carry portable skills and training data into material-sector credential systems (would create an indirect route)
- (+) Regulatory alignment → industrial workforce systems start using personal data wallets for access and certification (institutional foothold)
- (+) Cost-effectiveness → labor mobility in new material clusters improves through portable records (signals narrow overlap)
- (–) Existing bottlenecks → material supply, chemistry, and certification remain far more important than personal-data portability (confirms non-linkage)

## ART 12.095 - Interoperable Digital Currency Payment Networks

Score: 1 (Impact in GVN 6)

Justification: Faster, more interoperable settlement can reduce some cross-border friction in material trade and local circular transactions, but payments are not the main bottleneck in this GVN. The effect is concrete yet limited. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Reliability of supply → smaller cross-border material suppliers get paid through interoperable digital rails faster than legacy banking allows (creates a trade route)
- (+) Local economic growth → reuse and recycling marketplaces adopt low-friction programmable payments (supports smaller actors)
- (+) Cost-effectiveness → procurement systems automate conditional settlement on delivery and quality proofs (reduces admin friction)
- (–) Existing bottlenecks → quality assurance, certification, and logistics still dominate more than payment speed (keeps impact limited)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

Score: 5 (Impact in GVN 6)

Justification: Regulatory barriers are explicit inhibitors in the GVN, so turning rules into machine-readable, updateable logic has unusually high leverage. First-order it reduces interpretation delays in compliance-heavy material systems; second-order it lowers adoption friction for new materials, recycling pathways, and local production models; third-order it can also advantage actors with the strongest compliance software stacks. That is significant enough for 5.

Weak signals (8):

- (+) Regulatory alignment → chemical, construction, and waste rules begin publishing machine-readable compliance logic alongside text (signals operationalization)
- (+) Cost-effectiveness → firms automate permit checks, labeling, and eligibility screening for new material routes (cuts interpretation overhead)
- (+) Innovation and adaptability → novel materials are tested against codified rule sets before costly qualification work (reduces dead-end development)
- (+) Reliability of supply → rule changes propagate faster into procurement and logistics systems (lowers transition lag)
- (+) Limited expertise → smaller firms use packaged compliance engines instead of specialist legal teams (widens access)



- (–) Bargaining power → compliance-platform vendors become gatekeepers for interpreting and updating rules (concentrates institutional power)
- (–) Existing structures → ambiguous discretionary rules remain outside code, preserving incumbent advantage in gray zones (limits full effect)
- (–) Accountability → disputes rise over whether coded logic captures legal intent correctly (tests legitimacy)

## ART 12.097 - Open Metaverse Interoperability Protocols

Score: 0 (Impact in GVN 6)

Justification: Despite possible design or training spillovers, open metaverse protocols do not meaningfully alter material access, quality, or supply structure in this GVN. The linkage is too weak and indirect. So 0.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Limited expertise → material-training and plant-design workflows begin depending on interoperable 3D environments (would create an indirect route)
- (+) Innovation and adaptability → shared virtual design spaces become common in distributed materials collaboration (signals overlap)
- (+) Regulatory alignment → conformance or safety training for new material processes uses portable immersive environments (institutional foothold)
- (–) Existing bottlenecks → procurement, feedstocks, and certification continue to matter far more than immersive interoperability (confirms non-linkage)

## ART 12.098 - Content Authenticity Infrastructure

Score: 1 (Impact in GVN 6)

Justification: The meaningful route is more trustworthy documentation of inspections, quality evidence, provenance claims, and remote support content. Useful, but still a secondary trust layer rather than a primary driver of material-system change. So 1.

Signal density: LOW (linkage weak; additional signals would be speculative).

Weak signals (4):

- (+) Adequate quality → buyers begin requiring credentialed photos and video for remote material inspections (creates a direct documentation route)
- (+) Regulatory alignment → audit and compliance workflows prefer authenticated media from sites and labs (supports evidentiary trust)
- (+) Reliability of supply → dispute resolution over damaged or substituted material shipments leans on signed media trails (reduces claim friction)
- (–) Existing bottlenecks → authenticated media helps proof, but not core process economics or material performance (keeps impact limited)



## ART 12.099 - Privacy-Preserving Collaboration Protocols

Score: 3 (Impact in GVN 6)

Justification: These protocols matter where firms need shared insight on material quality, sourcing, or process performance but cannot pool sensitive data. First-order they lower collaboration friction; second-order they can let smaller firms join sector intelligence without surrendering raw data; third-order they may still centralize power in whoever runs the secure compute layer. The likely effect is material but enabling, so 3.

Weak signals (7):

- (+) Limited expertise → SMEs join shared analytics on defects, yields, and maintenance without exposing raw process data (widens participation)
- (+) Adequate quality → buyers and suppliers run secure joint checks on composition or compliance without full disclosure (supports trust under competition)
- (+) Reliability of supply → critical-material planning uses cross-firm secure analytics rather than manual bilateral reconciliation (improves coordination)
- (+) Regulatory alignment → compliance collaborations use privacy-preserving protocols to satisfy data and competition constraints (opens lawful sharing)
- (+) Cost-effectiveness → secure collaboration replaces costly audit-heavy data-sharing arrangements in some consortia (reduces overhead)
- (–) Bargaining power → neutral-compute or protocol operators become strategic intermediaries (captures coordination value)
- (–) Performance friction → latency and redesign costs limit which analyses are practical (keeps impact bounded)

## ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

Score: 20 (Impact in GVN 6)

Justification: This is a keystone institutional technology for this GVN because many challenger materials and processes fail not on technical promise but on qualification, trust, and comparability. First-order it makes novel materials, additive methods, and circular inputs bankable and contractable; second-order it rewrites procurement, insurance, training, liability, and access to markets; third-order it can either unlock broad diffusion of challengers or be captured by incumbents to slow them down. Given the GVN's explicit regulatory and expertise barriers, this infrastructure is one of the few true linchpins of regime change, so 20.

Weak signals (12):

- (+) Regulatory alignment → standards bodies publish new conformance suites for recycled, bio-based, and additively made materials (opens mainstream qualification)
- (+) Adequate quality → buyers start accepting machine-readable certificates tied to recipes, machines, and batch histories (improves trust at scale)
- (+) Cost-effectiveness → time to qualify a new material or process falls sharply once standardized test routes exist (reduces commercialization delay)
- (+) Reliability of supply → alternative suppliers can enter faster because performance evidence is comparable across sites (improves resilience)

- (+) Sustainability → reused and secondary materials become eligible for more demanding applications once conformance evidence matures (unlocks circular demand)
- (+) Limited awareness and expertise → repeatable test artifacts and procedures reduce dependence on a few experts or bespoke audits (widens access)
- (+) Local economic growth → smaller regional producers gain access to serious markets once certification is portable and legible (broadens participation)
- (+) Innovation and adaptability → designers target known certification pathways from the start rather than retrofitting for approval later (speeds transition)
- (–) Bargaining power → incumbents try to write standards around their own materials, machines, and test labs (reveals governance struggle)
- (–) Existing structures → firms without resources for certification tooling and audits risk exclusion even when technically capable (can widen inequality)
- (–) Security/fraud → forged certificates, test-data tampering, or benchmark gaming become high-value attack surfaces (tests credibility)
- (–) Path dependence → once codified, weak or biased standards can lock in suboptimal material regimes for years (shows systemic stakes)

## GVN 7: Built Environment ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

Score: 5 (Impact in GVN 7)

Justification: In mature form it makes any site, vehicle, and remote community continuously connectable, which weakens the built environment's dependence on prime location and local expert presence. First-order effects are remote inspection, distributed building automation, and more viable living and working in peripheral areas; second-order effects include changed property demand, wider commuting and service catchments, and new dependence on telecom operators. That can plausibly move hundreds of millions of euros of location premiums, travel time, and maintenance cost in a 5.5M society, but a 10 would require telepresence and remote service substitution to become mainstream.

Weak signals (5):

- [Remote areas] → housing developments marketed with guaranteed satellite or mesh service (location penalty shrinking)
- [Municipal facilities] → maintenance contracts bundle always-on connectivity SLAs (remote support normalizing)
- [Planning] → rural work hubs and homes win approvals without fiber extensions (connectivity substituting roads)
- – [Telecom governance] → disputes rise over rooftop and streetside antenna siting (infrastructure externalities surfacing)
- – [Property market] → price gap narrows between connected peripheral and core locations (spatial demand rebalancing)

## ART 01.002 - Ultra-Low Latency Networks

Score: 5 (Impact in GVN 7)

Justification: Millisecond-grade links make remote control, coordinated site robots, and immersive maintenance support stable enough for routine use. The direct effect is better automation in construction, traffic management, and smart buildings; the second-order effect is centralization of expertise and liability into network and service providers, with outage or cyber risk becoming more consequential. That is significant rather than transformative on its own—plausibly in the €100M–€1B band if used across sites, depots, and dense districts.

Weak signals (5):

- [Construction sites] → tenders specify deterministic network performance for machines (teleoperation becoming feasible)
- [Building ops] → edge nodes appear inside business parks and campuses (latency-sensitive control localizing)
- [Mobility systems] → cities certify low-latency corridors for connected traffic control (real-time coordination scaling)
- – [Insurers] → outage clauses appear in robot and teleoperation policies (network dependency priced in)
- [Procurement] → landlords pay premium for latency-guaranteed connectivity (timing becoming infrastructure value)

## ART 01.003 - Edge AI for Sensor Data

Score: 5 (Impact in GVN 7)

Justification: Edge AI turns raw building and infrastructure data into local decisions—fault detection, safety alerts, occupancy management, and machine control—without continuous cloud dependence. That directly improves resilience and response time, while second-order effects include vendor lock-in around models, opaque automated decisions, and lower demand for routine inspection labor. In a 5.5M society it can plausibly affect tens to hundreds of millions of euros of operations and many millions of person-hours, but the full 10 would require broad autonomy without strong human review.

Weak signals (5):

- [Facility management] → BMS upgrades advertise on-device anomaly detection (local judgment moving onsite)
- [Construction safety] → cameras and wearables trigger automatic stop-work alerts (real-time intervention arriving)
- [Utilities] → roadside and pipe sensors send summaries rather than raw feeds (bandwidth burden dropping)
- – [Governance] → procurement adds explainability and audit clauses for edge decisions (accountability pressure rising)
- – [Labor] → fewer routine site visits are budgeted in maintenance frameworks (inspection work shrinking)

## ART 01.004 - Quantum & High-Precision Sensing

Score: 3 (Impact in GVN 7)

Justification: The main built-environment value is niche but real: better subsurface mapping, structural drift detection, indoor positioning, leak detection, and infrastructure surveying in places where coarse sensing forces wide safety margins. Institutional effects show up through altered surveying standards, new high-end service markets, and disputes over which measurements regulators accept. That is material for selected asset classes—tens of millions of euros annually in avoided errors and targeted works—but not a general operating-model shift.

Weak signals (5):

- [Surveying] → tunnel, rail, and foundation projects procure ultra-precision sensing packages (hidden conditions becoming visible)
- [Utilities] → non-destructive leak and location pilots replace some excavation-heavy surveys (precision reducing disruption)
- [Standards] → metrology bodies publish acceptance methods for field precision sensing (regulatory doorway opening)
- – [Procurement] → only flagship assets budget the instruments initially (benefit staying concentrated)
- – [Liability] → design disputes cite sensor-derived subsurface evidence (measurement authority increasing)

## ART 01.005 - Micro/Nano Sensor Networks

Score: 10 (Impact in GVN 7)

Justification: Dense low-cost sensor constellations make the built environment continuously legible at material, room, corridor, street, and network scale. First-order gains are early fault detection, traffic and occupancy awareness, and automated maintenance scheduling; second- and third-order effects include stronger central control over tenants and workers, new cyberattack surfaces, and regulatory pressure for standardized telemetry. The shift from periodic observation to ambient monitoring is large enough to plausibly cross the transformative threshold in a 5.5M society.

Weak signals (6):

- [Buildings] → new developments specify embedded sensor meshes in slabs, façades, and ducts (continuous telemetry normalizing)
- [Municipal infrastructure] → road, bridge, and sewer renewals include sensor-grid line items (civil assets becoming instrumented)
- [Operations] → facility dashboards move from ticket-based to anomaly streams (maintenance logic changing)
- [Standards] → interoperability profiles emerge for high-density sensor fleets (scale deployment becoming practical)
- – [Cybersecurity] → penetration tests cite weak nodes in sensor swarms (attack surface widening)
- – [Power asymmetry] → tenant contracts reference occupancy and environment data ownership (data rights contested)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

Score: 5 (Impact in GVN 7)

Justification: This ART does not add sensing value by itself; it makes sensor-rich buildings, public spaces, and mobility systems politically and legally deployable at larger scale. The direct effect is more acceptable occupancy, safety, and accessibility sensing, while the second-order effect is a shift in bargaining power over what landlords, municipalities, and vendors may observe and monetize. That unlocks material operational value, but a 10 would require privacy-preserving methods to become the default architecture across major building and city systems.

Weak signals (5):

- [Public buildings] → procurement requires on-device anonymization for cameras and microphones (trust barrier lowering)
- [Landlords] → tenant apps expose granular sensing permissions and retention settings (consent becoming operational)
- [Regulators] → guidance approves privacy-preserving occupancy analytics for compliance uses (legal pathway opening)
- – [Vendors] → offers without local processing lose bids in schools and hospitals (raw-data models losing ground)
- [Civil society] → fewer complaints accompany smart-space deployments using local analytics (social license improving)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

Score: 3 (Impact in GVN 7)

Justification: For the built environment the main value is protective: keeping building controls, infrastructure telemetry, access systems, and remote operations trustworthy over long asset lifetimes. Second-order effects include earlier network-refresh cycles, certification burdens, and concentration of advantage in owners who can afford secure upgrades. That is material for critical facilities and city infrastructure, but not large enough by itself to reconfigure how the GVN delivers its goal.

Weak signals (5):

- [Critical facilities] → hospitals, transit nodes, and utilities specify post-quantum upgrades (long-life assets hardening)
- [Certification] → building-control vendors advertise quantum-safe device identity (security becoming procurement criterion)
- – [Capex] → security retrofits are bundled into major BMS replacements only (adoption pacing slow)
- – [Insurance] → cyber policies differentiate between legacy and quantum-resilient networks (risk pricing changing)
- [Public procurement] → secure-comms clauses expand for remote operations centers (integrity concerns rising)

## ART 01.008 - Integrated Sensing and Communication (ISAC)

Score: 5 (Impact in GVN 7)

Justification: ISAC lets the communications layer double as a space-awareness layer, reducing the need for separate occupancy, traffic, and safety sensors in buildings and streets. That can change operations, permitting, and maintenance economics, while second-order effects include more invisible monitoring, conflicts over acceptable resolution, and stronger dependence on telecom actors inside the built environment. It is significant because it can affect both mobility and facilities at scale, though a 10 would require broad regulatory acceptance for routine control use.

Weak signals (5):

- [Transport corridors] → 6G and base-station upgrades are sold with traffic sensing (dual-use infrastructure arriving)
- [Commercial buildings] → indoor connectivity tenders include occupancy analytics from radio reflections (sensor stack collapsing)
- [Municipal planning] → cities test ISAC data for curb, parking, or crowd management (planning data source shifting)
- – [Privacy regulators] → radio-sensing guidance and complaints emerge around passive tracking (social limits surfacing)
- [Vendors] → telecom and BMS suppliers form joint offerings for smart districts (sector boundary blurring)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 7)

Justification: Their built-environment value is mainly as a power-efficient substrate for always-on sensing, local control, and robotics. That can lower energy and latency barriers for smart buildings and infrastructure, while second-order effects include new hardware dependencies and specialized vendor ecosystems. The impact is material but indirect—more enabling layer than primary operating-model shift.

Weak signals (4):

- [Edge devices] → building and roadside controllers advertise event-based AI chips (always-on analytics getting cheaper)
- [Robotics] → site robots extend runtime after low-power accelerator upgrades (field autonomy improving)
- – [Procurement] → buyers demand software-toolchain support before specifying chips (ecosystem bottleneck visible)
- – [Semiconductor supply] → control vendors dual-source specialized accelerators for critical assets (dependency management starting)

## ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

Score: 1 (Impact in GVN 7)

Justification: Better switches help every digital layer in the built environment, but the link is diffuse and mostly folded into other systems rather than visible as a separate change driver. Any effect would arrive through cheaper sensors, controls, or edge devices rather than through facility design or mobility directly. That makes it worth tracking but too indirect for more than limited standalone impact.

Weak signals (4):

- [Building electronics] → controller datasheets tout ultra-low-leakage post-CMOS devices (embedded runtime extending)
  - [Asset OEMs] → long-life control modules promise longer replacement cycles (maintenance interval shifting)
  - – [Procurement] → tenders do not name the device class directly (impact still submerged)
  - [Supply chains] → specialty fabs market rugged variants to infrastructure vendors (niche pathway forming)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

Score: 1 (Impact in GVN 7)

Justification: The plausible path is through niche optimization for urban planning, traffic control, materials, or portfolio scheduling. That could create some value at the level of large owners or public agencies, but it does not directly reshape facilities, construction, or mobility in most settings. Standalone impact therefore remains limited.

Weak signals (4):

- [Major cities and utilities] → pilot contracts test quantum optimization for routing or capex sequencing (niche planning use)
  - [AEC software] → consultants add quantum-backed solvers to premium planning services (specialist market appearing)
  - – [Procurement] → outputs still require classical verification before decisions (trust barrier persisting)
  - – [Budgets] → use stays concentrated in flagship portfolios and agencies (scale still narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

Score: 1 (Impact in GVN 7)

Justification: This mostly changes the economics of data centers, simulation, and high-throughput AI that later feed built-environment tools. The built environment sees the effect indirectly through faster digital twins or analytics, not through a direct shift in how sites are built or used. That keeps the standalone score low.



Weak signals (4):

- [Simulation vendors] → high-end AEC or traffic platforms market optical acceleration (compute-heavy planning improving)
  - [Edge infrastructure] → campus or district servers pilot photonic interconnect modules (local model capacity rising)
  - – [Facility demand] → projects do not redesign spaces around this compute form (spatial effect absent)
  - – [Cloud pricing] → premium simulation tiers remain niche services (impact still back-end)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

Score: 3 (Impact in GVN 7)

Justification: Long-lived, denser memory makes persistent digital twins, high-frequency monitoring, and asset-history archives cheaper and more reliable. That matters institutionally because it expands what can be audited, proven, and monetized across long-lifetime assets. The impact is material for operators and regulators, but it is still an enabling layer under higher-order shifts.

Weak signals (5):

- [Digital twin platforms] → vendors retain full-fidelity asset histories by default (state retention getting affordable)
- [Compliance] → regulators accept richer event logs for long-life assets (audit depth increasing)
- [Maintenance] → operators keep more sensor and video history for failure forensics (learning loop lengthening)
- – [Data governance] → storage-rich platforms face disputes over retention and tenant data (memory enabling surveillance)
- [Procurement] → archival tiers become standard in infrastructure software bids (persistent records normalizing)

## ART 02.014 - Molecular Computing

Score: 0 (Impact in GVN 7)

Justification: No clear built-environment pathway is visible beyond distant spillovers from chemistry or biosensing. It does not plausibly affect how facilities for mobility and activity are planned, built, or operated without a separate, more proximate application layer. For now it sits below the threshold of meaningful standalone impact.

Weak signals (3):

- [Construction materials R&D] → molecular-computing language appears in building-material roadmaps (linkage would be created)
- [Infrastructure sensing] → pilot devices embed molecular logic in site-monitoring packages (application layer emerging)

- [Standards bodies] → built-environment consortia open workstreams on molecular control or sensing (institutional bridge forming)  
Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

Score: 5 (Impact in GVN 7)

Justification: Causal models improve planning, code compliance, maintenance, and retrofit decisions by estimating what interventions will actually change outcomes rather than just extrapolating patterns. That can improve resource allocation across buildings, mobility networks, and land use, while second-order effects include more explicit accountability for assumptions and new disputes over model governance. In a 5.5M society the avoided rework, downtime, and policy mistakes can plausibly reach the significant 5 band.

Weak signals (5):

- [Planning agencies] → scenario tools expose intervention effects, not only forecasts (policy design maturing)
- [Facility portfolios] → retrofit programs rank measures by causal effect (capex targeting improving)
- [Codes] → regulators ask modelers to show counterfactual audit trails (assumption transparency rising)
- – [Liability] → project disputes cite causal-model assumptions after underperformance (model governance contested)
- [Software market] → BIM and BMS vendors add “what-if” engines (decision support deepening)

#### ART 03.016 - Federated & Privacy-Preserving Learning

Score: 5 (Impact in GVN 7)

Justification: This ART lets building owners, municipalities, hospitals, campuses, and utilities train shared models without pooling raw operational or personal data. Directly, that improves maintenance, occupancy, and traffic models; institutionally, it redistributes value from central platforms toward consortia and local operators while lowering some privacy barriers. The impact is significant if major portfolios collaborate, but not necessarily transformative without broader automation layers.

Weak signals (5):

- [Building portfolios] → landlords join shared model programs without central raw-data lakes (collaboration barrier dropping)
- [Municipal mobility] → cities train traffic models across districts via local nodes (cross-owner learning scaling)
- [Procurement] → tenders ask for federated training compatibility in BMS and ITS platforms (architecture shifting)

- – [Governance] → data-sharing agreements shrink while compute-governance clauses expand (institutional logic changing)
- [Competition] → smaller owners gain access to benchmark-quality models (platform power redistributing)

## ART 03.017 - Trustworthy AI Systems

Score: 10 (Impact in GVN 7)

Justification: Because the built environment is safety-critical and regulation-heavy, trustworthy AI is a direct adoption gate for autonomous construction, building control, mobility, permitting, and inspection. Its first-order value is safer and auditable automation; second- and third-order effects include faster regulatory acceptance, clearer liability allocation, but also more formalized exclusion if certified systems become mandatory. If trustworthiness becomes the basis on which high-stakes automation is licensed, the annual effect in a 5.5M society plausibly crosses the transformative threshold.

Weak signals (6):

- [Regulators] → AI assurance cases become mandatory for building-control or mobility deployments (licensing gate forming)
- [Procurement] → public clients require traceability, fallback modes, and bias audits (trust becoming spend item)
- [Insurers] → premiums discount certified self-monitoring AI stacks (risk transfer updating)
- [Courts and liability] → incident investigations rely on AI provenance logs (accountability infrastructure hardening)
- – [Market structure] → only vendors with certified assurance pipelines win large contracts (barriers to entry rising)
- – [Labor] → oversight roles shift from operation to audit and escalation (work content changing)

## ART 03.018 - Automated Machine Learning (AutoML)

Score: 3 (Impact in GVN 7)

Justification: AutoML lowers the expertise barrier for routine optimization across buildings, sites, and transport operations. That can speed experimentation and spread analytics beyond top-tier owners, but it also increases the number of mediocre or weakly governed models in live environments. The overall effect is material, though mostly as productivity gain and governance burden rather than a sectoral transformation.

Weak signals (5):

- [Facility management] → non-specialist teams deploy predictive models through low-code tools (analytics democratizing)
- [SME contractors] → smaller firms start using automated risk and maintenance models (capability diffusing downward)
- – [Governance] → owners create model-approval boards after poor deployments (quality control tightening)
- [Software vendors] → BMS and CMMS suites add one-click model generation (routine modeling commoditizing)

- – [Documentation] → audit failures cite missing model lineage from AutoML pipelines (oversight lagging)

## ART 03.019 - Collaborative Multi-Agent AI

Score: 10 (Impact in GVN 7)

Justification: Multi-agent AI is a strong fit for the built environment because assets, robots, vehicles, sensors, and service actors are inherently distributed. Directly it enables coordinated construction sites, adaptive traffic, and shared maintenance fleets; second- and third-order effects include concentration of control in orchestration platforms, new collective failure modes, and shifts from fixed staffing to supervision. At city and portfolio scale that plausibly changes everyday operations for hundreds of thousands of users and workers, so the 10 band is justified.

Weak signals (6):

- [Construction] → sites run shared task allocators across robots, cranes, and crews (coordination logic changing)
- [Buildings] → districts coordinate HVAC, storage, lifts, and cleaning fleets (portfolio-level control emerging)
- [Mobility] → cities pilot agent-based curb, parking, and transit management (distributed control normalizing)
- [Vendors] → orchestration platforms replace single-device dashboards in procurement (control layer centralizing)
- – [Cybersecurity] → failures spread across connected agents during incidents (systemic coupling appearing)
- – [Labor] → supervisors manage larger mixed human-machine fleets per shift (attention bottleneck moving upward)

## ART 03.020 - Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 7)

Justification: The plausible route is better optimization or search inside high-end planning tools, not a direct built-environment shift. Benefits would be concentrated in large portfolios, infrastructure agencies, or vendors running complex simulations. That makes it worth watching, but the standalone impact remains limited.

Weak signals (4):

- [AEC and ITS software] → premium solvers advertise hybrid quantum routines (niche performance edge appearing)
- [Major owners] → digital planning programs test quantum-assisted optimization (early concentrated adoption)
- – [Operations] → no frontline workflows depend on the quantum layer yet (limited operational penetration)
- – [Procurement] → buyers still frame gains as optional accelerator services (not core infrastructure)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

Score: 1 (Impact in GVN 7)

Justification: Its effect on the built environment is mostly upstream through faster discovery of materials, designs, and control strategies. That matters over time but is too indirect to count as a major standalone impact on how facilities are delivered. The linkage stays limited unless discovery systems become tightly tied to construction product pipelines.

Weak signals (4):

- [Materials labs] → building-material firms use autonomous discovery for new cements and coatings (upstream linkage forming)
- [Codes] → test programs accelerate approval of AI-discovered materials (translation path opening)
- – [Construction practice] → site operations remain mostly unaffected directly (distance from use remains large)
- – [R&D spending] → adoption is concentrated in large suppliers and public labs (narrow initial footprint)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

Score: 10 (Impact in GVN 7)

Justification: The GVN already points to VR and AR as a challenger-regime driver because it changes both how space is designed and how much physical space is needed for work, services, and social activity. Direct effects include remote inspection, design review, training, and partial substitution of travel and floor area; second-order effects include new premium on digitally instrumented spaces, accessibility gains for some users, and exclusion for others. At population scale that is plausibly transformative in both land use and facility operations.

Weak signals (6):

- [Design and procurement] → public projects require immersive model reviews (workflow shifting spatially)
- [Maintenance] → service contracts include remote mixed-reality expert support (travel substitution growing)
- [Corporate real estate] → new offices cut fixed desks and add immersive rooms (space demand changing)
- [Remote living] → peripheral housing markets sell “telepresence-ready” homes (location logic weakening)
- – [Safety] → incident reports track headset distraction in active worksites (new operational risk surfacing)
- – [Accessibility and equality] → schools or employers subsidize devices to avoid exclusion complaints (digital access becoming civic issue)

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 1 (Impact in GVN 7)

Justification: BCIs matter to the built environment mainly through accessibility and specialized control interfaces for people who cannot use conventional inputs. That is socially valuable but unlikely to reshape construction, land use, or mainstream facility operations on its own. The impact is therefore limited but concrete.

Weak signals (4):

- [Accessibility] → assistive-housing pilots include BCI-based environmental control (niche control use appearing)
- [Rehabilitation facilities] → smart-building systems certify BCI input compatibility (accessibility stack widening)
- – [Standards] → mainstream building codes still treat BCIs as exceptional assistive tech (not system-wide yet)
- – [Procurement] → demand is concentrated in care and disability services (limited deployment base)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 5 (Impact in GVN 7)

Justification: Exoskeletons and advanced prosthetics directly affect construction work, maintenance labor, and the accessibility of buildings and public spaces. They can extend who can do physically demanding tasks and reduce injuries, while second-order effects include new expectations for worker productivity, insurance changes, and a slower retirement of physically strained roles. In a 5.5M society that is significant across labor, inclusion, and safety, though not fully transformative without broader automation.

Weak signals (5):

- [Construction labor] → major contractors buy exoskeleton fleets for repetitive tasks (injury-control becoming routine)
- [Insurance] → workers' compensation premiums shift for firms with wearables (risk pricing adapting)
- [Accessibility] → transit nodes and public buildings redesign around augmented mobility users (user profile broadening)
- – [Labor relations] → unions contest productivity targets linked to powered wearables (augmentation coercion appearing)
- [Training] → licenses emerge for exoskeleton use onsite (new work standard forming)

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 3 (Impact in GVN 7)

Justification: These systems mostly matter where remote or assisted manipulation is hard—maintenance, inspection, training, and accessibility. They improve precision and confidence, but their effect depends on broader teleoperation and robotics adoption. That keeps the standalone impact material but limited.

Weak signals (5):

- [Remote maintenance] → utility teams trial haptic teleoperation for delicate repairs (remote dexterity improving)
- [Training] → vocational simulators add force and tactile feedback (skills transfer strengthening)
- – [Procurement] → uptake clusters in high-risk or high-precision tasks only (general use still narrow)
- – [Safety] → incident reports distinguish haptic versus non-haptic systems (performance evidence forming)
- [Accessibility] → assistive interfaces offer richer tactile cues for navigation (inclusive control expanding)

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 5 (Impact in GVN 7)

Justification: Intent-aware AI can make buildings, public spaces, and mobility services adapt more smoothly to users, especially for accessibility, safety, and service coordination. Second-order effects include more behavioral inference by landlords and municipalities, new fairness disputes, and a stronger premium on data-rich environments. That is significant because it changes how facilities respond to people, even if it stops short of full operating-model transformation.

Weak signals (5):

- [Smart buildings] → interfaces shift from command menus to context-aware assistance (friction of use dropping)
- [Accessibility] → public-service pilots infer need for guidance without explicit requests (support becoming anticipatory)
- [Facility security] → systems distinguish confusion, distress, and routine behavior in alerts (human-state sensing operationalized)
- – [Privacy] → complaints rise over emotional or behavioral inference in workplaces and public spaces (social acceptability tested)
- – [Governance] → procurement adds bias and consent rules for contextual inference (institutional guardrails forming)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 0 (Impact in GVN 7)

Justification: No meaningful direct pathway to built-environment design, construction, mobility, or asset operation is visible beyond speculative collaboration effects. The technology could matter socially in general, but not yet as a distinct change driver for this GVN. It remains below the threshold for a plausible standalone impact.

Weak signals (3):

- [Remote operations] → experimental site-control systems test direct neural exchange (application layer would be emerging)



- [Accessibility research] → assistive programs mention BBI-mediated coordination (niche bridge forming)
  - [Standards] → HMI standards groups open work on inter-brain channels (institutional relevance appearing)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

Score: 0 (Impact in GVN 7)

Justification: Any built-environment effect would be indirect through general human capability, not through facilities or mobility systems themselves. There is no clear pathway to major change in construction, maintenance, spatial form, or infrastructure governance. Standalone impact is therefore not meaningful here.

Weak signals (3):

- [Critical operations] → maintenance systems pilot memory-support implants for workers (linkage would be created)
  - [Accessibility housing] → assistive-living packages incorporate implanted recall support (specific use case emerging)
  - [Work regulation] → safety authorities consider implanted memory aids in licensing rules (institutional bridge forming)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

Score: 20 (Impact in GVN 7)

Justification: This is a linchpin because the built environment's current regime is deeply organized around human driving, parking, and location premiums tied to daily travel friction. Mature self-driving vehicles change street design, curb management, parking demand, logistics, accessibility, commuting radii, and the viability of MaaS; second- and third-order effects include labor displacement, new platform power over mobility, and strong land-value redistribution. In a 5.5M society the spatial, time-use, and capital impacts plausibly exceed the 20 threshold even before accounting for safety, surveillance, and equity externalities.

Weak signals (7):

- [Planning] → zoning codes start cutting parking minimums for autonomous fleets (land-use model shifting)
- [Mobility services] → driverless MaaS licenses expand into normal procurement (human driver no longer default)
- [Real estate] → developers repurpose parking structures into housing or logistics (stranded car infrastructure appearing)
- [Road design] → cities designate autonomous pickup and freight corridors (street hierarchy reworking)

- – [Labor] → taxi, bus, and freight unions escalate transition disputes (displacement becoming political)
- – [Insurance and liability] → claims handling moves from driver fault to software responsibility (accountability regime flipping)
- – [Equity and governance] → platform operators negotiate privileged curb or data access (mobility power centralizing)

## ART 05.030 - Drone Swarms & Aerial Robots

Score: 5 (Impact in GVN 7)

Justification: Drone swarms can materially change inspection, surveying, façade work, traffic incident response, and last-meter delivery for certain assets. The second-order effects are more centralized supervision, new airspace governance, privacy conflict, and pressure on manual inspection roles. The impact is significant but concentrated in infrastructure, utilities, and dense service zones rather than across the whole operating model.

Weak signals (5):

- [Infrastructure maintenance] → bridge and roof contracts shift to drone fleets (inspection economics changing)
- [Municipal services] → cities procure swarm-based mapping after storms or works (rapid awareness normalizing)
- [Construction] → large sites use drones for inventory and progress verification daily (airborne oversight becoming routine)
- – [Airspace regulation] → low-altitude corridor rules and geofencing expand (governance layer thickening)
- – [Privacy and security] → complaints and anti-drone measures rise near residential deployments (social friction growing)

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 7)

Justification: General-purpose robots matter because buildings, tools, and maintenance routines are designed around human bodies; reliable robots can therefore automate a wide range of tasks without full redesign. Direct effects are in construction, retrofits, cleaning, repair, and logistics; second-order effects include major labor substitution, new supervision roles, and capital shifts from labor budgets to robot-service platforms. The scale of affected work and service continuity can plausibly push this into the transformative 10 band.

Weak signals (6):

- [Construction] → contractors lease multi-task humanoid crews (site labor mix changing)
- [Property operations] → facilities contracts specify robot-performed routine maintenance (service model shifting)
- [Retrofits] → landlords use robots for disruptive work in occupied buildings (work windows widening)
- [Training] → vocational programs add robot supervisor roles (labor structure adjusting)
- – [Labor relations] → headcount reductions are tied explicitly to robot deployment (displacement becoming concrete)

- – [Safety and regulation] → authorities publish human-robot site rules for occupied premises (mainstreaming underway)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 5 (Impact in GVN 7)

Justification: Soft robotics is significant where the built environment needs safe, compliant handling in cluttered or fragile spaces—retrofits, care settings, tight maintenance zones, and variable materials. It widens the range of tasks automatable near people, though the institutional impact is smaller than for general-purpose robots. The result is meaningful but not a full operating-model rewrite.

Weak signals (5):

- [Retrofit works] → soft grippers appear in occupied-building maintenance tools (safe automation entering tight spaces)
- [Utilities] → crawlspace and duct inspections use compliant robots (intrusion cost dropping)
- [Care and public facilities] → service robots switch to soft end-effectors (human proximity normalizing)
- – [Certification] → test standards emerge for compliant robots around people (safety pathway formalizing)
- [Procurement] → adoption is strongest where damage risk once blocked automation (distinctive value validating)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 10 (Impact in GVN 7)

Justification: This ART transforms infrastructure upkeep by making persistent autonomous presence possible in hard-to-reach, hazardous, or geographically dispersed assets. First-order effects include cheaper and more frequent inspection, repair, and emergency response across utilities, tunnels, coastlines, and remote facilities; second-order effects include fewer local crews, more centralized control rooms, and new cyber-physical failure chains. The direct maintenance and resilience effects are large enough to justify a 10.

Weak signals (6):

- [Utilities] → owners shift from manual patrols to autonomous inspection subscriptions (continuous presence replacing visits)
- [Water and coastal infrastructure] → underwater robot programs move from pilots to operating budgets (submerged assets becoming visible)
- [Disaster response] → emergency plans name autonomous fleets as first-arrival assets (response doctrine changing)
- [Remote communities] → service levels improve where human crews were intermittent (geography penalty weakening)
- – [Cybersecurity] → regulators require fail-safe isolation after fleet incidents (systemic risk becoming visible)
- – [Labor and ownership] → local depots shrink as central operations centers expand (regional job geography shifting)

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 20 (Impact in GVN 7)

Justification: This ART is a direct redesign of the built environment around robot-readable, machine-negotiable operation, making autonomy cheaper, safer, and denser across buildings, streets, depots, and logistics nodes. Its first-order effect is to embed docking, localization, transfer, and rule-enforcement into space itself; second- and third-order effects include new standards battles, vendor lock-in, reallocation of public space, and a step change in what tasks can be automated profitably. Because it changes the environment rather than just the machine, it is a keystone shift in how the GVN operates.

Weak signals (7):

- [Building design] → new hospitals, warehouses, and campuses include robot docks and machine lanes (spaces becoming autonomy-native)
- [Municipal streets] → curb and sidewalk retrofits add robot-readable wayfinding (public realm re-coded)
- [Codes and standards] → building manuals add autonomy-support specifications (institutional embedding underway)
- [Procurement] → simpler robots win bids in autonomy-ready sites (infrastructure lowering robot complexity)
- – [Governance] → disputes intensify over shared machine lanes and priority rules (new spatial politics emerging)
- – [Market structure] → platform vendors push proprietary docking or localization ecosystems (lock-in risk rising)
- – [Accessibility and equity] → advocacy groups challenge robot-priority layouts (distributional conflict surfacing)

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

Score: 3 (Impact in GVN 7)

Justification: The main value is longer robot endurance in difficult-to-access sites, especially for inspection, security, and some temporary works. That can lower servicing labor and increase coverage, but line-of-sight and safety regimes keep the effect concentrated in selected corridors or facilities. The impact is therefore material but niche.

Weak signals (5):

- [Industrial sites] → fixed beam-power nodes appear in ports or tunnels (endurance constraint easing)
- [Inspection fleets] → aerial robots stay aloft for multi-shift monitoring (coverage density increasing)
- – [Safety regulation] → exclusion-zone and exposure rules enter design reviews (beam risk entering governance)
- – [Procurement] → deployment remains confined to high-value predictable paths (broad urban use limited)
- [Grid operations] → beam nodes are planned alongside masts or substations (infrastructure coupling emerging)

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Score: 3 (Impact in GVN 7)

Justification: Dry adhesion mainly matters for façade, bridge, roof, and panel work where vertical access or delicate surfaces make current methods expensive or risky. It can reduce scaffolding, drilling, and manual rope access, with some second-order effects on work-at-height regulation and inspection routines. The impact is real but specialized.

Weak signals (5):

- [Façade maintenance] → climbing robots replace some rope-access inspections (vertical access cost falling)
- [Bridge and tunnel work] → owners procure dry-adhesion tools for overhead checks (attachment without drilling gaining value)
- – [Surface constraints] → deployment clusters on smooth modern envelopes (applicability boundaries clarifying)
- – [Safety codes] → new tests emerge for adhesion reliability in weathered conditions (regulatory acceptance pathway)
- [Equipment rental] → access-equipment firms add dry-adhesion systems (commercial channel forming)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 5 (Impact in GVN 7)

Justification: This ART matters where construction components become more integrated, customized, and sensorized without long supplier coordination chains. It can reduce assembly steps and enable locally optimized building parts, while second-order effects include shifts toward offsite fabrication, new certification needs, and weaker bargaining power for traditional component trades. The plausible impact is significant in targeted product families and retrofit parts.

Weak signals (5):

- [Building products] → suppliers launch one-piece printed components with embedded channels (assembly steps collapsing)
- [Public procurement] → low-volume custom parts are specified as printed assemblies (customization normalizing)
- [Retrofits] → irregular building repairs use printed fit-to-site parts (geometry constraints easing)
- – [Certification] → approval pathways expand for printed building elements (regulatory gate opening)
- – [Trade structure] → subcontract scopes merge as printed assemblies replace multiple trades (industry boundaries shifting)

### ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 3 (Impact in GVN 7)

Justification: For this GVN the impact is upstream in factories making components, modules, and

equipment for buildings and infrastructure. Better twins reduce defects and changeovers, and they can help localize production, but the direct operating-model effect on the built environment is one step removed. That keeps the score in the material but not central range.

Weak signals (5):

- [Prefab plants] → production twins become mandatory for module factories (upstream quality control tightening)
- [Construction supply] → delivery reliability improves as factories simulate schedule changes (site uncertainty dropping)
- – [Adoption] → use concentrates in larger suppliers rather than fragmented subcontractors (diffusion limits visible)
- [Procurement] → clients ask for factory-process digital evidence with components (manufacturing transparency increasing)
- [Capex] → new automated plants budget simulation stacks from day one (embedded practice forming)

## **ART 06.039 - Reconfigurable & Agile Factories**

Score: 3 (Impact in GVN 7)

Justification: Agile factories can shorten response times for prefabricated building elements, temporary structures, and retrofit kits. The second-order effect is a more local, modular supply base with less dependence on long batch runs, but the change still works through manufacturing rather than through space use directly. That makes the impact material, not transformative.

Weak signals (5):

- [Prefab suppliers] → factories switch between module variants without long shutdowns (custom building supply speeding up)
- [Regional policy] → incentives target agile local plants for construction components (localization becoming strategic)
- – [Certification] → frequent reconfiguration triggers more audits and recipe approvals (governance burden rising)
- [Procurement] → buyers value short reconfiguration time in tenders (flexibility monetizing)
- [SME entry] → smaller regional factories win niche retrofit work (market structure diversifying)

## **ART 06.040 - Circular & Sustainable Manufacturing**

Score: 5 (Impact in GVN 7)

Justification: This ART directly matters to lifecycle cost, waste, and environmental impact in a sector dominated by heavy materials and demolition streams. It can increase reuse of construction inputs and make material provenance more valuable, while second-order effects include new recovery markets, stricter disclosure, and pressure on virgin-material producers. That is significant for both cost and regulation in the built environment.

Weak signals (5):

- [Demolition and rebuild] → contracts specify recovery rates and recirculation targets (waste becoming input stream)

- [Material markets] → secondary construction materials gain stable pricing indices (recovered inputs maturing)
- [Public clients] → tenders score material passports and recycled-content traceability (procurement logic shifting)
- – [Quality assurance] → labs expand testing of variable recycled feedstocks (trust infrastructure growing)
- – [Incumbents] → virgin-material suppliers lobby against circular-content thresholds (distributional conflict surfacing)

## ART 06.041 - Bio-fabrication technologies

Score: 0 (Impact in GVN 7)

Justification: Its main applications lie outside buildings and infrastructure. Any built-environment effect would be indirect via biomaterials research or medical facilities, not through how mobility and activity facilities are generally delivered. That is below the meaningful-impact threshold here.

Weak signals (3):

- [Building materials R&D] → biofabrication platforms target structural or envelope materials (linkage would be created)
- [Lab buildings] → construction briefs mention biofabrication-specific facility demand (spatial demand channel emerging)
- [Codes] → standards bodies evaluate bioprinted non-medical building components (institutional bridge forming)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

Score: 5 (Impact in GVN 7)

Justification: Adaptive components could change façades, ventilation elements, shading, seals, and temporary structures from manually adjusted or overbuilt systems into material logic. The second-order effects include less maintenance labor, new failure modes, and a shift of value from assembly to design libraries and material recipes. That is significant for selected building systems and climate-responsive structures.

Weak signals (5):

- [Façades] → shading or venting products advertise passive shape-change functions (adjustment moving into material)
- [Retrofits] → hard-to-access sites use self-deploying components (maintenance access penalty shrinking)
- [Procurement] → clients specify lifecycle-state behavior, not just static geometry (design brief changing)
- – [Certification] → durability tests expand to repeated transformation cycles (new failure regime recognized)
- – [Maintenance] → FM systems track activation-cycle counts like wear data (material becoming operational concern)



## ART 06.043 - Volumetric Additive Manufacturing

Score: 3 (Impact in GVN 7)

Justification: The main built-environment value is fast production of custom parts, small components, and potentially some complex fittings with minimal tooling. That compresses downtime and spare-part delays, but the effect stays concentrated unless the technology moves far up the size or structural-value chain. So the impact is material but modest.

Weak signals (5):

- [Facility maintenance] → local hubs print replacement parts with day-scale turnaround (downtime window shrinking)
- [MEP products] → complex housings and fixtures shift to volumetric suppliers (small-batch supply speeding up)
- – [Certification] → adoption stays strongest in non-structural components (regulatory limit visible)
- [Inventory] → owners reduce stored spare parts where print-on-demand contracts exist (physical stock substituting files)
- [Service firms] → maintenance contractors add print capacity for rare parts (response model changing)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 5 (Impact in GVN 7)

Justification: Metamaterials matter to the built environment as smart skins: façades, windows, antennas, and surfaces that steer light or radio without bulky hardware. They can improve indoor connectivity, glare control, sensing, and façade performance, while second-order effects include new façade standards and competition between telecom and building vendors for control of surfaces. That is significant, especially in dense urban buildings and public infrastructure.

Weak signals (5):

- [Façades] → new commercial envelopes integrate reconfigurable radio and light panels (surface functionality multiplying)
- [Telecom and building convergence] → landlords lease wall and roof surfaces as signal-shaping assets (building skin gaining network value)
- [Codes] → daylight, glare, or connectivity standards reference tunable surfaces (regulatory uptake beginning)
- – [Maintenance] → FM teams treat surfaces as software-updatable systems (operations complexity increasing)
- [Procurement] → premium districts market connectivity-enhancing façades (location value reframing)

## ART 07.045 - Room-Temperature Superconductors

Score: 5 (Impact in GVN 7)

Justification: If mature and deployable, ambient superconductors would materially affect district power, transport equipment, high-end sensors, and possibly compact building energy systems. The direct pathway is through lower losses and denser electrical and magnetic equipment; second-order effects include network redesign, safety and certification challenges, and capital concentration in early flagship systems. Significant impact is plausible, but slow turnover of infrastructure keeps it below linchpin status.

Weak signals (5):

- [Power infrastructure] → urban feeders or substations pilot superconducting replacements (grid architecture beginning to shift)
- [Transit and building systems] → high-performance motors or lifts advertise superconducting cores (compact electrification gaining value)
- [Megaprojects] → new districts reserve space for superconducting equipment rooms (design assumptions changing)
- – [Standards] → electrical codes open annexes for quench and fault behavior (institutional adaptation starting)
- – [Capex] → adoption clusters in prestige or high-density assets first (rollout likely unequal)

## ART 07.046 - Self-Healing & Smart Polymers

Score: 5 (Impact in GVN 7)

Justification: The built environment spends heavily on seals, coatings, membranes, joints, and composite parts whose failure starts small and propagates expensively. Self-healing polymers can reduce inspection and replacement burden, while smart polymers add adaptable performance; institutionally this shifts maintenance timing, warranties, and liability for hidden degradation. The cumulative lifecycle impact is significant.

Weak signals (5):

- [Building envelope] → roof and waterproofing products sell self-healing warranties (minor damage no longer immediate failure)
- [Infrastructure maintenance] → joints and protective coatings switch to healing formulations (access-difficult components targeted)
- [Insurance] → warranty periods lengthen for assets using self-healing materials (risk expectations updating)
- – [Inspection regimes] → visual inspections are reduced where healing materials are used (maintenance doctrine changing)
- [Waste streams] → replacement volumes fall for polymer-heavy components (lifecycle economics shifting)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 5 (Impact in GVN 7)

Justification: Advanced coatings are a strong built-environment fit because so much performance is surface-governed: corrosion, fouling, heat, friction, dirt, and chemical exposure. Direct effects are

longer asset life and lower cleaning and energy burden; second-order effects include new maintenance service models, monitoring of coating wear, and dependence on specialty materials suppliers. The overall impact is significant and broad-based.

Weak signals (5):

- [Public assets] → anti-corrosion and anti-fouling coatings become standard in bridge and tunnel tenders (surface lifetime gaining priority)
- [Buildings] → self-cleaning or thermal-control coatings move from premium to mainstream façade specs (maintenance and energy link strengthening)
- [FM contracts] → service intervals are extended based on coated-surface performance (operations cost structure changing)
- – [Inspection] → digital markers or wear indicators are added to coating specs (performance becoming auditable)
- – [Supply chains] → specialty coating suppliers gain bargaining power in renewal budgets (value shifting to surface chemistry)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 3 (Impact in GVN 7)

Justification: HEAs chiefly matter where the built environment faces heat, wear, corrosion, or fatigue in demanding components. That can lower failure and maintenance costs in bridges, transit equipment, lifts, energy systems, and marine assets, but the effect stays targeted rather than systemic. It is material for selected components and networks.

Weak signals (5):

- [Critical components] → bearings, fasteners, or transit parts adopt HEA grades (failure-prone parts targeted)
- [Standards] → long-life infrastructure specs add HEA options after trials (design palette widening)
- – [Cost] → use concentrates in components with expensive access or downtime (premium justified by avoided maintenance)
- [Procurement] → guarantee terms lengthen when advanced alloys are used (risk allocation shifting)
- [Maintenance] → replacement cycles stretch in marine or high-vibration assets (lifecycle payback proving out)

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 7)

Justification: The main connection is through low-carbon district systems or niche building-integrated capture, not through the core provision of facilities. It could matter for environmental performance, especially in high-emission material or energy sites, but it is not a major built-environment operating model driver by itself. So the linkage is concrete but limited.

Weak signals (4):

- [Large buildings and district plants] → pilot systems add modular CO<sub>2</sub> capture cartridges (site-level use appearing)

- [Cement and heat clusters] → urban industrial sites test MOF capture as planning conditions (localized relevance)
  - – [Codes] → general building regulation still ignores capture media in normal projects (mainstream pathway absent)
  - – [Carbon markets] → only specialized portfolios monetize captured CO<sub>2</sub> from facilities (impact still niche)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

Score: 5 (Impact in GVN 7)

Justification: These composites can reduce weight, fatigue, and hidden damage in structures, panels, retrofits, mobility systems, and distributed equipment. The second-order effect is a stronger shift toward condition-monitored components and higher reliance on advanced-material suppliers. That makes the impact significant in both structural performance and maintenance practice.

Weak signals (5):

- [Building products] → lightweight structural components with embedded strain sensing win approvals (material and sensing converging)
- [Transport and building interfaces] → lifts, bridges, or ramps downsize due to lighter composites (weight constraints easing)
- [Maintenance] → electrical-resistance damage monitoring enters service contracts (inspection model changing)
- – [Health and regulation] → nanoparticle handling rules tighten for fabrication and demolition (new externalities surfacing)
- [Procurement] → premium projects justify capex via reduced loads and downtime (economics being proven)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 10 (Impact in GVN 7)

Justification: Thermal performance is central to building usability, cost, and emissions, especially in cold or heat-stressed societies. Smart thermal materials change envelopes and interiors from static insulators into dynamic heat-management systems, with second- and third-order effects on HVAC sizing, retrofit priorities, energy poverty, and district peak loads. Because they directly reshape how indoor conditions are provided across large building stocks, the transformative 10 band is appropriate.

Weak signals (6):

- [Retrofits] → renovation programs specify dynamic thermal layers (heat control becoming adaptive)
- [HVAC design] → engineers downsize plant capacity because materials buffer peaks (system architecture changing)
- [Affordable housing] → programs target smart thermal retrofits to cut energy poverty (distributional relevance rising)

- [Codes] → performance metrics shift toward dynamic heat response (regulation catching up)
- – [Maintenance] → facility teams monitor phase-change capacity like equipment health (material becoming operational asset)
- – [Insurance and safety] → fire and toxicity testing intensifies for advanced thermal composites (risk governance thickening)

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

Score: 3 (Impact in GVN 7)

Justification: The built environment benefits via cheaper or more secure motors in lifts, HVAC, pumps, tools, and vehicles. That matters for supply resilience and deployment pace, but the change is mainly component-level rather than a direct shift in spatial logic or service models. Material impact is plausible, especially through electrification.

Weak signals (5):

- [HVAC and elevator OEMs] → product lines shift to rare-earth-light motors (component substitution beginning)
- [Procurement] → public buyers favor motors with lower critical-mineral exposure (supply resilience monetizing)
- – [Performance trade-offs] → adoption starts in less space-constrained equipment (substitution limits clarifying)
- [Maintenance] → service intervals and corrosion specs become part of new magnet marketing (lifecycle case forming)
- – [Geopolitics] → supply-shock planning cites magnet chemistry choices in tenders (security logic entering design)

## ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination

Score: 1 (Impact in GVN 7)

Justification: This is mainly relevant where water scarcity strongly shapes settlement and facility viability. In a general western 5.5M-person society the pathway is through municipal water systems or special sites rather than most buildings and mobility facilities. It is worth tracking but remains a limited linkage.

Weak signals (4):

- [Municipal water] → new desal or reuse plants choose nano-engineered membranes (water constraint easing locally)
  - [Remote and coastal facilities] → islands or industrial campuses add low-energy membrane units (niche siting value appearing)
  - – [Building scale] → ordinary building projects rarely reference the membranes directly (limited direct penetration)
  - – [Planning] → only water-stressed development zones tie approvals to advanced desal or reuse (impact geographically narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 5 (Impact in GVN 7)

Justification: Power electronics sit inside EV charging, heat pumps, inverters, storage, lifts, data-rich buildings, and microgrids. UWBG devices can reduce size, heat, and losses across these systems, with second-order effects including quieter, denser equipment rooms and faster electrification retrofits. The cumulative infrastructure impact is significant even though it is mostly an enabling component.

Weak signals (5):

- [Buildings] → heat pumps, chargers, and inverters advertise smaller footprints (retrofit fit improving)
- [Microgrids] → switchgear and converters shrink in district-energy projects (distributed power becoming denser)
- [Mobility infrastructure] → ultra-fast charging sites use UWBG modules (high-power deployment easing)
- – [Codes] → electrical and fire rules adapt to higher-frequency power electronics (regulatory accommodation beginning)
- – [Service] → maintenance shifts toward module monitoring rather than bulky cooling upkeep (failure profile changing)

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 3 (Impact in GVN 7)

Justification: The built-environment relevance is in backup power, remote facilities, heavy-service depots, and hydrogen-ready districts where compressed gas is awkward or risky. That can improve safety and siting flexibility, but it is narrower than electrification and direct batteries. So the impact is material but not central.

Weak signals (5):

- [Critical facilities] → hospitals, ports, or remote campuses pilot solid-hydrogen backup modules (safer onsite storage being tested)
- [District energy] → planners consider cartridge-like hydrogen stores in new hubs (space-use flexibility rising)
- – [Safety codes] → fire authorities create siting and venting rules for solid storage media (institutional pathway opening)
- – [Procurement] → uptake favors sites where compressed gas was a blocking issue (distinctive niche value)
- [Logistics] → service contracts begin covering cartridge swaps and health monitoring (operational model forming)

## 8. Energy Generation, Storage & Conversion

## ART 08.056 - Fusion Energy Reactors

Score: 3 (Impact in GVN 7)

Justification: If mature, fusion mostly affects the built environment through abundant low-carbon electricity and process heat rather than through direct changes to buildings or streets. That could alter district-energy economics and industrial siting, but adoption within this GVN would likely begin through a small number of major facilities. Material impact is plausible, yet not a built-environment-specific operating-model shift.

Weak signals (5):

- [Regional planning] → industrial or district-energy strategies reserve capacity for future fusion sites (siting logic beginning)
- [Grid and building integration] → large demand centers plan around steady nearby power (energy assumptions shifting)
- – [Security and governance] → exclusion zones and public acceptance dominate early site debates (institutional friction high)
- – [Urban benefits] → claims focus on electricity price stability more than redesign of facilities (linkage remaining secondary)
- [Infrastructure] → only a few candidate locations are studied in detail (spatial effect concentrated)

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 5 (Impact in GVN 7)

Justification: SMRs can materially change district heating, high-reliability power, remote community viability, and industrial-location choices. Their second-order effects include new public acceptance conflicts, security zones, and stronger centralization of energy governance, but also reduced dependence on fossil heating logistics. In colder, dispersed societies that reaches the significant 5 band.

Weak signals (5):

- [District energy] → municipalities study SMRs as anchors for heating networks (local energy geometry changing)
- [Remote regions] → new industrial or housing plans rely on modular nuclear assumptions (location constraints easing)
- [Permitting] → land-use debates start treating SMR sites as mainstream infrastructure (nuclear entering planning)
- – [Public acceptance] → local opposition becomes central in siting decisions (social license decisive)
- – [Insurance and security] → liability and security requirements reshape nearby land-use plans (externalities entering design)

## ART 08.058 - Thin-film solar cells

Score: 10 (Impact in GVN 7)

Justification: Thin-film PV directly turns roofs, façades, glazing, vehicles, shelters, and temporary structures into power assets with lower weight and integration penalties. That changes building economics, retrofit strategies, and the relationship between surface area and energy autonomy;



second-order effects include new value for productive envelopes, tenant-landlord conflicts over generation rights, and more distributed grid complexity. At broad adoption it is clearly transformative for how facilities are conditioned and powered.

Weak signals (6):

- [Building envelopes] → façades, windows, roofs, and canopies are procured with integrated generation (surfaces becoming productive)
- [Retrofits] → older roofs and lightweight structures gain PV where rigid panels were infeasible (dead space monetizing)
- [Property finance] → valuations start crediting building-integrated generation separately (surface energy value formalizing)
- [Codes] → envelope rules include electricity generation alongside insulation metrics (design logic broadening)
- – [Tenant and owner governance] → disputes rise over who owns façade-generated electricity (rights to productive surfaces contested)
- – [Grid operations] → operators monitor neighborhood overproduction from vertical surfaces (local power flows changing)

## ART 08.059 - Bionic Leaf Technology

Score: 1 (Impact in GVN 7)

Justification: The plausible pathway is niche distributed fuel or feedstock production on certain sites, not broad change in buildings or mobility networks. It could matter for remote or resilience-oriented assets, but it is too specialized to count as a major built-environment driver by itself. So the score stays low.

Weak signals (4):

- [Remote facilities] → pilots use building-integrated artificial-photosynthesis panels (niche autonomy use appearing)
  - [Campuses and districts] → resilience plans test bionic-leaf fuel production (localized relevance emerging)
  - – [Codes] → mainstream building rules still ignore such panels (no broad adoption channel yet)
  - – [Procurement] → buyers frame systems as special-purpose chemistry units (built-environment link still narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

Score: 5 (Impact in GVN 7)

Justification: Storage matters because it changes the reliability, peak management, and siting flexibility of electrified buildings, transit, and district systems. Second-order effects include new neighborhood land uses for storage yards, more sophisticated energy-market participation by property owners, and fresh fire and safety politics. The aggregate effect is significant, though the built environment is still shaped through the wider power system.

Weak signals (5):

- [District planning] → large developments reserve parcels or basements for multi-hour storage (energy infrastructure entering site design)
- [Utilities and buildings] → portfolios monetize flexibility through storage-linked tariffs (buildings acting as grid actors)
- [Permitting] → fire and siting rules for storage become routine planning issues (new infrastructure class normalizing)
- – [Equity] → communities contest concentration of storage risk near lower-value land (distributional politics surfacing)
- – [Operations] → outage and peak-shaving decisions move from diesel backup to storage dispatch (resilience logic changing)

## ART 08.061 - Solid-State Batteries

Score: 5 (Impact in GVN 7)

Justification: Safer, denser batteries directly affect building storage, construction tools, micromobility, EVs, and mobile robots in the built environment. They can reduce fire risk and space penalties, while second-order effects include faster electrification of equipment fleets and new recycling and certification requirements. The cumulative effect is significant across mobility and facility operations.

Weak signals (5):

- [Buildings] → indoor or under-building storage projects gain approvals once blocked on fire risk (siting barrier lowering)
- [Construction equipment] → electric tools and small machines replace combustion gear faster (site electrification accelerating)
- [Mobility] → parking and charging designs change as safer packs reduce separation needs (space planning adapting)
- – [Insurance] → property insurers revise premiums for battery rooms and EV-heavy garages (risk models changing)
- [Recycling] → asset plans include pack health and second-life pathways by default (lifecycle governance emerging)

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 3 (Impact in GVN 7)

Justification: The built-environment connection is strongest in district energy, heavy construction logistics, backup power, and some industrial-urban interfaces. It can reduce fossil dependence, but second-order effects include land and water competition, safety rules, and concentration of advantage in sites with cheap power and permitting access. That yields material but not dominant impact.

Weak signals (5):

- [District energy] → new hubs pair electrolysis with local heat or backup uses (molecules entering local infrastructure)
- [Construction logistics] → depots trial hydrogen-derived fuels for hard-to-electrify fleets (service decarbonization broadening)

- – [Planning] → water use and safety setbacks slow urban siting of hydrogen assets (institutional friction visible)
- – [Procurement] → demand clusters around ports and remote sites more than ordinary buildings (use-case boundaries clarifying)
- [Certification] → green-molecule provenance becomes part of energy-service contracts (traceability becoming spend item)

## ART 08.063 - High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 7)

Justification: Wind mainly shapes the built environment through regional power supply, land use, and grid connection rather than through everyday facility design. It can still alter permitting, coastal infrastructure, and community politics around siting, but the pathway is indirect. Material impact is plausible, not transformative within this GVN.

Weak signals (5):

- [Regional planning] → transmission, port, and assembly expansions tie to larger wind programs (spillover growing)
- [Industrial siting] → energy-intensive facilities cluster where new wind capacity is expected (location logic shifting)
- – [Community conflict] → land-use disputes intensify around turbine and line corridors (spatial politics sharpening)
- – [Building design] → ordinary facilities change little except through energy assumptions (direct link limited)
- [Ports and logistics] → waterfront construction reorients around turbine servicing needs (selective physical impact emerging)

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 7)

Justification: The plausible built-environment value is supplying remote or temporary sites where cables or fuel logistics are difficult. That is useful but niche, and it does not broadly change how buildings, streets, or mobility facilities are organized. So the direct impact remains limited.

Weak signals (4):

- [Remote worksites] → temporary construction or emergency sites test beamed-power receivers (cabling constraint easing locally)
- [Ports and airfields] → specialized zones host wireless-power pilots for drones or sensors (site-specific use emerging)
- – [Planning] → normal urban developments do not yet design around beamed-power infrastructure (mainstream linkage absent)
- – [Safety and governance] → exposure and mispointing rules dominate early deployment debates (non-technical barrier central)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

Score: 5 (Impact in GVN 7)

Justification: Advanced geothermal can materially change district heating, campus energy, and the viability of dense low-carbon settlements with steady heat loads. Second-order effects include drilling rights, subsurface data control, seismicity governance, and a new locational premium for geothermal-ready districts. In cold and heating-intensive contexts this clearly reaches the significant 5 band.

Weak signals (5):

- [District heating] → cities budget deep drilling or closed-loop geothermal for new districts (heat source shifting underground)
- [Campus and industrial sites] → briefs compare geothermal fields against gas or biomass baselines (steady thermal supply gaining weight)
- [Planning] → subsurface rights and seismic-risk mapping enter development review (underground governance thickening)
- – [Public acceptance] → induced-seismicity concerns alter neighborhood siting debates (social license mattering)
- [Real estate] → developments market low-volatility heating costs tied to geothermal access (energy security affecting location value)

## ART 08.066 - Resilient microgrids

Score: 10 (Impact in GVN 7)

Justification: Microgrids change buildings and districts from passive loads into semi-autonomous energy systems, directly affecting resilience, design, and operational governance. First-order effects are better continuity for housing, hospitals, campuses, and mixed-use districts; second- and third-order effects include new local energy politics, tariff redesign, and unequal resilience between microgrid-rich and microgrid-poor areas. Because this changes how facilities remain usable under stress, the transformative 10 band is justified.

Weak signals (6):

- [District design] → new developments include islanding capability in base plans (grid relationship rewriting)
- [Critical facilities] → hospitals, campuses, and estates procure black-start microgrids routinely (resilience becoming designed-in)
- [Municipal policy] → zoning or incentives favor neighborhood energy islands (local autonomy institutionalizing)
- [Utilities] → DSOs create interfaces specifically for microgrid coordination (governance model changing)
- – [Equity] → wealthier districts gain superior outage resilience first (resilience gap widening)
- – [Operations] → facility managers become energy dispatch actors, not only building operators (role boundaries shifting)

## 9. Bio-engineering & Life-Science Technologies

## ART 09.067 - Next-Generation Gene Editing

Score: 0 (Impact in GVN 7)

Justification: There is no clear direct pathway from gene editing itself to how facilities for mobility and activity are planned, built, or operated. Any effects would be mediated by agriculture, health, or biomaterials sectors and are too indirect to count as meaningful standalone impact here. So the score is 0.

Weak signals (3):

- [Construction biomaterials] → edited organisms are developed for structural material production (linkage would be created)
- [Urban vegetation] → municipalities deploy edited plants for built-environment performance goals (niche pathway emerging)
- [Codes] → building-material standards reference gene-edited biological inputs (institutional bridge forming)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

Score: 0 (Impact in GVN 7)

Justification: Its value is overwhelmingly in health systems rather than the built environment's operating model. While healthier populations affect labor and occupancy indirectly, that is not a distinct built-environment pathway. Standalone impact for this GVN is therefore negligible.

Weak signals (3):

- [Facility design] → long-term building programs change because mRNA care delivery shifts service footprints (linkage would be created)
- [Construction labor] → workforce planning depends on recurring mRNA protection programs (specific pathway emerging)
- [Urban resilience] → building-use standards tie directly to routine mRNA delivery infrastructure (institutional bridge forming)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

Score: 3 (Impact in GVN 7)

Justification: This can alter built-environment demand by shifting food production from rural land and transport chains toward urban and peri-urban industrial facilities. Direct effects are new facility types and possible changes in land use and service proximity; second-order effects include power and water demand concentration and revaluation of agricultural versus industrial sites. That is material but not core to the GVN.

Weak signals (5):

- [Industrial real estate] → urban and peri-urban food bioproduction facilities seek planning approvals (facility mix changing)
- [Land use] → redevelopment plans cite reduced need for some livestock-linked land uses (spatial substitution beginning)

- – [Utilities] → power and water capacity becomes decisive for siting (resource intensity shaping location)
- [Logistics] → distribution hubs co-locate with cultured-food plants (urban supply geography changing)
- – [Public acceptance] → zoning hearings debate biosecurity and utility loads (new siting politics appearing)

## ART 09.070 - Organoids & Tissue Engineering

Score: 0 (Impact in GVN 7)

Justification: Its main impacts remain in research and medicine. There is no meaningful standalone pathway to the design or operation of general facilities for mobility and activity. The GVN linkage is therefore negligible.

Weak signals (3):

- [Building programs] → large shifts in lab and clinical demand are attributed to organoid production (linkage would be created)
  - [Materials] → tissue-engineering platforms begin supplying construction-relevant bio materials (application bridge emerging)
  - [Planning] → urban policies treat organoid infrastructure as a significant land-use category (relevance would become visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

Score: 3 (Impact in GVN 7)

Justification: Designer microbes matter through waste treatment, bioremediation, low-temperature material production, and some onsite sensing or control. These are real built-environment channels, but they remain selective and governance-heavy; second-order effects include biosecurity rules, new maintenance practices, and reduced dependence on harsh chemical processes. That puts the impact in the material 3 band.

Weak signals (5):

- [Wastewater and buildings] → facilities pilot microbe-based treatment or contaminant control (living process entering operations)
- [Materials] → suppliers market microbially produced binders or coatings (biological manufacturing crossing over)
- – [Biosecurity] → containment and monitoring rules enter procurement and permitting (governance burden surfacing)
- [Maintenance] → FM teams track biological process health alongside mechanical systems (operational role expanding)
- [Remediation] → contaminated-site projects prefer programmable microbes over harsher methods (cleanup model shifting)

## ART 09.072 - Microbiome Engineering

Score: 1 (Impact in GVN 7)

Justification: The built-environment relevance is mainly indoor air quality, wastewater, soil health, and limited contamination control. Those are useful but niche compared with the core drivers of spatial form, mobility, and construction. So the impact is concrete but limited.

Weak signals (4):

- [Buildings] → indoor air or moisture problems are treated with targeted microbial interventions (niche service market forming)
  - [Water systems] → utilities test microbiome steering to stabilize treatment outcomes (infrastructure operations gaining a new lever)
  - – [Codes] → building standards still frame microbes mostly as hazards (institutional adoption lagging)
  - – [Procurement] → uptake stays concentrated in specialized remediation or health-sensitive facilities (limited deployment scope)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

Score: 0 (Impact in GVN 7)

Justification: This ART primarily changes healthcare delivery and personal health decisions, not the built environment's operating model. Any spatial effects would be indirect and secondary. Standalone impact is therefore below threshold here.

Weak signals (3):

- [Facility demand] → built-environment planning shifts due to decentralized genomic services (linkage would be created)
  - [Workforce] → operators use genomic diagnostics in ways that change facility design or regulation (specific bridge emerging)
  - [Urban policy] → planners treat genomic access as a major locational driver (relevance would become visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

Score: 0 (Impact in GVN 7)

Justification: Its likely effects are upstream in research, testing, and biotech production rather than direct changes to facilities for mobility and activity. The built-environment linkage is too indirect to count as a meaningful standalone impact. So the score remains 0.

Weak signals (3):

- [Building materials testing] → organ-on-chip platforms are used for construction-product safety standards (linkage would be created)
- [Lab real estate] → urban development reserves capacity for chip-based bio-testing clusters (spatial channel emerging)



- [Codes] → built-environment regulation references these systems in compliance processes (institutional bridge forming)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

Score: 3 (Impact in GVN 7)

Justification: Longer healthy functional lives would alter housing demand, accessibility standards, commuting patterns, and the construction and maintenance labor pool. Those are second- and third-order effects rather than direct interventions in space, but they could still move many millions of person-hours and substantial capital allocations. That supports a material 3 score.

Weak signals (5):

- [Housing] → older cohorts delay moves into care-oriented housing (demand timing shifting)
- [Labor] → skilled trades remain active longer, easing shortages (workforce age structure changing)
- – [Accessibility design] → standards debate whether to raise or delay adaptations (design assumptions contested)
- – [Real estate finance] → forecasts revise senior housing demand downward or later (asset mix adjusting)
- [Mobility] → travel behavior of older adults resembles younger cohorts for longer (service demand changing)

## ART 09.076 - Engineered Living Materials

Score: 10 (Impact in GVN 7)

Justification: This ART is directly aligned with long-lived built assets because it turns materials themselves into slow maintenance, repair, and carbon-management systems. First-order effects are self-sealing cracks, longer service life, and embedded condition signaling; second-order effects include new maintenance protocols, bio-governance rules, and shifts from replacement to regeneration business models. Given the scale of maintenance and materials spend in a 5.5M society, the transformative 10 band is justified.

Weak signals (6):

- [Concrete and envelope products] → suppliers launch self-healing or CO<sub>2</sub>-mineralizing living materials (repair shifting into material itself)
- [Infrastructure owners] → bridges and tunnels specify living materials in hard-access components (maintenance model changing)
- [Codes] → regulators open approval pathways for biologically active structural materials (institutional door opening)
- [Monitoring] → maintenance systems ingest simple signals emitted by living materials (material and sensing converging)
- – [Biosecurity] → survivability and deactivation requirements enter procurement (governance layer thickening)
- – [Business models] → service contracts pay for regeneration, not replacement volume (value capture shifting)

## ART 09.077 - Gene Drive Pest Control

Score: 1 (Impact in GVN 7)

Justification: The relevant pathway is reduced pest pressure on buildings, green spaces, utility corridors, and public-health management around settlements. That can save costs and reduce unpleasant control work, but it is not a central built-environment operating model shift and brings heavy ecological and governance risk. So the impact is limited but worth watching.

Weak signals (4):

- [Municipal utilities] → vector or pest programs evaluate gene-drive options near settlements (niche infrastructure use appearing)
- [Public-health zoning] → built-risk maps integrate gene-drive scenarios (spatial management link forming)
- – [Governance] → local opposition and ecological review dominate decisions (social license decisive)
- – [Adoption] → any use remains tightly bounded to exceptional pest cases (broad uptake unlikely)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

Score: 0 (Impact in GVN 7)

Justification: There is no clear direct route from this ART to the design, construction, or operation of facilities for mobility and activity beyond very indirect demographic effects. That is too remote for meaningful standalone impact in this GVN. Score 0 is appropriate.

Weak signals (3):

- [Demography and planning] → regional growth forecasts depend on ectogenesis capacity (linkage would be created)
- [Facility demand] → major new urban health or lab facility types scale because of these systems (spatial pathway emerging)
- [Regulation] → land-use plans treat these facilities as a significant new category (institutional relevance appearing)

Signal density: LOW (linkage weak; additional signals would be speculative).

# 10. Space & Aeronautical Engineering

## ART 10.079 - Satellite Mega-Constellations & Space Internet

Score: 5 (Impact in GVN 7)

Justification: For the built environment, mega-constellations matter through ubiquitous connectivity, resilient backhaul, and high-frequency earth observation for planning, asset monitoring, and emergency response. They can reduce the locational penalty of remote areas and improve oversight of dispersed infrastructure, while second-order effects include surveillance expansion and dependence on a small set of orbital operators. The impact is significant, though not as structurally central as autonomy or materials.

Weak signals (5):

- [Remote settlements] → housing and service plans advance without terrestrial broadband extensions (distance penalty shrinking)
- [Infrastructure monitoring] → owners subscribe to satellite change-detection for roads or land movement (external visibility entering operations)
- [Emergency planning] → continuity plans treat satellite connectivity as default backup (resilience architecture changing)
- – [Governance] → public agencies negotiate priority access with constellation operators (infrastructure power centralizing)
- – [Privacy and security] → debates intensify over routine overhead monitoring (oversight externality growing)

## ART 10.080 - Space Resource Utilization (SRU)

Score: 0 (Impact in GVN 7)

Justification: Any terrestrial built-environment effect would be indirect through future material markets, not through a plausible direct pathway in this GVN. That is too remote to count as meaningful standalone impact. Score 0 is appropriate.

Weak signals (3):

- [Construction metals] → civil-material suppliers begin planning around asteroid-derived inputs (linkage would be created)
  - [Traceability] → procurement standards include off-Earth provenance classes (institutional bridge emerging)
  - [Markets] → construction hedging models reference space-derived metal supply (relevance would become visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

Score: 1 (Impact in GVN 7)

Justification: The main built-environment linkage is via extreme remote habitats, sealed facilities, and high-resilience buildings that reuse air and water more tightly. That is interesting for certain military, research, remote, and disaster-resilient sites, but too narrow to reshape the wider GVN. Hence a limited score.

Weak signals (4):

- [Remote habitats] → Arctic, island, or emergency shelter projects use highly closed loops (niche facility type gaining relevance)
- [Resilience design] → critical facilities adopt spacecraft-like recycling metrics (extreme uptime logic crossing over)
- – [Mainstream buildings] → ordinary housing and offices do not procure full closed-loop plants (broad diffusion absent)

- – [Codes] → treatment remains special-case engineering rather than normal rules (institutional niche persists)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

Score: 3 (Impact in GVN 7)

Justification: HAPs can materially improve connectivity, situational awareness, and disaster response for remote or disrupted areas without waiting for full terrestrial build-out. That affects infrastructure resilience and certain location choices, but mostly as a supplement to ground systems rather than a direct redesign of facilities. So the impact is material but limited.

Weak signals (5):

- [Emergency management] → continuity plans contract HAP coverage for disaster-hit districts (rapid resilience layer emerging)
- [Remote projects] → temporary sites buy HAP connectivity instead of permanent towers (short-horizon siting flexibility increasing)
- – [Airspace governance] → permissions and corridor rules become regular constraints (regulatory dependence visible)
- – [Municipal planning] → cities treat HAPs as backup rather than primary infrastructure (supplementary role confirmed)
- [Monitoring] → high-altitude observation feeds live works and traffic dashboards (persistent oversight improving)

# 11. Digital Platforms & Collective-Intelligence Systems

## ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

Score: 3 (Impact in GVN 7)

Justification: The real built-environment pathways are land and asset records, material provenance, peer energy exchange, and multi-party contracting where trust and reconciliation are costly. Those can improve coordination, but second-order effects include governance ambiguity, code risk, and concentration around infrastructure providers despite decentralization rhetoric. That is material, not transformative.

Weak signals (5):

- [Property and asset records] → pilot land, permit, or maintenance ledgers move to official use (shared record costs falling)
- [Energy and building services] → peer settlement for microgrids or shared facilities becomes operational (programmable exchange entering operations)
- – [Liability] → disputes over smart-contract errors reach courts or insurers (code-governance gap surfacing)
- [Procurement] → buyers demand auditable material or payment trails without full platform trust (trust cost becoming visible)
- – [Market structure] → a few managed wallet or node providers dominate deployments (power recentralizing)

## ART 11.084 - Platform Cooperatives & Fair Work

Score: 3 (Impact in GVN 7)

Justification: This ART matters where construction, maintenance, cleaning, mobility, and local services become platform-mediated. Cooperative platforms can redistribute bargaining power and data rights, but they do not directly change physical facilities except through labor markets and service availability. That supports a material 3 score.

Weak signals (5):

- [Maintenance and local mobility work] → worker-owned platforms win municipal or housing-association contracts (labor intermediation changing)
- [Procurement] → public buyers add fair-work criteria favoring cooperative platforms (institutional support emerging)
- – [Capital access] → co-op platforms struggle to finance scale while retaining member control (growth constraint visible)
- [Data rights] → service workers gain access to pricing and rating logic (bargaining power shifting)
- [Coverage] → strongest uptake appears in localized service territories (spatial business model differing)

## ART 11.085 - Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 7)

Justification: The built environment is fragmented across owners, operators, municipalities, utilities, and vendors; data marketplaces can unlock cross-boundary optimization in maintenance, planning, mobility, and insurance. Second-order effects include new monetization of asset and occupancy data, asymmetric advantage for data-rich owners, and stronger demand for governance and quality assurance. That is significant at city and portfolio scale.

Weak signals (5):

- [Municipal and owner collaboration] → operational datasets are sold or licensed through common exchanges (data silos opening)
- [Insurers and financiers] → pricing models use purchased building or infrastructure data routinely (data becoming market asset)
- [Procurement] → tenders require machine-readable data-sharing rights (data clause becoming standard)
- – [Privacy and competition] → disputes intensify over who may sell operational and tenant data (distributional conflict surfacing)
- [SMEs] → smaller service firms access data once monopolized by large incumbents (capability barrier lowering)

## ART 11.086 - Secure & Resilient Social Platforms

Score: 1 (Impact in GVN 7)

Justification: The connection is mainly through coordination resilience for communities, workforces, and emergency response around the built environment. Useful as a supporting layer, but

it does not materially alter how facilities are designed or operated in most cases. So the impact is limited.

Weak signals (4):

- [Emergency coordination] → housing associations or utilities migrate crisis communications to resilient platforms (coordination continuity improving)
  - [Construction crews] → decentralized secure messaging is specified for outage-prone sites (operational communication hardening)
  - – [Adoption] → routine building and mobility workflows still rely on mainstream platforms (limited penetration)
  - – [Governance] → benefits are framed as continuity support, not infrastructure redesign (secondary role confirmed)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 11.087 - Collective Open Innovation Networks**

Score: 1 (Impact in GVN 7)

Justification: These networks mostly affect the pace of problem-solving and product development around the built environment, not the operating model directly. They can shorten innovation cycles, but the linkage to facilities for mobility and activity remains indirect. Hence only limited standalone impact.

Weak signals (4):

- [Construction and material challenges] → open challenge platforms become routine sourcing channels (innovation pipeline opening)
  - [Public agencies] → cities post planning or maintenance problems to solver networks (problem search widening)
  - – [Implementation] → many winning ideas stall before procurement or code acceptance (translation bottleneck persisting)
  - – [Market structure] → value accrues mainly to organizers and integrators (indirect pathway dominating)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 11.088 - Scalable Decentralized Governance**

Score: 3 (Impact in GVN 7)

Justification: The strongest pathways are in neighborhood assets, shared energy systems, community land stewardship, and multi-party project governance where conventional coordination is slow and distrustful. That can alter who makes binding decisions and how quickly, but it depends on legal embedding and still affects selected governance domains rather than the whole GVN. Material impact is plausible.

Weak signals (5):

- [Neighborhood assets] → housing or district groups adopt software-mediated voting (coordination cost dropping)
- [Microgrids and shared mobility] → rule changes and budget allocations execute through digital governance tools (shared asset governance formalizing)

- – [Manipulation risk] → governance attacks or identity fraud incidents reshape trust (systemic vulnerability surfacing)
- [Legal integration] → public bodies recognize digital governance outcomes in agreements (institutional bridge opening)
- – [Participation] → delegation mechanisms are introduced to combat voter fatigue (scale challenge visible)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

Score: 5 (Impact in GVN 7)

Justification: Construction and facilities are skills-constrained and fragmented; scalable digital training can quickly change who is qualified to install, maintain, or supervise new systems. Second-order effects include new gatekeeping via platform credentials, faster retraining after automation shocks, and less dependence on location-bound instructors. That is significant for labor supply and adoption speed across the built environment.

Weak signals (5):

- [Construction training] → robot, retrofit, and smart-building credentials are accepted in hiring (new skills market forming)
- [Labor transition] → displaced drivers or site workers move into digitally credentialed roles (reskilling pathway operational)
- [Regulators] → compliance training and license renewal move to continuous digital credentials (training governance changing)
- – [Platform power] → a few credential providers become gatekeepers for high-volume roles (new bargaining asymmetry emerging)
- [Regional inclusion] → remote communities gain access to scarce technical training without travel (location barrier falling)

## ART 11.090 - Prediction-Market Forecasting Platforms

Score: 1 (Impact in GVN 7)

Justification: Prediction markets can improve project risk, demand, and policy forecasting, but they do not directly change the physical delivery of facilities. Their value is mostly as a decision-support overlay for sophisticated actors. That makes the linkage worth tracking but limited.

Weak signals (4):

- [Major projects] → agencies or developers use forecast markets for schedule and permitting risk (uncertainty pricing entering planning)
- [Urban policy] → city strategies run internal markets on traffic or housing scenarios (collective forecasting operationalized)
- – [Governance] → decisions still rely on conventional committees even when markets exist (support tool, not control layer)
- – [Verification] → settlement disputes or manipulation concerns limit high-stakes use (trust boundary visible)

Signal density: LOW (linkage weak; additional signals would be speculative).



## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

Score: 10 (Impact in GVN 7)

Justification: Fragmented devices and data models are a major brake on smart buildings, infrastructure sensing, and automated maintenance. Universal interoperability directly lowers integration cost, shortens troubleshooting, and weakens vendor lock-in; second- and third-order effects include more contestable service markets, faster regulation-by-data, and broader cyber exposure if standards are poorly secured. Because it changes the deployability of sensing and control across the whole asset base, it merits a 10.

Weak signals (6):

- [Procurement] → tenders reject non-interoperable building and asset devices by default (market rule changing)
- [Retrofits] → mixed-vendor upgrades beat rip-and-replace projects on cost and speed (integration cost collapsing)
- [Maintenance] → service firms manage multi-brand portfolios from unified layers (operating model broadening)
- [Competition] → smaller vendors win bids once proprietary lock-in weakens (market power redistributing)
- – [Cybersecurity] → common-standard vulnerabilities trigger sector-wide patch programs (shared protocol risk materializing)
- [Regulation] → authorities reference interoperable telemetry schemas in compliance rules (data standard becoming quasi-regulatory)

### ART 12.092 - Interoperable Digital Twin Ecosystems

Score: 10 (Impact in GVN 7)

Justification: Digital twins become transformative when they survive across design, construction, operations, maintenance, and ownership rather than staying trapped in one tool. Interoperable ecosystems directly change coordination, diagnostics, permitting, and lifecycle planning; second-order effects include more auditable responsibilities, greater advantage for data-rich owners, and stronger expectations that physical changes be mirrored digitally. At broad adoption, this changes how the built environment is managed, not just represented.

Weak signals (6):

- [Project delivery] → contracts require handover of portable twins, not only drawings (lifecycle continuity becoming contractual)
- [Operations] → maintenance decisions are rehearsed in multi-vendor twins before field work (remote intervention planning normalizing)
- [Permitting and compliance] → authorities accept live twin data for inspections and rule checks (regulatory process digitizing)
- [Ownership transfer] → asset sales value high-quality twins in due diligence (data becoming capitalized)

- – [Liability] → disputes arise over twin drift versus physical reality after failures (model accountability becoming material)
- – [Platform competition] → owners push to escape twin lock-in and demand open schemas (market structure contesting incumbents)

## ART 12.093 - Global Supply Chain Traceability Networks

Score: 5 (Impact in GVN 7)

Justification: Construction and infrastructure depend on long, opaque material chains with major cost, fraud, compliance, and circularity problems. Traceability networks can materially change procurement, recalls, carbon accounting, and waste recovery, while second-order effects include greater leverage for large buyers and more burden on small suppliers. The impact is significant across the value chain.

Weak signals (5):

- [Public procurement] → major projects require machine-readable provenance for key materials (traceability becoming baseline)
- [Circular construction] → reused components enter projects with verified history files (secondary markets gaining trust)
- [Compliance] → customs, labor, and carbon checks query shared rails routinely (paperwork converting to data)
- – [SME pressure] → smaller suppliers face higher onboarding and audit costs (power tilting to large actors)
- [Quality failures] → defect or counterfeit investigations close faster through batch history (root-cause speed improving)

## ART 12.094 - Personal Data Portability & Trust Frameworks

Score: 3 (Impact in GVN 7)

Justification: The built-environment pathway is through user-controlled sharing of accessibility needs, mobility rights, tenancy data, and service preferences across buildings and urban services. That can reduce friction and improve personalization, but it does not by itself reshape the core asset base. So the impact is material but modest.

Weak signals (5):

- [Accessibility and mobility] → users carry reusable preference profiles across buildings and transit (friction of use dropping)
- [Housing and tenant services] → renters move verified data between landlords without repeated checks (transaction overhead falling)
- – [Governance] → disputes emerge over which actors may request necessary personal data (power boundary redrawn)
- [Vendors] → service platforms expose consent receipts and revocation dashboards (trust infrastructure operationalizing)
- – [Inclusion] → users without strong digital wallets face slower service access (new exclusion mode appearing)

## ART 12.095 - Interoperable Digital Currency Payment Networks

Score: 3 (Impact in GVN 7)

Justification: The strongest built-environment pathways are in frictionless payment across mobility, utilities, shared facilities, and micro-transactions inside digitally managed spaces. That can improve access and reduce back-office cost, but it remains an infrastructural enabler rather than a direct driver of spatial change. Material impact is plausible, not transformative.

Weak signals (5):

- [Mobility-as-a-service] → one flow settles across transit, parking, charging, and shared vehicles (service bundling friction dropping)
- [Buildings] → shared amenities and utilities move to automated small-value payments (micro-usage billing normalizing)
- – [Compliance] → identity and AML rules become central design features (institutional load staying high)
- [Offline resilience] → pilots test low-connectivity settlement during outages (continuity value becoming visible)
- – [Operators] → reduced reconciliation staff or delays are cited in procurement (administrative labor shrinking)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

Score: 10 (Impact in GVN 7)

Justification: The built environment is heavily constrained by planning, code compliance, safety rules, and maintenance obligations; turning these into executable rules directly attacks one of the GVN's stated inhibitors. First-order effects are faster design iteration, permitting, inspection, and compliance checking; second-order effects include more legible accountability, but also possible over-formalization and exclusion where discretionary judgment once helped. Because regulation is such a central bottleneck, this becomes a transformative operating layer.

Weak signals (6):

- [Permitting] → authorities publish machine-readable zoning and building rules (manual interpretation burden dropping)
- [Design tools] → BIM and planning software run live code checks during design (compliance shifting left)
- [Inspection] → regulators accept software-generated rule traces in approvals (administration digitizing)
- [SMEs] → smaller firms use rule APIs to compete without big compliance teams (expertise barrier lowering)
- – [Edge cases] → appeals rise where coded rules clash with contextual judgment (formalization limits surfacing)
- – [Vendor power] → software providers embedding official rules gain gatekeeper positions (regulatory intermediation centralizing)

## ART 12.097 - Open Metaverse Interoperability Protocols

Score: 1 (Impact in GVN 7)

Justification: The relevant pathway is through virtual collaboration, remote design and use of space, and some substitution of travel or floor area. That is real but largely secondary to the more direct AR, VR, and broadband layers. On its own, protocol interoperability has limited standalone impact for this GVN.

Weak signals (4):

- [Design collaboration] → clients request portable 3D spaces across platforms (interoperability need becoming concrete)
- [Corporate real estate] → virtual workspaces are treated as complements, not replacements (effect staying bounded)
- – [Procurement] → adoption talks focus on niche ecosystems, not mainstream buildings (limited scope)
- – [Standards] → protocol work advances faster than physical-space planning changes (technology outpacing impact)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 - Content Authenticity Infrastructure

Score: 1 (Impact in GVN 7)

Justification: Its main built-environment value is trusted remote evidence: site photos, inspection videos, incident media, and compliance documentation. That can reduce some fraud and dispute costs, but it is a narrow governance improvement rather than a major operating-model shift. So the score stays low.

Weak signals (4):

- [Inspection and compliance] → authenticated photo and video evidence is accepted instead of some site visits (remote verification gaining trust)
  - [Construction claims] → clients and contractors use signed media trails in disputes (evidence handling improving)
  - – [Adoption] → many ordinary site media workflows remain unsigned (coverage incomplete)
  - – [Toolchains] → certified capture tools are required only in high-risk projects (niche first)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 - Privacy-Preserving Collaboration Protocols

Score: 5 (Impact in GVN 7)

Justification: Built-environment optimization often stalls because landlords, utilities, cities, and service providers cannot safely pool data. Privacy-preserving collaboration makes joint analytics and some joint control more feasible, while second-order effects include new governance markets and less power concentration in central data hoarders. That unlocks significant value across energy, mobility, maintenance, and compliance.

Weak signals (5):

- [City-owner collaboration] → encrypted joint analytics are used for mobility or energy planning (coordination barrier dropping)
- [Utilities and buildings] → grid-flex programs run on secure multi-party data (shared optimization becoming possible)
- [Public procurement] → collaboration protocols appear in smart-district tenders (institutional pathway opening)
- – [Performance] → latency or compute overhead becomes a visible trade-off (technical cost staying relevant)
- – [Governance] → audit logs and safe-output rules become standard negotiation points (new collaboration bureaucracy forming)

## **ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure**

Score: 10 (Impact in GVN 7)

Justification: Construction is conservative because unfamiliar methods and products are hard to trust, insure, and approve; strong conformance infrastructure directly reduces that bottleneck. It changes adoption speed for robotics, additive manufacturing, new materials, and modular systems, while second-order effects include stronger roles for test labs, insurers, and dominant certifiers. Because it systematically converts novelty into bankable and regulatable practice, it has transformative importance for the built environment.

Weak signals (6):

- [Robotic and additive construction] → buyers require standardized conformance certificates before bids (novelty becoming procureable)
- [Insurers] → premiums and warranties are linked to accredited process certification (risk transfer formalizing)
- [Codes] → regulators reference conformance suites for new methods and materials (approval pathway shortening)
- [SME adoption] → smaller firms use shared test and certification services (capability barrier lowering)
- – [Power concentration] → a few labs and certifiers become bottlenecks (gatekeeper risk rising)
- [Supply chains] → certified recipes travel across sites with less local requalification (scaling frictions easing)

## **GVN 8: Exchange ART Impact**

### **1. Sensing, Measurement & Connectivity**

#### **ART 01.001 - Global Broadband Connectivity**

Score: 20 (Impact in GVN 8)

Justification (3–5 sentences):

This is a keystone technology for the Exchange GVN because it makes digital exchange reachable almost everywhere, sharply reducing search, coordination, and transaction frictions. At 1st order, it expands e-commerce, remote services, platform work, and always-on payments into places and time windows that were previously poorly served. At 2nd order, it shifts bargaining power toward platforms, identity/payment intermediaries, and infrastructure operators while also bringing rural households and micro-firms into the same marketplaces as urban incumbents. At 3rd order, exchange becomes more software-mediated, reputation-mediated, and continuously cross-border; that is a direct operating-model transformation well above the >€1B / hundreds-of-thousands-of-people threshold.

Weak signals (9):

- (+) [Time and location independence] → rural merchants reach urban conversion rates on national platforms (distance penalty collapses)
- (+) [Low transaction costs] → platforms launch full-service seller onboarding in previously underconnected areas (new supply unlocked)
- (+) [Prevalence and flexibility] → remote diagnostics, tutoring, care, and legal services bundle instant payment (services delocalize)
- (+) [Locality and cultural relevance] → local-language niche marketplaces appear outside major cities (identity-based trade grows)
- (+) [Peer trust] → portable reputation profiles work across multiple networks (reputation gains liquidity)
- (−) [Dependency on global platforms] → connectivity bundles include preferred marketplace placement (gatekeeper leverage rises)
- (−) [Taxation and public revenue] → more micro-cross-border sales fall into delayed VAT capture (compliance lags)
- (−) [Reliability and security] → outage drills expose retail dependence on satellite backbones (infrastructure fragility visible)
- (−) [Consumer responsibility] → scam and counterfeit complaints spike in newly connected segments (trust systems lag)

## ART 01.002 - Ultra-Low Latency Networks

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Ultra-low latency networks significantly change high-speed service exchange, cloud robotics, immersive commerce, and machine-to-machine coordination, but they are not as foundational as universal access. At 1st order, they make remote control, live assistance, shared digital environments, and real-time matching feel immediate rather than sluggish. At 2nd order, they advantage firms controlling edge infrastructure and allow more dynamic pricing, routing, and robotic service coordination; at 3rd order they may intensify algorithmic competition and reduce tolerance for slower local providers. The likely total impact is in the significant range for this GVN, plausibly €100M–€1B annually in affected cost, value, and labor time.

Weak signals (9):

- (+) [Ease and convenience] → remote expert services advertise live-control guarantees (lag stops being visible)
- (+) [Flexibility] → marketplaces sell milliseconds-guaranteed service tiers (timing becomes monetized)

- (+) [Individuality] → customer agents negotiate inventory and price in-session (real-time trading emerges)
- (+) [Delivery costs] → robotic fulfillment contracts specify edge-node proximity (network quality affects logistics)
- (+) [VR/AR commerce] → spatial shopping platforms publish maximum-jitter standards (immersion becomes reliable)
- (–) [Market structure] → edge access is bundled by a few cloud-network firms (infrastructure rent rises)
- (–) [Equality] → rural or small merchants get slower default service classes (latency gap stratifies markets)
- (–) [Accountability] → disputes shift to network-service logs and timing guarantees (proof burdens move)
- (–) [Security] → flash fraud exploits faster decision loops before human review (speed amplifies harm)

## ART 01.003 - Edge AI for Sensor Data

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Edge AI significantly changes how physical exchange environments operate by embedding interpretation directly into stores, kiosks, lockers, cameras, and service devices. At 1st order, it lowers the cost of checkout, fraud detection, routing, and quality control while enabling more unattended service. At 2nd order, it favors firms that control the best models, hardware, and safety cases; at 3rd order, it may normalize continuous automated judgment in exchange spaces and raise new surveillance and liability concerns. The total impact is significant, though not a full GVN linchpin.

Weak signals (9):

- (+) [Ease and convenience] → unattended retail expands beyond trial sites (autonomy becomes routine)
- (+) [Low transaction costs] → merchants retire manual review for delivery and photo disputes (inspection labor falls)
- (+) [Reliability] → quality exceptions are flagged before goods are listed (fewer defective transactions)
- (+) [Flexibility] → mobile vendors use AI kiosks without stable backhaul (local inference broadens access)
- (+) [Peer trust] → marketplaces accept machine-generated condition grades for resale (trust gets automated)
- (–) [Equality] → model quality differs sharply by merchant scale (AI capability gaps widen)
- (–) [Accountability] → consumer complaints focus on opaque local refusals or misclassifications (appeal channels strain)
- (–) [Privacy] → regulators scrutinize on-device customer behavior inference at point of sale (acceptability contested)
- (–) [Security] → adversarial spoofing incidents target local cameras and sensors (physical fraud evolves)



## ART 01.004 - Quantum & High-Precision Sensing

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

This technology has a concrete but narrow relationship to Exchange. At 1st order, it could matter in premium authenticity checks, indoor positioning, very high-value logistics, and anti-counterfeit verification. At 2nd and 3rd order, it may strengthen proof regimes in selected sectors, but it does not broadly alter how goods, services, and rights are exchanged across society. That keeps it in the “worth considering, but limited scale” category.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → insurers require precision sensing for high-value cargo (trust becomes instrumented)
- (+) [Peer trust] → luxury or pharma resale platforms advertise sensor-backed authenticity (niche fraud control)
- (+) [Delivery bottlenecks] → GNSS-denied warehouses test precision navigation tools (specialized efficiency gain)
- (–) [Market structure] → certified sensing providers dominate a few premium sectors (trust centralizes)
- (+) [Watchpoint] → consumer-facing marketplaces start pricing sensor-verified provenance premiums (linkage would strengthen)

## ART 01.005 - Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Dense low-cost sensing across inventories, environments, and assets materially changes the Exchange GVN by making state and location much more legible. At 1st order, this reduces stock uncertainty, spoilage, shrinkage, and periodic inspection labor. At 2nd order, it supports pay-per-state contracts, automated replenishment, and secondary markets built on condition histories; at 3rd order, it shifts power toward actors who control the interpretation layer for these ambient data streams. That is a significant shift in transaction reliability and coordination.

Weak signals (9):

- (+) [Reliability] → product listings include continuous condition timelines (quality becomes tradable)
- (+) [Low transaction costs] → warehouses shift from periodic counts to always-on inventory confirmation (reconciliation shrinks)
- (+) [Flexibility] → shared tools and vehicles unlock by sensed availability and state (micro-rental markets expand)
- (+) [Prevalence] → insurers price policies using live asset-health streams (monitoring enters contracts)
- (+) [Time independence] → maintenance and refill tasks trigger automatically after thresholds (human polling fades)
- (–) [Individuality and privacy] → sellers retain telemetry access after transfer of ownership (rights remain contested)

- (–) [Bargaining power] → platform operators aggregate sensor histories into proprietary risk scores (data moats deepen)
- (–) [Governance] → regulators require disclosure of embedded sensors in consumer goods (social acceptance tested)
- (–) [Security] → spoofed sensor nodes appear in return, warranty, or shrinkage fraud (attack surface spreads)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

This technology is significant because it removes one of the main inhibitors to sensing-heavy exchange models: privacy and trust concerns. At 1st order, it allows personalization, verification, and ambient monitoring without requiring centralized raw-data accumulation. At 2nd order, it lowers cross-border compliance friction and broadens the settings where automated retail and context-aware services can operate; at 3rd order, it shifts competition from only convenience and price toward privacy defaults and trust architecture. That makes it a strong enabler of wider adoption of sensor-mediated exchange.

Weak signals (9):

- (+) [Peer trust] → merchants advertise “no raw video leaves site” shopping environments (acceptability rises)
- (+) [Ease and convenience] → privacy-preserving loyalty and recommendation systems replace invasive tracking (personalization survives backlash)
- (+) [Flexibility] → cross-border marketplaces certify local data retention by default (jurisdiction friction drops)
- (+) [Reliability] → insurers accept encrypted summary outputs for dispute resolution (evidence without raw data)
- (+) [Individuality] → personal devices negotiate data-sharing terms at checkout (consent becomes granular)
- (–) [Market structure] → only large vendors can afford secure hardware and compliance stacks (privacy becomes scale advantage)
- (–) [Governance] → disputes focus on unverifiable local inferences rather than stored records (audit tensions grow)
- (–) [Security] → attacks shift to model extraction and enclave compromise (privacy stack becomes target)
- (–) [Equality] → low-cost merchants keep using invasive legacy sensing (privacy divides the market)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Quantum-resilient networking is materially relevant to Exchange because secure payments, contracting, identity, and remote operation depend on long-lived communication trust. At 1st order, it hardens transaction confidentiality and integrity for high-trust sectors. At 2nd order, it raises migration and compliance costs and may concentrate power in certified vendors and managed providers; at 3rd order, it reduces some catastrophic long-horizon data exposure risks while

introducing new transition frictions. The overall impact is material but not transformative.

Weak signals (9):

- (+) [Reliability] → payment and identity providers publish post-quantum migration dates (transaction trust hardens)
- (+) [Peer trust] → procurement rules require quantum-resilient messaging for marketplaces (secure exchange normalizes)
- (+) [Flexibility] → cross-border trade platforms advertise long-life encrypted records (future-proof contracting grows)
- (+) [Accountability] → algorithm-agile key rotation appears in service-level contracts (security enters pricing)
- (+) [Security of supply] → critical merchants test fallback routes across trusted carriers (resilience becomes commercial)
- (–) [Market structure] → certified hardware and network vendors gain preferred status (assurance centralizes power)
- (–) [Transaction costs] → small platforms delay upgrades due to compliance burden (security gap widens)
- (–) [Regulation] → legal disputes emerge over which cryptographic standard was reasonable (liability shifts)
- (–) [Threat surface] → downgrade or migration-failure incidents disrupt checkout or identity flows (transition risk appears)

## ART 01.008 - Integrated Sensing and Communication (ISAC)

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

ISAC matters because it allows commercial environments to gain situational awareness through communications infrastructure they already need. At 1st order, this improves occupancy, movement, and handoff visibility in retail, mobility, and logistics spaces. At 2nd order, it favors operators that control wireless infrastructure and raises privacy issues because behavior becomes ambiently measurable; at 3rd order it supports more automated routing, queueing, and dynamic space management. The impact is clearly material in selected domains, but not broad enough for a higher score.

Weak signals (9):

- (+) [Delivery reliability] → depots and malls use network-native tracking instead of separate sensors (infrastructure converges)
- (+) [Low transaction costs] → temporary venues buy one service for both connectivity and occupancy sensing (bundle value rises)
- (+) [Flexibility] → curbside and pickup systems route customers from live radio sensing (queues get optimized)
- (+) [Peer trust] → handoff proofs combine communication and presence data (delivery verification improves)
- (+) [Time independence] → after-hours retail and service spaces rely on ambient network awareness (staffing needs fall)
- (–) [Privacy] → regulators treat telecom infrastructure as behavioral sensing in commercial zones (acceptability contested)

- (–) [Market structure] → operators monetize access to sensed environment data (new toll point appears)
- (–) [Accountability] → disputes arise over inferred rather than camera-recorded movements (evidence norms shift)
- (–) [Security] → spoofing or jamming affects both connectivity and sensing at once (coupled failure risk)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

These chips matter to Exchange mainly as enabling infrastructure for local AI in stores, devices, vehicles, and customer agents. At 1st order, they make always-on inference cheaper and less power-hungry, helping unattended commerce and offline-capable service tools. At 2nd order, they reduce some dependence on remote clouds and may widen AI access beyond the largest firms; at 3rd order they still mainly amplify other automation trends rather than independently transforming exchange. That supports a material but indirect score.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Ease and convenience] → checkout, fraud, and recommendation models run fully on low-power devices (AI localizes)
- (+) [Reliability] → merchants deploy offline-capable smart shelves and kiosks (service continuity improves)
- (–) [Market structure] → specialized chip vendors become default platform suppliers (hardware dependence grows)
- (–) [Governance] → procurement starts requiring explainable edge-AI hardware stacks (compliance enters hardware choice)
- (+) [Watchpoint] → SMEs buy packaged neuromorphic commerce appliances rather than cloud subscriptions (linkage strengthens)

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Novel transistor families affect Exchange through lower power use, smaller form factors, and more durable embedded computation. At 1st order, that supports always-on merchant devices, sensors, and secure hardware with lower maintenance. At 2nd order, it can extend device life and reduce operating costs; at 3rd order, it may deepen dependence on whichever fabrication ecosystems achieve scale first. The linkage is real and material, but clearly indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → always-on merchant devices run longer without servicing (device uptime improves)
- (+) [Prevalence] → more commerce hardware ships in sticker-scale or invisible form factors (interaction surface expands)
- (–) [Market structure] → a few foundries dominate qualified low-power commerce chips (supply risk concentrates)
- (–) [Security] → legacy secure elements are replaced faster than certification can keep up (trust gaps appear)
- (+) [Watchpoint] → retailers market maintenance-free device guarantees enabled by new chips (commercial relevance rises)

## ART 02.011 - Quantum Computing Platforms

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Quantum computing has a concrete but narrow relationship to Exchange. At 1st order, it may improve some difficult pricing, routing, matching, or fraud problems. At 2nd order, most gains would accrue through premium cloud services used by large operators rather than broad changes in everyday exchange behavior. That keeps it worth monitoring but below the material threshold for this GVN.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → logistics or pricing vendors sell quantum-assisted optimization services (niche premium appears)
- (+) [Reliability] → fraud platforms benchmark quantum routines on rare detection problems (specialized capability emerges)
- (–) [Market structure] → only a few hyperscalers offer exchange-relevant quantum access (benefits concentrate)
- (–) [Governance] → procurement excludes quantum-opaque decision support in regulated marketplaces (adoption constrained)
- (+) [Watchpoint] → marketplace APIs start exposing quantum-optimized routing or auction modules (linkage would strengthen)

## ART 02.012 - Photonic and Optical Computing

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Photonic computing materially affects Exchange through cheaper, faster AI, search, personalization, and media processing at scale. At 1st order, this helps large digital marketplaces and immersive commerce workloads. At 2nd order, it strengthens firms running large platforms and dense infrastructure; at 3rd order it can widen performance gaps between infrastructure-rich ecosystems and smaller rivals. The effect is important but remains a support layer under other changes.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → large marketplaces cite falling inference and network costs after optical upgrades (scale economics improve)
- (+) [Prevalence] → immersive commerce and live translation services expand without price increases (back-end bottleneck eases)
- (–) [Market structure] → only hyperscale platforms can finance early optical stacks (concentration risk rises)
- (–) [Reliability] → outages trace to electro-optic conversion bottlenecks in commercial systems (new failure mode appears)
- (+) [Watchpoint] → cloud vendors sell optical-accelerated commerce models as a standard tier (linkage strengthens)

## ART 02.013 - Next-Gen Memory & Storage

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

New memory and storage technologies matter because Exchange increasingly depends on retaining histories: product provenance, personalization, fraud evidence, asset states, and digital twins. At 1st order, they make more of that state cheaper to store and query. At 2nd order, they may deepen data moats for large platforms; at 3rd order, they support more persistent and stateful commercial relationships. The impact is material, but mostly as a hidden enabler of other changes.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Peer trust] → resale and warranty platforms keep lifetime product histories by default (memory enables provenance)
- (+) [Individuality] → merchants retain richer local preference state without cloud dependence (personalization deepens)
- (–) [Market structure] → biggest platforms widen lead via cheaper long-horizon behavioral archives (data advantage compounds)
- (–) [Governance] → retention disputes rise because cheap storage weakens deletion discipline (privacy conflict grows)
- (+) [Watchpoint] → condition histories become standard in second-hand marketplaces (direct linkage strengthens)

## ART 02.014 - Molecular Computing

Score: 0 (Impact in GVN 8)

Justification (3–5 sentences):

Molecular computing has too weak a plausible linkage to the Exchange GVN to justify more than a watchpoint score. Its likely mature uses remain in specialized biochemical or embedded sensing environments, not in routine mainstream retail, services, payments, or contracting. Any exchange impact would be niche and indirect rather than socially meaningful at GVN scale. That keeps it below the threshold for a clear linkage.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint] → freshness-triggered packaging starts using embedded molecular logic (niche commerce bridge)
- (+) [Product individuality] → labs sell molecular-compute diagnostic services through subscription marketplaces (specialized market forms)
- (–) [Reliability] → commercial procurement excludes molecular processors from non-lab settings (mainstream link stays weak)
- (–) [Regulation] → biosecurity rules classify molecular-compute devices as controlled lab tools (market remains narrow)
- (+) [Watchpoint] → insurers accept molecular outputs in supply-chain disputes (would create exchange relevance)

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Causal AI significantly affects Exchange because it improves intervention design in pricing, recommendations, fraud control, market design, and operational policy. At 1st order, it helps actors ask what happens if we change a price, ranking, promotion, or rule rather than only correlating past behavior. At 2nd order, it strengthens platform steering and supplier management while also enabling more effective manipulation; at 3rd order, it shifts disputes toward the assumptions embedded in causal models. The total effect is significant for how exchange decisions are made, though not a complete operating-model reset.

Weak signals (9):

- (+) [Low transaction costs] → marketplaces test counterfactual pricing and promotion engines (trial-and-error shrinks)
- (+) [Individuality] → customer agents explain “why this option” using intervention logic (recommendations gain credibility)
- (+) [Reliability] → fraud teams switch from correlation rules to action-effect models (false positives fall)
- (+) [Governance] → regulators request causal evidence for ranking or pricing changes (platform decisions become auditable)
- (+) [Flexibility] → sellers simulate inventory and delivery promises before listing (commitment quality improves)
- (–) [Bargaining power] → dominant platforms use causal models to steer supplier behavior (dependence deepens)
- (–) [Consumer autonomy] → personalized nudges become more effective and less visible (manipulation risk rises)
- (–) [Accountability] → disputes hinge on hidden assumptions in causal graphs (explanation contests grow)
- (–) [Equality] → smaller merchants lack data to build equally strong models (capability asymmetry widens)



## ART 03.016 - Federated & Privacy-Preserving Learning

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

This technology is significant because it lets fragmented actors in the exchange system benefit from shared AI without handing over raw sensitive data. At 1st order, it enables fraud, demand, and personalization models across institutions, merchants, and devices. At 2nd order, it reduces some platform lock-in and compliance barriers, although coordinators of federated systems may still capture strategic advantage; at 3rd order, it makes cross-organizational AI collaboration more normal while keeping data local. That is a meaningful institutional shift in how AI-enabled exchange is organized.

Weak signals (9):

- (+) [Peer trust] → retailers and banks join shared fraud models without central data pooling (cooperation gets safer)
- (+) [Individuality] → devices personalize offers locally while contributing only updates (privacy-friendly personalization scales)
- (+) [Prevalence] → SME software bundles federated demand forecasting by default (smaller actors gain capability)
- (+) [Governance] → sector consortia publish common secure-aggregation standards (trust framework emerges)
- (+) [Locality] → local marketplaces adapt models without surrendering full user histories (regional relevance improves)
- (–) [Market structure] → coordinators control model rules and benefit distribution (new chokepoint appears)
- (–) [Accountability] → participants dispute whether biased outputs came from local or global updates (responsibility blurs)
- (–) [Security] → poisoning or update-manipulation incidents hit shared models (new trust surface opens)
- (–) [Equality] → weak devices or small datasets contribute less and benefit less (participation skews value)

## ART 03.017 - Trustworthy AI Systems

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Trustworthy AI is transformative for Exchange because it determines whether customers, merchants, lenders, and regulators are willing to delegate meaningful commercial decisions to AI. At 1st order, it enables bounded purchase authority, audited recommendations, explainable moderation, and safer automated support. At 2nd order, it reallocates liability, certification, and monitoring power toward actors who can prove robustness and compliance; at 3rd order, it broadens AI-mediated exchange while also risking concentration in a few trusted stacks. Because it changes how the GVN is realized rather than merely optimizing it, it clears the transformative threshold.

Weak signals (9):

- (+) [Peer trust] → marketplaces certify transaction-safe AI agents (delegation becomes acceptable)

- (+) [Ease and convenience] → consumer agents receive authority to complete bounded purchases (automation crosses legal line)
- (+) [Reliability] → audit logs and confidence scores appear in AI-mediated checkout flows (decisions become inspectable)
- (+) [Governance] → regulators require provenance and rollback for pricing or ranking models (AI gets compliance wrappers)
- (+) [Prevalence] → insurers discount platforms using monitored safe-deployment pipelines (trust changes financing)
- (–) [Market structure] → a few certified AI stacks dominate merchant tooling (trust centralizes power)
- (–) [Accountability] → disputes shift to model versions, prompts, and fallback rules (new evidence layer matters)
- (–) [Labor] → routine customer service and broker roles shrink rapidly (oversight replaces execution)
- (–) [Security] → adversarial prompt or policy exploits trigger transaction incidents (new fraud channel stabilizes)

## ART 03.018 - Automated Machine Learning (AutoML)

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

AutoML significantly affects Exchange because it lowers the expertise threshold for building models that optimize pricing, recommendations, support, churn, and fraud detection. At 1st order, it lets many more firms deploy useful models without dedicated data science teams. At 2nd order, it can spread capability while also standardizing behavior around the same vendors and pipelines; at 3rd order, it accelerates experimentation cycles and may promote algorithmic convergence. That makes it a significant but not fully transformative shift.

Weak signals (9):

- (+) [Low transaction costs] → SMEs launch custom pricing or churn models from packaged tools (AI capability diffuses)
- (+) [Flexibility] → marketplaces let sellers auto-generate campaigns and support models (optimization becomes self-service)
- (+) [Reliability] → AutoML pipelines include drift rollback in merchant dashboards (model upkeep industrializes)
- (+) [Individuality] → local sellers deploy niche recommendation systems without data science teams (variety grows)
- (+) [Prevalence] → procurement of “AI store in a box” software accelerates (standardization spreads)
- (–) [Market structure] → a few vendors become default model factories for commerce (toolchain dependence rises)
- (–) [Accountability] → merchants blame AutoML defaults for discriminatory pricing or ranking effects (responsibility blurs)
- (–) [Security] → mass-produced but poorly governed models create synchronized vulnerabilities (systemic fragility grows)
- (–) [Competition] → many sellers converge on the same optimization logic (behavior homogenizes markets)

## ART 03.019 - Collaborative Multi-Agent AI

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Collaborative multi-agent AI is transformative because it lets customers, merchants, logistics systems, payment tools, and service bots coordinate as a distributed exchange system rather than as isolated applications. At 1st order, it automates search, matching, negotiation, routing, exception handling, and fulfillment across many actors. At 2nd order, it can slash coordination labor while raising new antitrust, collusion, and governance problems; at 3rd order, it creates the possibility of machine-speed exchange ecosystems with cascading positive and negative feedback loops. That clearly changes how the GVN operates and reaches the transformative anchor.

Weak signals (9):

- (+) [Low transaction costs] → inventory, pricing, and delivery agents negotiate automatically across firms (coordination labor falls)
- (+) [Flexibility] → consumer agents reserve, compare, and switch offers without manual browsing (search becomes delegated)
- (+) [Reliability] → multi-agent fulfillment networks rebalance late orders in real time (service continuity improves)
- (+) [Time independence] → after-hours service transactions complete with no human intervention (exchange becomes continuous)
- (+) [Prevalence] → standard APIs for agent-to-agent contracting appear in commerce stacks (ecosystem hardens)
- (–) [Governance] → antitrust scrutiny targets agent coordination rules and shared optimizers (collusion risk surfaces)
- (–) [Accountability] → no single actor can explain a bad joint outcome (blame becomes distributed)
- (–) [Labor] → schedulers, dispatchers, and many intermediaries are displaced or downgraded (role mix changes fast)
- (–) [Security] → interacting agents create flash oscillations or exploit loops in price and stock systems (feedback amplifies harm)

## ART 03.020 - Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Quantum-accelerated AI has a plausible but narrow path into Exchange through especially hard search, allocation, and optimization problems. At 1st order, some premium logistics, auction, or planning services could improve. At 2nd order, the benefits would likely flow mainly through elite cloud services and large incumbents, and at 3rd order it does not by itself reconfigure the exchange model. The linkage is therefore non-trivial but limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → premium logistics software advertises quantum-accelerated planning (niche performance edge)

- (+) [Reliability] → market-clearing or auction platforms test quantum-assisted optimization (specialized application emerges)
- (–) [Market structure] → only the largest platforms can justify access costs (benefits concentrate)
- (–) [Accountability] → procurement asks for proof that quantum subroutines are auditable (trust slows rollout)
- (+) [Watchpoint] → consumer-facing or SME tools expose quantum-backed decision modules (linkage would strengthen)

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

This technology affects Exchange mainly upstream by accelerating the creation of new products, materials, and services. At 1st order, that changes what is available to buy rather than how exchange itself is organized. At 2nd and 3rd order, it could reshape innovation markets, IP licensing, and supplier advantage, but these are still one step removed from the core GVN logic of ownership and access transfer. So it remains a limited but relevant watchpoint.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → marketplaces list rapidly iterated AI-designed products in specific sectors (upstream novelty reaches buyers)
- (+) [Bargaining power] → large platforms acquire autonomous-discovery startups for exclusive supply advantage (innovation control matters)
- (–) [Regulation] → product approvals lag far behind discovery cycles (exchange uptake stays narrow)
- (–) [Trust] → sellers need new provenance claims for AI-discovered products (credibility burden rises)
- (+) [Watchpoint] → contract-research marketplaces sell autonomous discovery as a service to SMEs (link strengthens)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Immersive AR/VR significantly changes how buyers inspect goods, compare options, and receive services before and after purchase. At 1st order, it reduces uncertainty for spatially complex, expensive, or experience-based purchases and enables remote co-presence in services. At 2nd order, it shifts value from physical storefronts toward platform-controlled immersive environments; at 3rd order, it normalizes remote commercial presence and richer behavioral data extraction from gaze, gesture, and movement. That is a significant change in how parts of the Exchange GVN are realized, though not a universal linchpin.

Weak signals (9):

- (+) [Ease and convenience] → major retailers offer persistent 3D inspection before purchase (visual uncertainty falls)
- (+) [Flexibility] → remote service sessions bundle shared AR view plus payment (services delocalize)
- (+) [Individuality] → configurable products are sold through immersive preview rather than static catalogues (customization becomes easier)
- (+) [Locality and cultural relevance] → local venues and artisans run immersive storefronts for remote buyers (local identity scales)
- (+) [Time independence] → virtual showrooms stay open continuously with agent support (store hours lose meaning)
- (–) [Market structure] → a few headset and app platforms control discovery and fees (new storefront gatekeepers)
- (–) [Equality] → non-immersive users see degraded access to premium offers (interface stratification appears)
- (–) [Privacy] → gaze and emotion data becomes commercial optimization input (behavioral extraction deepens)
- (–) [Peer trust] → fake or manipulated 3D product representations trigger disputes (representation risk grows)

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

BCIs have a concrete but narrow link to Exchange through accessibility and hands-free interaction. At 1st order, they can widen participation for users with severe motor limitations in shopping, payments, and service access. At 2nd and 3rd order, however, they create unusually sensitive privacy, security, and consent issues that will limit mainstream commercial adoption. That keeps the impact limited at GVN scale.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Ease and convenience] → accessibility-focused commerce apps add BCI input support (niche inclusion improves)
- (+) [Time independence] → users with severe motor limits complete purchases without caregiver mediation (access barrier drops)
- (–) [Privacy] → commercial vendors request neural-data consent for personalization (sensitive data conflict emerges)
- (–) [Regulation] → payment and identity standards exclude BCI-only authentication (mainstream use remains narrow)
- (+) [Watchpoint] → large service platforms certify BCI-compatible customer journeys (linkage would strengthen)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Advanced prosthetics and exoskeletons affect Exchange mainly by changing who can participate in physical service and logistics work. At 1st order, they may reduce labor bottlenecks in warehousing,

delivery, and certain service roles. At 2nd and 3rd order, they could change insurance, safety, and labor standards, but they do not strongly alter the core transaction model itself. That keeps the score low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Labor bottleneck] → warehouses and service fleets subsidize wearable augmentation (participation widens)
- (+) [Reliability] → workers using exosuits qualify for lower injury-risk premiums (labor becomes more insurable)
- (–) [Bargaining power] → employers shift physical standards around augmented workers (new labor pressure emerges)
- (–) [Equality] → only premium firms can finance augmentation at scale (capability gap widens)
- (+) [Watchpoint] → gig platforms create equipment-linked task classes for augmented workers (exchange linkage strengthens)

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Richer haptics materially improves remote demonstration, tele-service, virtual try-before-buy, and precise mediated work. At 1st order, it can make remote service exchange more trustworthy where force, touch, or physical intuition matters. At 2nd order, it supports higher-value remote labor and immersive service markets; at 3rd order, it may shift liability toward interface providers when felt representations mislead users. The impact is real but bounded to selected sectors.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Peer trust] → remote repair, fitting, or training services advertise tactile guidance (service quality improves)
- (+) [Individuality] → product sampling shifts from visual-only to multi-sensory previews (confidence increases)
- (–) [Accountability] → disputes cite mismatch between haptic preview and real product or service (representation liability grows)
- (–) [Market structure] → proprietary feedback ecosystems lock users into specific marketplaces (interface control hardens)
- (+) [Watchpoint] → insurers or standards bodies certify haptic-assisted remote service protocols (link strengthens)

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Intent- and context-aware AI significantly changes how people search, compare, and commit to transactions by reducing the need for explicit commands. At 1st order, it makes exchange more anticipatory, accessible, and individualized. At 2nd order, it raises the power of platforms and

assistants to time offers, steer decisions, and interpret vulnerability; at 3rd order, it can normalize invisible behavioral optimization and sharpen debates over autonomy and fairness. That is a significant shift in how exchange is experienced and governed.

Weak signals (9):

- (+) [Ease and convenience] → assistants complete routine purchases from inferred context with minimal prompts (friction disappears)
- (+) [Individuality] → platforms adapt modality, timing, and payment method per user state (commerce gets anticipatory)
- (+) [Locality and cultural relevance] → services localize offers using social and situational cues (fit improves)
- (+) [Peer trust] → accessible interfaces reduce transaction abandonment in edge cases (participation widens)
- (+) [Time independence] → tasks are queued and executed around user availability automatically (exchange synchronizes better)
- (–) [Consumer autonomy] → regulators target exploitative timing and context-based nudging (manipulation becomes visible)
- (–) [Pricing fairness] → inferred stress or urgency shows up in personalized prices (discrimination risk grows)
- (–) [Privacy] → multimodal behavioral capture becomes default at point of exchange (surveillance intensifies)
- (–) [Accountability] → sellers cannot easily explain why the AI chose or withheld an offer (decision opacity matters)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 0 (Impact in GVN 8)

Justification (3–5 sentences):

The linkage between brain-to-brain interfaces and the Exchange GVN is too weak and speculative to justify a meaningful impact score. Any plausible commercial effect would stay in niche collaboration or accessibility services rather than mainstream transfer of goods, services, or access rights. That keeps it below the threshold for a clear GVN linkage.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint] → consumer or workplace platforms add BBI communication APIs (mainstream bridge appears)
- (+) [Remote services] → premium collaboration vendors sell BBI-assisted co-working packages (niche service market forms)
- (–) [Reliability] → courts reject neural-state evidence in contract or consent disputes (commercial use stays weak)
- (–) [Privacy] → insurers or employers seek access to inferred neural states (conflict, not broad adoption)
- (+) [Governance] → standards define neural consent for commercial interaction (would create clearer linkage)



## ART 04.028 - Memory Prostheses

Score: 0 (Impact in GVN 8)

Justification (3–5 sentences):

Memory prostheses primarily affect health and individual capability rather than the operating model of exchange. Any Exchange impact would be indirect through labor participation, assistive services, or continuity of service use, not through major changes in how markets coordinate. That is below a meaningful threshold for this GVN.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint] → marketplaces for assistive work tools integrate prosthesis-compatible workflows (niche labor bridge forms)
- (+) [Ease and convenience] → service providers offer memory-linked authentication or reminders for vulnerable users (specialized inclusion grows)
- (–) [Governance] → regulators prohibit commercial use of stored or replayed memory traces (linkage stays narrow)
- (–) [Equality] → insurers cover prostheses only for limited groups (no broad market effect)
- (+) [Watchpoint] → platforms market memory-assisted shopping or service continuity subscriptions (would strengthen relevance)

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Self-driving vehicles are transformative for Exchange because they change the cost, timing, geography, and reliability of delivery and mobility services. At 1st order, they support unattended delivery, longer operating windows, and better asset utilization. At 2nd order, they reallocate value across retailers, fleet operators, labor, insurers, and municipalities; at 3rd order, they normalize same-hour service, mobile retail, and machine-scheduled logistics. That clearly reaches the transformative threshold for how this GVN is realized.

Weak signals (9):

- (+) [Time independence] → merchants advertise 24/7 autonomous delivery windows (service hours detach from labor)
- (+) [Low transaction costs] → verified unattended drop-off becomes a standard checkout option (handoff friction falls)
- (+) [Prevalence and flexibility] → suburban and rural service areas expand without human-driver premiums (catchment widens)
- (+) [Reliability] → insurers publish distinct autonomous fleet pricing classes (risk becomes financeable)
- (+) [Locality] → local shops re-enter same-day competition via autonomous fleets (geographic advantage shifts)

- (–) [Labor] → courier, taxi, and van-driving disputes intensify around deployment zones (job displacement becomes salient)
- (–) [Governance] → municipalities monetize curb access and autonomous loading rights (public space becomes market infrastructure)
- (–) [Market structure] → large fleet operators gain routing and utilization advantages over small merchants (scale power rises)
- (–) [Security] → spoofing, vandalism, or takeover incidents directly disrupt commercial flows (cyber-physical risk becomes routine)

## ART 05.030 - Drone Swarms & Aerial Robots

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Drone swarms significantly change high-speed small-item delivery, mapping, inspection, and some service-on-demand markets. At 1st order, they reduce time and labor in aerial logistics and monitoring. At 2nd order, they favor platform orchestration and raise airspace, privacy, and nuisance conflicts; at 3rd order, they increase expectations for rapid response in logistics and maintenance. The effect is significant, but not a full-system linchpin.

Weak signals (9):

- (+) [Time independence] → urgent delivery marketplaces guarantee minute-scale aerial dispatch (speed premium emerges)
- (+) [Flexibility] → remote areas get routine aerial parcel service contracts (coverage expands cheaply)
- (+) [Reliability] → multi-drone handoff and redundancy become standard in SLAs (service continuity improves)
- (+) [Prevalence] → building inspections and service calls are sold as subscription bundles using swarms (new service formats)
- (+) [Low delivery costs] → platforms expose aerial delivery as default for selected SKUs (modal shift becomes visible)
- (–) [Governance] → municipalities create drone corridors, curfews, or access auctions (airspace becomes regulated marketplace)
- (–) [Equality] → affluent or sparsely populated zones get better coverage first (service distribution skews)
- (–) [Peer trust] → complaints rise over damaged, misdropped, or privacy-invasive drone service (social acceptance tested)
- (–) [Security] → drone spoofing and cargo theft incidents force new insurance clauses (risk surface changes)

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

General-purpose robots are transformative because they can take over many physical service, retail, handling, inspection, and replenishment tasks in spaces already built for people. At 1st order, this reduces dependence on human presence for many everyday exchange functions. At 2nd order, it shifts bargaining power toward firms with capital, robot operations capability, and software libraries; at 3rd order, it supports platformized physical labor and remote supervision of many

locations at once. That is a major operating-model change for Exchange.

Weak signals (9):

- (+) [Ease and convenience] → stores and service sites run extended hours with robot staff (human scheduling matters less)
- (+) [Reliability] → merchants advertise consistent service quality across locations via shared robot task libraries (process standardizes)
- (+) [Flexibility] → small operators lease robots by task-hour through platforms (physical capacity becomes tradable)
- (+) [Prevalence] → remote experts supervise multiple embodied service points at once (skills scale geographically)
- (+) [Low transaction costs] → repetitive inspections, setup, and replenishment move off manual labor (operating cost drops)
- (−) [Labor] → service unions and gig platforms fight over robot substitution rules (employment model destabilizes)
- (−) [Market structure] → a few robot-stack vendors dominate operating software and updates (toolchain lock-in rises)
- (−) [Accountability] → customers dispute injuries or failures across vendor-operator-supervisor boundaries (liability fragments)
- (−) [Security] → robot misuse or remote takeover incidents affect public trust in automated services (safety becomes market-critical)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Soft robotics materially affects exchange in delicate handling, cluttered environments, food, and sensitive service contexts where rigid automation is poorly suited. At 1st order, it lowers damage and expands automatable task types. At 2nd order, it lowers automation barriers in selected sectors; at 3rd order, it can redistribute value toward vendors with specialized soft-control libraries and materials stacks. The impact is real but bounded to narrower commercial domains.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → fragile-goods marketplaces cite lower damage rates from soft handling systems (service quality improves)
- (+) [Labor bottleneck] → providers automate awkward last-meter tasks previously left manual (niche throughput rises)
- (−) [Market structure] → specialized soft-robot vendors dominate certain sensitive sectors (capability bottleneck appears)
- (−) [Accountability] → safety certifications lag deployment in close human-contact services (growth slows)
- (+) [Watchpoint] → contract service platforms offer soft-robot handling as a standard option (linkage strengthens)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Fully autonomous fleets significantly affect Exchange wherever distance, danger, or continuity of presence are major bottlenecks. At 1st order, they reduce delay and labor in inspection, servicing, logistics, and monitoring in hard-to-reach areas. At 2nd order, they shift value toward operators that own mission software, maps, and maintenance ecosystems; at 3rd order, they normalize continuous presence and remote intervention. That is a significant but not universal shift in exchange operations.

Weak signals (9):

- (+) [Reliability] → ports, utilities, and logistics operators buy continuous autonomous inspection subscriptions (maintenance gets externalized)
- (+) [Flexibility] → remote regions receive routine service fulfillment from unsupervised robotic fleets (distance penalty falls)
- (+) [Prevalence] → platforms sell always-on physical presence as a service tier (coverage becomes productized)
- (+) [Low transaction costs] → exception-only human intervention becomes standard in field-service contracts (labor intensity drops)
- (+) [Time independence] → night and off-weather windows become usable for selected tasks (operating hours expand)
- (–) [Governance] → unsupervised-operation permits become a competitive asset (regulatory capacity matters)
- (–) [Market structure] → fleet software and map providers capture most value (stack control centralizes)
- (–) [Accountability] → failure disputes span hardware maker, operator, and remote supervisor (liability fragments)
- (–) [Security] → navigation spoofing or mission hijacking events hit commercial operations (trust hinges on cyber safety)

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Autonomy-support infrastructure is significant because it makes physical automation economically viable in commercial spaces that would otherwise remain too messy or risky. At 1st order, it lowers the sensing and coordination burden on robots and enables denser machine activity. At 2nd order, it can reorder commercial geography by favoring autonomy-ready buildings and districts; at 3rd order, it may create new toll points and gatekeeping around who gets access to high-efficiency machine corridors. That is a significant enabler of changed exchange models.

Weak signals (9):

- (+) [Delivery bottlenecks] → new retail and logistics developments include robot docks by default (space is redesigned)
- (+) [Low transaction costs] → buildings publish machine-readable access rules to service platforms (integration cost falls)

- (+) [Reliability] → autonomous handoff nodes become standard in service-level contracts (operations stabilize)
- (+) [Flexibility] → landlords market autonomy-ready premises to merchants (real-estate value shifts)
- (+) [Prevalence] → municipalities pilot curb, corridor, or indoor-lane reservations for robots (shared rules emerge)
- (–) [Equality] → non-retrofitted districts lose service quality or coverage (infrastructure access stratifies markets)
- (–) [Market structure] → infrastructure owners charge toll-like access fees to autonomous operators (new chokepoint forms)
- (–) [Governance] → disputes arise over priority rules between humans and machines (coordination politics intensify)
- (–) [Security] → attacks or outages at shared autonomy posts disrupt many firms at once (centralized fragility appears)

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Power beaming has a narrow Exchange linkage through persistent robots and sensors in fenced or remote commercial environments. At 1st order, it may extend uptime for inspection, patrol, or specialized logistics. At 2nd and 3rd order, safety and infrastructure constraints keep it niche rather than a broad exchange-shaping technology. That keeps the impact limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → fixed logistics yards use beamed power for persistent robotic patrols (niche uptime gain)
- (+) [Low delivery costs] → long-endurance drones operate in fenced commercial corridors (specialized economics improve)
- (–) [Governance] → safety exclusion zones raise permitting conflicts around commercial sites (rollout stays bounded)
- (–) [Market structure] → only large operators can finance beaming infrastructure (niche concentration appears)
- (+) [Watchpoint] → service contracts start promising multi-day untethered robot uptime via beaming (linkage strengthens)

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Dry-adhesion mobility mainly matters to Exchange through niche climbing, inspection, and delicate handling services. At 1st order, it may lower access costs for hard-to-reach maintenance or overhead work. At 2nd and 3rd order, the influence remains specialized rather than society-wide. So the score remains low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → building or vehicle inspection platforms advertise residue-free climbing automation (niche service value)
- (+) [Low transaction costs] → delicate overhead maintenance tasks are packaged into routine subscriptions (access cost falls)
- (–) [Governance] → safety certification lags for commercial public-space use (adoption remains narrow)
- (–) [Market structure] → a few tooling vendors dominate adhesion-enabled service niches (capability bottleneck forms)
- (+) [Watchpoint] → logistics or retail systems adopt dry-adhesion manipulation in standard workflows (linkage would strengthen)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Multi-material printing significantly changes Exchange by shortening the path from design to tradable physical goods. At 1st order, it supports local production, custom products, spare-part availability, and lower inventory burdens. At 2nd order, it unbundles design rights, fabrication rights, and service rights while shifting counterfeiting toward file piracy and certification disputes; at 3rd order, it can support more distributed production ecosystems. That is a significant shift in how some goods are produced and exchanged.

Weak signals (9):

- (+) [Flexibility] → marketplaces sell designs separately from local fabrication services (rights unbundle)
- (+) [Individuality] → buyers configure functional product properties before production (customization gets routine)
- (+) [Low transaction costs] → retailers shrink spare-part stock in favor of print-on-demand fulfillment (inventory burden drops)
- (+) [Locality] → local print hubs integrate with delivery apps and commerce platforms (production relocalizes)
- (+) [Reliability] → insurers and certifiers publish standard classes for printed consumer and industrial parts (trust scales)
- (–) [Peer trust] → disputes shift from product authenticity to file provenance and print settings (fraud changes layer)
- (–) [Market structure] → platforms controlling printable design libraries gain outsized leverage (IP gatekeeping rises)
- (–) [Governance] → product liability cases center on designer vs printer vs seller (responsibility fragments)
- (–) [Security] → tampered design files create hidden defects in traded goods (safety attack surface opens)

## ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Digital twins materially affect Exchange through more predictable supply, shorter ramp-up time, and lower failure rates in production. At 1st order, they improve delivery confidence and reduce scrap or downtime that would otherwise disrupt exchange. At 2nd order, they favor suppliers that can expose better operational data and simulation evidence; at 3rd order, they make more contracts and warranties data-mediated. This is meaningful, but still primarily a production-side enabler rather than a direct market redesign.

Weak signals (9):

- (+) [Reliability] → suppliers expose live production-state confidence to buyers (delivery promises get sharper)
- (+) [Low transaction costs] → procurement platforms compare suppliers using simulated lead-time and quality data (search improves)
- (+) [Flexibility] → product variants are quoted from twin-based capacity forecasts (custom supply gets easier)
- (+) [Accountability] → warranties reference twin-predicted operating envelopes (service terms become data-rich)
- (+) [Prevalence] → contract manufacturers publish digital acceptance tests from twins (qualification time drops)
- (–) [Market structure] → buyers prefer suppliers with rich twin interoperability (data-poor firms lose visibility)
- (–) [Governance] → disputes focus on whether the twin or the plant reflected truth (evidence shifts layers)
- (–) [Security] → manipulated twin data distorts procurement or maintenance choices (digital sabotage gains leverage)
- (–) [Labor] → tacit shop-floor judgment is displaced by model-centered oversight (skill mix changes)

## ART 06.039 - Reconfigurable & Agile Factories

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Reconfigurable factories significantly change Exchange by making small-batch, local, and variable production more economically viable. At 1st order, they reduce long setup times, lower inventory dependence, and support more tailored offerings. At 2nd order, they weaken some scale advantages of fixed lines and support regional resilience; at 3rd order, they shift power toward orchestration software and standardized modules rather than static plant layout. That is a significant change in the supply side of exchange.

Weak signals (9):

- (+) [Prevalence and flexibility] → contract manufacturers advertise rapid product-family switches as a service (capacity becomes fluid)
- (+) [Locality] → regional microfactories win business previously sourced abroad (supply relocates)



- (+) [Low transaction costs] → platforms route orders dynamically to whichever cell is free (coordination improves)
- (+) [Individuality] → sellers offer more configurable SKUs without holding finished stock (variety expands)
- (+) [Reliability] → buyers pay premiums for reconfigurable surge capacity during disruptions (resilience gets priced)
- (–) [Market structure] → orchestration-software vendors capture access to modular capacity pools (stack power rises)
- (–) [Labor] → fewer specialized changeover roles and more general supervisory roles emerge (skill profile shifts)
- (–) [Governance] → certification struggles to keep pace with frequent line reconfiguration (compliance burden grows)
- (–) [Peer trust] → buyers demand proof that same product from different cells is equivalent (consistency becomes key)

## ART 06.040 - Circular & Sustainable Manufacturing

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Circular manufacturing materially affects Exchange by strengthening remanufactured-goods markets, recycled feedstock flows, and product-passport-backed sustainability claims. At 1st order, it creates tradable circularity and traceability attributes. At 2nd order, it changes bargaining power among brands, recyclers, and platforms; at 3rd order, it may create new exclusion risks for suppliers that cannot verify circular claims. The impact is meaningful but not system-defining.

Weak signals (9):

- (+) [Peer trust] → product listings include recycled-content and recirculation credentials by default (sustainability becomes searchable)
- (+) [Low transaction costs] → take-back and remanufacture offers are embedded at first sale (reverse logistics normalizes)
- (+) [Prevalence] → marketplaces create certified remanufactured categories with warranty parity (secondary markets upgrade)
- (+) [Locality] → local feedstock recovery hubs sign supply contracts with nearby manufacturers (waste becomes input)
- (+) [Accountability] → digital product passports link material claims to transactions (verification gets easier)
- (–) [Market structure] → brands control access to repair and feedstock data and limit independent remanufacture (circular lock-in appears)
- (–) [Governance] → disputes focus on what qualifies as circular or recycled enough (label boundary becomes strategic)
- (–) [Equality] → small suppliers struggle to meet passport and traceability requirements (compliance burden excludes)
- (–) [Security] → fraud shifts toward forged environmental attributes, not just forged products (claim integrity matters)

## ART 06.041 - Bio-fabrication technologies

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Bio-fabrication affects Exchange mainly in specialized biomedical and research product markets. At 1st order, it creates new tradable tissue, reagent, and biological-material categories. At 2nd and 3rd order, it changes quality assurance, cold-chain, and facility concentration in those niches, but it does not broadly alter exchange across society. That keeps the score limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → new biofabricated tissue or reagent categories appear in specialized marketplaces (niche exchange forms)
- (+) [Reliability] → chain-of-custody and sterile handling become visible sales differentiators (trust gets procedural)
- (–) [Governance] → cross-border shipping and approval rules slow market formation (scaling remains narrow)
- (–) [Market structure] → a few facilities dominate high-value biofabrication services (capacity concentrates)
- (+) [Watchpoint] → general healthcare procurement platforms treat biofabricated products as routine catalog items (link strengthens)

## ART 06.042 - 4D Printed & Programmable Materials

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Programmable materials matter to Exchange mainly through niche adaptive-product and maintenance models rather than broad transaction redesign. At 1st order, they may reduce service needs and enable configurable products. At 2nd and 3rd order, they could influence warranties and product claims in selected sectors, but the overall GVN linkage stays limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Individuality] → configurable self-adjusting goods appear in premium product categories (niche differentiation emerges)
- (+) [Reliability] → service contracts include self-deploying or self-calibrating components (maintenance burden falls)
- (–) [Governance] → standards lag on lifecycle claims for adaptive materials (trust grows slowly)
- (–) [Peer trust] → buyers dispute whether transformed states match the promised specification (representation risk appears)
- (+) [Watchpoint] → mainstream marketplaces add programmable-material product filters or warranties (linkage would strengthen)

## ART 06.043 - Volumetric Additive Manufacturing

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Volumetric printing materially affects Exchange by making some custom and spare-part production much faster and more local. At 1st order, it reduces wait times for complex low-volume goods. At 2nd order, it supports compact distributed production and design-file commerce; at 3rd order, it may shift value from inventory holders to design and certification layers. The impact is meaningful but not as broad as more general additive manufacturing shifts.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → on-demand spare parts are delivered from compact local print units (response time drops)
- (+) [Individuality] → custom items move from special order to routine purchase (small-batch economics improve)
- (–) [Governance] → liability and material-certification disputes slow adoption in safety-critical goods (trust bottleneck remains)
- (–) [Market structure] → design-file platforms capture more value than local fabricators (IP layer dominates)
- (+) [Watchpoint] → retailers replace stocked niche inventory with volumetric print fulfillment (linkage strengthens)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Metamaterials affect Exchange through better antennas, coverage shaping, signal handling, and compact optics in communications-heavy commercial systems. At 1st order, they can improve coverage and hardware performance in cluttered retail, logistics, and mobile environments. At 2nd and 3rd order, they shift value toward infrastructure providers and component suppliers rather than directly transforming transaction structure. That makes the impact material but indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → buildings and vehicles adopt wave-shaping surfaces to improve commerce connectivity (coverage becomes engineered)
- (+) [Low transaction costs] → compact high-gain terminals reduce installation barriers for merchants (access cost falls)
- (–) [Market structure] → qualified metamaterial suppliers become embedded in network rollouts (supply leverage grows)
- (–) [Governance] → exposed smart surfaces trigger safety and privacy certification debates (deployment slows)

- (+) [Watchpoint] → retail or logistics sites market metamaterial-enabled coverage guarantees (direct relevance rises)

## ART 07.045 - Room-Temperature Superconductors

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Room-temperature superconductors matter to Exchange mainly through power and data infrastructure efficiency. At 1st order, they could lower losses and compress equipment size in hubs that support payments, platforms, logistics, and automation. At 2nd and 3rd order, benefits would concentrate in energy-intensive or infrastructure-rich settings, making the impact material but mostly indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → data-center and logistics hubs sign pilots for superconducting power hardware (infrastructure cost pressure eases)
- (+) [Reliability] → compact high-current installations support dense commercial sites (capacity constraint loosens)
- (–) [Market structure] → early access is limited to large campuses and utilities (benefits concentrate)
- (–) [Governance] → safety and joining standards dominate commercial procurement (rollout remains selective)
- (+) [Watchpoint] → exchange-critical sites advertise superconducting uptime or cost advantages (linkage strengthens)

## ART 07.046 - Self-Healing & Smart Polymers

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

These materials affect Exchange mostly through better durability in packaging, devices, vehicles, and fixtures used by commercial systems. At 1st order, they may lower returns, downtime, and maintenance in selected categories. At 2nd and 3rd order, the effect remains incremental and sector-specific rather than GVN-wide. So the overall linkage stays limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → packaging or device vendors market self-healing lifetime guarantees (niche trust premium appears)
- (+) [Low transaction costs] → fewer damage-related returns are reported in pilot product classes (small friction reduction)
- (–) [Market structure] → specialty polymer suppliers control certified formulations (supplier leverage rises)
- (–) [Governance] → recyclability concerns delay procurement in consumer-facing uses (adoption stays narrow)
- (+) [Watchpoint] → major marketplaces create filters for self-healing goods with lower warranty risk (linkage would strengthen)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Nano-catalysts and advanced coatings affect Exchange indirectly through better machinery, lower maintenance, and improved product surfaces. At 1st order, they may enhance cold-chain, packaging, anti-counterfeit, or equipment uptime. At 2nd and 3rd order, these remain mainly upstream cost and reliability improvements rather than changes to the transaction model. That keeps the score low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → cold-chain, packaging, or vehicle suppliers market coating-backed uptime gains (niche efficiency matters)
- (+) [Peer trust] → anti-counterfeit or wear-indicating coatings appear in premium goods (verification gets easier)
- (–) [Market structure] → proprietary coating recipes become qualification bottlenecks (supplier power concentrates)
- (–) [Governance] → nanoparticle handling or disposal rules slow wider uptake (commercial reach stays bounded)
- (+) [Watchpoint] → marketplaces start pricing certified coated components separately from standard ones (linkage strengthens)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Better alloys improve the durability and performance of vehicles, robots, and equipment used in exchange, but mostly as hidden infrastructure. At 1st order, they reduce failures and maintenance in harsh commercial settings. At 2nd and 3rd order, the benefits remain incremental and asset-specific rather than market-structuring. So the score remains limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → logistics and warehouse equipment suppliers market HEA-based long-life components (maintenance burden falls)
- (+) [Delivery bottlenecks] → harsh-environment service assets last longer before replacement (specialized uptime rises)
- (–) [Market structure] → qualified alloy supply remains concentrated in few producers (benefits stay narrow)
- (–) [Governance] → certification timelines slow use in broad commercial fleets (adoption lags)
- (+) [Watchpoint] → resale markets start valuing HEA-equipped assets at a premium (direct linkage strengthens)

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Advanced CO<sub>2</sub> capture materials matter to Exchange mainly through carbon-accounted supply chains and tradable low-emission claims. At 1st order, they can support new product attributes and compliance categories. At 2nd and 3rd order, the main effects are in certification, procurement, and cost structure rather than market coordination itself. The linkage is therefore limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Accountability] → product listings include capture-backed carbon attributes with auditable evidence (claim markets form)
- (+) [Reliability] → long-term CO<sub>2</sub> service contracts appear for industrial sellers (niche cost predictability improves)
- (–) [Market structure] → access to certified capture modules becomes a barrier for small suppliers (compliance burden rises)
- (–) [Governance] → disputes over capture accounting reduce buyer trust in low-carbon labels (verification remains contested)
- (+) [Watchpoint] → buyers systematically pay premiums only for capture-verified goods (linkage strengthens)

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Graphene and nanotube composites materially affect Exchange through lighter assets, longer-lived equipment, and condition-sensing components. At 1st order, they can improve delivery economics and reduce hidden damage or fatigue. At 2nd order, they support better monitoring and maintenance regimes; at 3rd order, they shift value toward advanced-material suppliers and condition-data interpreters. The impact is material but remains one step removed from core exchange logic.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low delivery costs] → lighter service vehicles or drones reach better economics with composite upgrades (range-cost improves)
- (+) [Reliability] → goods and assets self-report strain or damage in commercial use (condition becomes visible)
- (–) [Governance] → occupational and recycling concerns slow broad consumer adoption (material externalities matter)
- (–) [Market structure] → premium composite supply stays concentrated in a few firms (capability access narrows)
- (+) [Watchpoint] → secondary markets routinely price embedded condition-sensing composite parts (linkage strengthens)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Smart thermal materials mainly affect Exchange through packaging, buildings, vehicles, and cold-chain reliability. At 1st order, they can lower spoilage, energy use, and temperature-related service interruptions. At 2nd and 3rd order, the effects remain supportive rather than market-transforming. So the score stays low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → cold-chain sellers use smart thermal packaging to reduce spoilage claims (quality protection improves)
- (+) [Low transaction costs] → merchants market lower energy or cooling fees in thermally upgraded sites (small cost shift)
- (–) [Governance] → fire or toxicity standards delay mass rollout in consumer spaces (adoption remains selective)
- (–) [Market structure] → premium thermal materials become concentrated in building retrofits for large operators (benefits skew upward)
- (+) [Watchpoint] → marketplaces explicitly label smart-thermal features as resale or rental value drivers (link strengthens)

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Rare-earth-free magnets materially affect Exchange through supply resilience for motors in delivery fleets, robots, appliances, and infrastructure. At 1st order, they reduce vulnerability to concentrated supply chains. At 2nd order, they stabilize asset procurement and cost planning; at 3rd order, they may reallocate manufacturing advantage across regions and vendors. That is meaningful for resilience, though still indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Security of supply] → fleet and robot procurements specify rare-earth-free motor options (sourcing risk enters buying)
- (+) [Reliability] → vendors offer longer price locks tied to magnet supply stability (planning improves)
- (–) [Market structure] → first qualified manufacturers capture public procurement and OEM contracts (transition advantage concentrates)
- (–) [Performance trust] → buyers demand proof that lower rare-earth content does not hurt uptime (equivalence must be shown)
- (+) [Watchpoint] → mainstream exchange assets advertise rare-earth-independent sourcing as a selling point (linkage strengthens)



## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

This ART affects Exchange mainly in water-stressed locations where service continuity or production depends on water availability. At 1st order, it can improve viability and reliability for local commerce in those settings. At 2nd and 3rd order, the effects remain geographically narrow and infrastructural rather than broadly market-shaping. That keeps the score limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Locality] → water-stressed commercial zones secure lower-cost supply using advanced membranes (local commerce viability improves)
- (+) [Reliability] → food or tourism services market resilient water-backed operation (site risk falls)
- (–) [Market structure] → specialized membrane replacement contracts favor large operators (benefits concentrate)
- (–) [Governance] → disposal and concentrate rules slow broader commercial deployment (indirect reach stays narrow)
- (+) [Watchpoint] → municipal or industrial water markets materially reshape local seller participation (linkage strengthens)

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

UWBG semiconductors materially affect Exchange through more compact, efficient chargers, drives, converters, and automation power systems. At 1st order, they improve uptime and lower losses in fleets, depots, autonomous devices, and commercial infrastructure. At 2nd order, they favor firms that can redesign around better power electronics; at 3rd order, they reinforce automation and electrification trends already reshaping exchange. The impact is meaningful but indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → fleet depots and automated sites report lower power-conversion losses (operating cost drops)
- (+) [Reliability] → uptime guarantees improve for chargers and autonomous equipment using UWBG modules (hardware resilience rises)
- (–) [Market structure] → scarce qualified modules constrain smaller equipment makers (supply bottleneck forms)
- (–) [Governance] → new thermal and safety certification slows diffusion into mass-market hardware (adoption stays staged)
- (+) [Watchpoint] → merchants or operators advertise compact high-power infrastructure as a service differentiator (linkage strengthens)

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Solid hydrogen storage has a narrow Exchange linkage through remote energy supply, specialized transport, and backup power. At 1st order, it may help selected logistics or off-grid service models. At 2nd and 3rd order, safety, cost, and infrastructure constraints keep the impact bounded. So the score remains low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → remote logistics or backup sites trial cartridge-based hydrogen supply (niche service continuity improves)
- (+) [Security of supply] → commercial operators market lower handling risk than compressed gas (fuel trust grows)
- (–) [Market structure] → specialized cartridge and heat-management suppliers dominate early markets (niche concentration appears)
- (–) [Governance] → safety and transport codes keep use limited to selected sectors (broad linkage stays weak)
- (+) [Watchpoint] → delivery or microgrid operators standardize on solid-storage hydrogen modules (relevance would rise)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Fusion affects Exchange mainly through steadier, cleaner, large-scale power for data centers, logistics hubs, manufacturing, and payment infrastructure. At 1st order, it could reduce power volatility in exchange-critical sites. At 2nd order, it may shift advantage toward regions and firms with access to fusion-backed baseload; at 3rd order, it changes infrastructure economics more than transaction architecture. That makes the impact material but indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → major commercial hubs sign interest agreements for fusion-backed uptime (power continuity becomes strategic)
- (+) [Low transaction costs] → energy-intensive exchange infrastructure starts modeling fusion-based cost curves (future cost expectations shift)
- (–) [Market structure] → only large campuses or utilities can secure early output (benefits concentrate)
- (–) [Governance] → licensing timelines dominate commercial planning assumptions (indirect effect delayed)
- (+) [Watchpoint] → merchants or platforms market fusion-sourced operations as a trust or price differentiator (link strengthens)

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

SMRs materially affect Exchange through reliable heat and power for large facilities that support commercial activity. At 1st order, they improve continuity for cold chains, data, logistics, and industrial supply. At 2nd order, they may favor well-capitalized operators and sites with regulatory capacity; at 3rd order, they reshape the geography of resilient commercial infrastructure rather than exchange mechanics themselves. So the impact is material but not transformative.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → logistics parks or data campuses procure SMR-backed supply options (uptime becomes financeable)
- (+) [Low transaction costs] → long-term service pricing assumes lower energy volatility near SMR sites (cost risk falls)
- (–) [Market structure] → nuclear-grade access advantages large hubs over smaller regional operators (capacity centralizes)
- (–) [Governance] → public opposition or security rules delay commercial tie-ins (adoption remains selective)
- (+) [Watchpoint] → exchange-critical facilities market SMR-backed continuity guarantees (linkage strengthens)

## ART 08.058 - Thin-film solar cells

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Thin-film solar materially affects Exchange by widening where local electricity can be harvested for devices, kiosks, lockers, vehicles, and remote service points. At 1st order, it supports self-powered small-scale commerce infrastructure. At 2nd order, it lowers entry barriers for some small operators and supports more distributed exchange endpoints; at 3rd order, it makes more infrastructure partially independent from centralized grids. That is meaningful, but mainly as enabling infrastructure.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Locality] → small shops, kiosks, and vehicles adopt integrated solar skins (local autonomy improves)
- (+) [Reliability] → remote lockers and sensors remain operable with minimal grid access (service continuity rises)
- (–) [Market structure] → high-quality integrated solar is bundled by a few device and building vendors (supplier leverage grows)
- (–) [Governance] → installation and disposal standards vary enough to slow market confidence (rollout fragments)
- (+) [Watchpoint] → commerce platforms certify solar-self-powered service points as a standard feature (linkage strengthens)

## ART 08.059 - Bionic Leaf Technology

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Bionic leaf systems have only a limited link to the Exchange GVN through niche local molecule or fuel production. At 1st order, they might support specialized remote commercial autonomy. At 2nd and 3rd order, the broader exchange effect stays too narrow and indirect to justify a higher score.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → distributed chemical or fuel products from leaf-like panels enter niche marketplaces (new category forms)
- (+) [Locality] → remote commercial sites pilot local molecule production from sunlight (specialized autonomy grows)
- (–) [Governance] → safety and product-purity rules delay commercial sale (market remains narrow)
- (–) [Market structure] → only integrated hardware-chemistry vendors can offer bankable systems (benefits concentrate)
- (+) [Watchpoint] → exchange platforms treat bionic-leaf output as a routine tradable commodity (link strengthens)

## ART 08.060 - Grid-Scale Energy Storage

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Grid-scale storage significantly affects Exchange because many exchange systems now depend on continuous electricity quality and timing, not just average supply. At 1st order, storage stabilizes payments, cold chains, fulfillment, and automated service operations. At 2nd order, it rewards flexible sites and operators while potentially widening inequality between protected and unprotected zones; at 3rd order, it helps normalize 24/7 automated exchange even under variable renewable supply. That places it in the significant-impact category.

Weak signals (9):

- (+) [Reliability] → logistics and payment hubs buy uptime backed by storage-capacity contracts (exchange continuity monetized)
- (+) [Time independence] → automated fulfillment expands into overnight and volatile-price windows (operations detach from grid timing)
- (+) [Low transaction costs] → retailers and platforms expose flexible delivery or processing tied to cheap stored power (cost optimization broadens)
- (+) [Prevalence] → outage-sensitive merchants adopt storage-linked service guarantees (resilience enters competition)
- (+) [Flexibility] → micro-warehouses co-locate storage to smooth robotic operations (local autonomy rises)
- (–) [Market structure] → storage-rich nodes attract more commerce concentration than weaker regions (geographic imbalance grows)
- (–) [Governance] → fire, land, and permitting fights determine which exchange zones get resilient power (infrastructure politics intensify)

- (–) [Accountability] → disputes emerge over who pays when stored-energy promises fail during blackouts (contract complexity rises)
- (–) [Security] → cyber or control failures in large storage fleets threaten many dependent services at once (new systemic risk)

## ART 08.061 - Solid-State Batteries

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Solid-state batteries significantly affect Exchange through safer, lighter, and longer-lived mobile infrastructure: delivery fleets, robots, devices, and mobile retail systems. At 1st order, they extend operating windows and reduce downtime or fire-related constraints. At 2nd order, they shift insurance, leasing, and fleet economics; at 3rd order, they expand autonomous and mobile exchange formats by making electrified assets more practical. That is a significant impact on the GVN.

Weak signals (9):

- (+) [Delivery bottlenecks] → courier, robot, and service fleets rewrite procurement specs around solid-state packs (asset model shifts)
- (+) [Reliability] → insurers lower depot and fleet premiums for safer battery chemistry (risk cost falls)
- (+) [Time independence] → all-day service windows become standard without mid-shift charging (uptime expands)
- (+) [Flexibility] → battery leasing or swap contracts appear for small merchants and fleets (capital barrier lowers)
- (+) [Prevalence] → mobile retail, kiosks, and field-service gear operate longer untethered (new formats scale)
- (–) [Market structure] → early pack supply is concentrated among few OEMs (transition power centralizes)
- (–) [Governance] → recycling and health-reporting standards become conditions of resale (secondary markets need new rules)
- (–) [Equality] → smaller operators face delayed access to premium cells (capability gap persists)
- (–) [Accountability] → disputes move from fires toward warranty, degradation, and cold-weather performance claims (risk profile changes)

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Power-to-X materially affects Exchange through cleaner freight, shipping, industrial supply, and energy-buffering systems. At 1st order, it supports new tradable fuel-origin and carbon-content attributes. At 2nd order, it changes supply-chain economics and procurement strategies; at 3rd order, it may redistribute advantage toward actors controlling cheap electricity, water, and synthesis capacity. The linkage is real, but still mainly infrastructural and upstream.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Accountability] → contracts begin specifying certified green-molecule attributes and digital proof (origin becomes tradable)
- (+) [Reliability] → ports, freight operators, or industry clusters sign long-term supply offtakes (supply certainty improves)
- (–) [Market structure] → access to cheap electricity and electrolyzer capacity favors large incumbents (transition benefits skew)
- (–) [Governance] → safety, water, and permitting limits slow service availability (commercial reach stays bounded)
- (+) [Watchpoint] → delivery or logistics services market power-to-X fuel provenance as a buyer-facing differentiator (link strengthens)

## ART 08.063 - High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

High-efficiency wind materially affects Exchange through cheaper and more resilient electricity for exchange-supporting infrastructure. At 1st order, it lowers power costs in regions with strong wind resources. At 2nd order, it shifts competitive geography and supports cleaner logistics or data claims; at 3rd order, it remains mostly an energy-supply factor rather than a direct exchange redesign. So the impact is material but indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Low transaction costs] → energy-intensive commerce hubs secure lower-cost wind PPAs (operating cost pressure eases)
- (+) [Reliability] → storage-plus-wind packages support resilient service zones (power continuity improves)
- (–) [Locality] → regions with better wind-resource access gain commercial advantage (geography shifts competitiveness)
- (–) [Governance] → siting conflicts constrain where energy-backed exchange can scale (deployment remains uneven)
- (+) [Watchpoint] → merchants actively market wind-backed operations as price or trust differentiators (linkage strengthens)

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Wireless and space-based power transfer only weakly affects Exchange outside specialized remote or temporary operations. At 1st order, it may help certain mobile or disconnected service sites. At 2nd and 3rd order, safety, cost, and infrastructure constraints keep the linkage narrow rather than GVN-wide. That keeps the impact limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Flexibility] → remote commercial sites or events buy beam-fed temporary power services (niche mobility gains)

- (+) [Reliability] → emergency logistics platforms test untethered power support for critical operations (specialized resilience grows)
- (–) [Governance] → beam-safety and siting rules constrain normal urban deployment (broad linkage stays weak)
- (–) [Market structure] → only infrastructure-scale players can finance early systems (benefits concentrate)
- (+) [Watchpoint] → mobile retail or service fleets routinely contract wireless power access (linkage would strengthen)

## ART 08.065 - Advanced geothermal technology

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Advanced geothermal materially affects Exchange through stable local heat and power for commercial clusters. At 1st order, it improves the resilience and predictability of sites like data centers, industrial zones, and logistics hubs. At 2nd order, it shifts advantage toward geologically and politically suitable regions; at 3rd order, it changes infrastructure economics more than the transaction model itself. Thus the score remains material but indirect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → logistics parks and data campuses pair growth plans with geothermal projects (baseload becomes locational advantage)
- (+) [Low transaction costs] → long-term service pricing references geothermal-backed energy stability (cost volatility drops)
- (–) [Locality] → only geologically or politically suitable regions capture benefits (advantage remains uneven)
- (–) [Governance] → drilling risk and permitting dominate project finance decisions (indirect effect delayed)
- (+) [Watchpoint] → exchange-critical facilities advertise geothermal-backed uptime or sustainability guarantees (linkage strengthens)

## ART 08.066 - Resilient microgrids

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Resilient microgrids significantly affect Exchange because they keep retail, payments, cold storage, logistics, and digital services running through wider network failures. At 1st order, they improve continuity, power quality, and local autonomy. At 2nd order, they reward places and organizations able to invest in resilience while potentially widening inequality between protected and exposed zones; at 3rd order, they enable denser automation by making local power more reliable. That is a significant operating-model shift for many exchange contexts.

Weak signals (9):

- (+) [Reliability] → merchants and platforms start advertising outage-proof service zones (continuity becomes competitive)



- (+) [Time independence] → payment, locker, and pickup systems remain live through regional outages (exchange decouples from grid failures)
- (+) [Locality] → community or district microgrids anchor local marketplaces and services (place-based resilience gains value)
- (+) [Low transaction costs] → insurers and lenders price resilient power into commercial terms (risk cost falls)
- (+) [Flexibility] → microgrids integrate EVs, storage, and local generation into service packages (assets become multi-use)
- (–) [Equality] → affluent or strategic districts secure microgrid protection first (resilience gap grows)
- (–) [Market structure] → platform operators cluster in microgrid-rich zones, deepening concentration (infrastructure filters competition)
- (–) [Governance] → disputes rise over islanding priority and who gets power in scarcity (allocation politics intensify)
- (–) [Security] → cyber incidents against microgrid control systems directly interrupt commerce (local autonomy becomes attack surface)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Next-generation gene editing affects Exchange mainly through specialized healthcare, agriculture, and biotech product markets rather than through the core exchange model. At 1st order, it creates new high-value therapies, biological inputs, and trait-specific products. At 2nd order, it reshapes licensing, reimbursement, consent, and liability arrangements in those sectors; at 3rd order, it could concentrate power in firms controlling editing platforms and validation infrastructure. The linkage is concrete, but too narrow to be material for the Exchange GVN as a whole.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → edited therapies or organisms appear as routine catalog items in specialized markets (niche exchange expands)
- (+) [Accountability] → consent, traceability, and chain-of-custody are built into commercial offerings (trust gets procedural)
- (–) [Equality] → access and pricing diverge sharply across payers and regions (distribution conflict emerges)
- (–) [Governance] → advertising and cross-border sale limits constrain open market growth (market remains bounded)
- (+) [Watchpoint] → mainstream insurers or consumer platforms normalize edited products and services (linkage would strengthen)

### ART 09.068 - mRNA Therapies & Vaccines

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

mRNA platforms materially affect Exchange in healthcare because they make some products more software-like: faster to redesign, easier to update, and more dependent on delivery and verification infrastructure. At 1st order, this changes product variety, response speed, and manufacturing flexibility. At 2nd order, it increases the importance of cold-chain trust, lipid-carrier supply, regulatory adaptation, and rapid quality verification; at 3rd order, it normalizes more configurable medical commerce. The effect is material within healthcare exchange, though not broad enough for a higher score.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Flexibility] → pharma procurement shifts toward platform contracts rather than fixed product lines (product reconfiguration speeds up)
- (+) [Reliability] → cold-chain and potency telemetry become visible buyer requirements (quality evidence matters more)
- (–) [Market structure] → platform owners and delivery-carrier suppliers capture outsized rents (capability concentration grows)
- (–) [Governance] → rapid product-update approvals create reimbursement and advertising disputes (rules strain under speed)
- (+) [Watchpoint] → routine pharmacy or telehealth marketplaces sell frequently updated mRNA-based offerings (linkage strengthens)

## ART 09.069 - Cellular Agriculture & Cultured Meat

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Cellular agriculture significantly affects Exchange because food is a high-frequency, large-volume category in everyday life. At 1st order, cultured meat and precision-fermented ingredients expand product range and reduce dependence on conventional livestock supply chains. At 2nd order, they alter retailer bargaining power, labeling rules, local production possibilities, and trust dynamics; at 3rd order, they redistribute value among farmers, bioreactor operators, brands, and delivery platforms. The likely total impact is clearly significant at societal scale.

Weak signals (9):

- (+) [Prevalence] → retailers and delivery platforms create stable cultured-protein categories (new food class normalizes)
- (+) [Individuality] → meal services offer tailored composition or nutrition from cell-based inputs (food customization rises)
- (+) [Locality] → urban or regional mini-plants sign supply deals with local channels (production relocates)
- (+) [Peer trust] → labeling standards and transparent process data become visible in listings (novelty gets explained)
- (+) [Low transaction costs] → supply volatility in selected products falls versus conventional animal inputs (price predictability improves)
- (–) [Bargaining power] → brands or platforms with trusted labels dominate consumer acceptance (gatekeeper power rises)
- (–) [Governance] → farmers and incumbent processors push for restrictive naming or shelf-placement rules (distribution conflict intensifies)

- (–) [Equality] → premium early pricing limits access to affluent segments first (benefits diffuse unevenly)
- (–) [Reliability] → contamination or texture incidents trigger sharp trust shocks in platform reviews (social acceptance remains fragile)

## ART 09.070 - Organoids & Tissue Engineering

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Organoids and tissue engineering mainly affect upstream research, drug development, and specialist medical markets. At 1st order, they improve the tradability of biological test systems and some therapeutic materials. At 2nd and 3rd order, they may reduce uncertainty and improve product development pipelines, but they do not broadly change how ownership or access rights are exchanged across society. That keeps the impact limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → tissue models become standard purchasable inputs in R&D marketplaces (niche exchange grows)
- (+) [Reliability] → biobank and assay vendors advertise lower-variance organoid services (quality differentiation sharpens)
- (–) [Governance] → transport, ethics, and biosafety rules keep markets specialist-only (broad linkage remains weak)
- (–) [Market structure] → a few automated bioreactor firms dominate supply (capacity concentrates)
- (+) [Watchpoint] → organoid-based consumer or routine care services appear outside narrow specialties (linkage strengthens)

## ART 09.071 - Synthetic Biology & Designer Microbes

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Designer microbes materially affect Exchange by enabling more configurable production of ingredients, chemicals, materials, and sensing functions. At 1st order, they shorten some supply chains and make production more reprogrammable. At 2nd order, they shift value toward strain owners, recipe platforms, and bioprocess specialists; at 3rd order, they create new provenance, containment, and trust requirements around biologically produced goods. The impact is meaningful, but still more supply-side than exchange-core.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Locality] → small or regional fermentation services enter procurement platforms (distributed production grows)
- (+) [Flexibility] → buyers switch between outputs through software-like recipe changes (supply becomes more reconfigurable)
- (–) [Governance] → containment and traceability rules dominate commercial onboarding (trust remains procedural)

- (–) [Market structure] → strain and IP owners capture more value than local producers (recipe control centralizes)
- (+) [Watchpoint] → mainstream marketplaces sell designer-microbe-derived goods with explicit provenance premiums (linkage strengthens)

## ART 09.072 - Microbiome Engineering

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Microbiome engineering has a limited Exchange linkage through specialized health, agriculture, and environmental services. At 1st order, it creates new subscription and intervention markets. At 2nd and 3rd order, effects remain bounded by regulation, efficacy uncertainty, and context-specific use rather than broad changes to exchange processes. So the score remains low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Individuality] → personalized microbiome services become a stable subscription category (niche service market forms)
- (+) [Reliability] → agriculture or water-service providers advertise microbiome-managed outcomes (specialized trust improves)
- (–) [Governance] → safety and efficacy claims face tight scrutiny in consumer-facing sales (growth stays bounded)
- (–) [Equality] → premium access and data requirements exclude many users (benefits remain stratified)
- (+) [Watchpoint] → major general marketplaces begin treating microbiome interventions as routine goods and services (link strengthens)

## ART 09.073 - Precision Medicine & Genomic Diagnostics

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Precision diagnostics materially affect Exchange by turning parts of healthcare into more data-rich matching and monitoring markets. At 1st order, they improve selection of treatments, services, and follow-up. At 2nd order, they create new data-rights, insurer-provider bargaining, and consent-management issues; at 3rd order, they may normalize portable biological credentials and continuous molecular service relationships. This is significant within healthcare exchange, but not across the full GVN.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Individuality] → routine care marketplaces package services around genomic or biomarker profiles (matching gets granular)
- (+) [Peer trust] → portable diagnostic summaries are accepted across providers and payers (data becomes exchangeable)
- (–) [Equality] → insurers or employers differentiate access based on molecular risk categories (distribution conflict grows)

- (–) [Governance] → consent, secondary-use, and reinterpretation disputes slow platform integration (trust remains contested)
- (+) [Watchpoint] → general digital wallets carry actionable health credentials used in routine transactions (linkage strengthens)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

This ART mainly affects upstream testing and specialized life-science service markets. At 1st order, it improves the tradability of higher-fidelity biological test services. At 2nd and 3rd order, it may reduce R&D friction and standardize bio-assay infrastructure, but it does not broadly reshape everyday exchange. That keeps the score low.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → assay vendors sell chip-based testing as standard catalog services (specialized exchange expands)
- (+) [Low transaction costs] → pharma and biotech procurement shifts from bespoke tests to reusable chip workflows (niche efficiency rises)
- (–) [Governance] → regulatory uncertainty on evidentiary use limits broader market growth (linkage stays narrow)
- (–) [Market structure] → a few device and consumable suppliers dominate the stack (benefits concentrate)
- (+) [Watchpoint] → non-specialist service marketplaces adopt chip-based bio-testing products (link strengthens)

## ART 09.075 - Biological Aging & Longevity Barriers

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Longevity interventions materially affect Exchange through labor participation, consumer demand, insurance, and recurring health-service markets. At 1st order, they can extend active participation in work and consumption. At 2nd order, they may create inequality if access is stratified and shift spending toward preventive and maintenance-like interventions; at 3rd order, they alter expectations about career duration, service usage, and long-term planning. The effect is meaningful, but still indirect for the GVN core.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Prevalence] → employers or insurers begin covering periodic longevity treatments (new recurring markets form)
- (+) [Labor bottleneck] → older workers remain in service and skilled roles longer through treated healthspan (participation expands)
- (–) [Equality] → access is strongly segmented by income or employer status (distribution conflict intensifies)

- (–) [Governance] → marketing restrictions limit open retail-like sale of longevity services (exchange remains controlled)
- (+) [Watchpoint] → mainstream platforms bundle longevity-related subscriptions into routine benefit or consumer offers (linkage strengthens)

## ART 09.076 - Engineered Living Materials

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Engineered living materials affect Exchange mainly through buildings, infrastructure, and maintenance-related goods and services. At 1st order, they can reduce inspection and repair frequency and create new performance-based material categories. At 2nd and 3rd order, they mostly reshape maintenance contracts and material claims rather than exchange structure. So the score remains limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → materials vendors market self-repairing surfaces with service-life guarantees (niche trust premium appears)
- (+) [Low transaction costs] → maintenance contracts shrink where living materials reduce repair frequency (small friction reduction)
- (–) [Governance] → biosafety and disclosure rules slow procurement outside specialized sectors (growth stays bounded)
- (–) [Peer trust] → buyers question long-term behavior of living components in traded goods (acceptance remains fragile)
- (+) [Watchpoint] → resale or construction marketplaces treat living-material status as a standard attribute (link strengthens)

## ART 09.077 - Gene Drive Pest Control

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Gene-drive pest control influences Exchange mostly through agriculture, land use, public-health, and tourism conditions. At 1st order, it can reduce pests and stabilize selected commodity or service environments. At 2nd and 3rd order, it raises governance, stewardship, and liability issues rather than directly changing transaction structures. That keeps the impact limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Reliability] → agricultural supply contracts price in gene-drive-based pest suppression zones (niche risk reduction)
- (+) [Locality] → tourism or outdoor-service markets advertise pest-managed areas (specialized demand effect)
- (–) [Governance] → public authorization battles dominate any commercial planning (market remains constrained)
- (–) [Accountability] → liability debates over spillover effects deter commercial uptake (trust bottleneck persists)

- (+) [Watchpoint] → service or commodity markets start routinely differentiating by gene-drive stewardship status (linkage strengthens)

## ART 09.078 - Artificial Wombs & Synthetic Embryos

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

Artificial wombs and synthetic embryos create new reproductive, breeding, and developmental service markets, but in tightly regulated domains. At 1st order, they expand some specialized medical and livestock-related services. At 2nd and 3rd order, ethical limits, legality, and evidentiary requirements keep the effect narrow rather than exchange-wide. The impact is therefore limited.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product range] → regulated reproductive or breeding services appear in formal procurement channels (niche market forms)
- (+) [Reliability] → monitoring-heavy gestation support becomes a billable service layer (service complexity grows)
- (–) [Governance] → legality and ethics rules dominate market boundaries (broad exchange stays restricted)
- (–) [Equality] → access is highly income- and institution-dependent (distribution remains narrow)
- (+) [Watchpoint] → mainstream insurance or platform providers integrate these services into routine offerings (linkage strengthens)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Satellite mega-constellations are transformative for Exchange because they extend connectivity and situational awareness into places where terrestrial infrastructure is weak, fragile, or absent. At 1st order, they enable digital trade, payment, and service delivery almost anywhere. At 2nd order, they shift bargaining power toward a few connectivity and sensing operators while raising sovereignty and resilience questions; at 3rd order, they normalize global platform participation and remote service provision in previously excluded zones. This clearly changes how exchange is realized, even if it is not the sole linchpin.

Weak signals (9):

- (+) [Time and location independence] → rural and maritime merchants use the same platform stack as urban peers (coverage gap narrows)
- (+) [Reliability] → businesses market backup connectivity through satellite terminals (continuity becomes purchasable)
- (+) [Prevalence] → observation data is bundled into logistics, insurance, and commodity services (space data enters transactions)



- (+) [Flexibility] → pop-up or disaster-zone marketplaces stay live through satellite links (exchange detaches from local damage)
- (+) [Low transaction costs] → satellite-connected sellers onboard without fixed-line dependency (entry barrier falls)
- (–) [Dependency on global platforms] → connectivity and marketplace services are vertically bundled (stack power grows)
- (–) [Governance] → cross-border data-routing and spectrum disputes shape commercial availability (jurisdiction matters more)
- (–) [Security] → outages, jamming, or terminal theft directly interrupt retail and payment flows (space layer becomes critical)
- (–) [Equality] → terminal and service quality tiers create a new connectivity class divide (benefits diffuse unevenly)

## ART 10.080 - Space Resource Utilization (SRU)

Score: 1 (Impact in GVN 8)

Justification (3–5 sentences):

SRU affects Exchange mainly through possible future critical-material supply changes rather than through direct changes to transaction patterns. At 1st order, it may create new high-value materials channels. At 2nd and 3rd order, ownership, reentry, provenance, and concentration questions dominate any commercial pathway. That keeps the impact low for this GVN.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Security of supply] → commodity buyers hedge around prospective off-world material streams (future supply relevance appears)
- (+) [Accountability] → provenance schemes emerge for space-sourced materials (novel origin claims form)
- (–) [Governance] → ownership and reentry rules dominate commercialization discussions (market remains remote)
- (–) [Market structure] → only mega-project actors can participate in early SRU chains (broad effect stays tiny)
- (+) [Watchpoint] → commercial catalogs begin listing Earth-returned SRU materials in routine procurement (linkage strengthens)

## ART 10.081 - Closed-Loop Life Support System

Score: 0 (Impact in GVN 8)

Justification (3–5 sentences):

Closed-loop life support has essentially no meaningful direct linkage to mainstream Exchange in a 5.5M-person society. Any commercial impact would stay confined to extreme environments, remote installations, or niche habitat services. That is below the threshold for a clear GVN effect.

Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint] → terrestrial remote camps or disaster shelters buy life-support-as-a-service systems (niche bridge forms)

- (+) [Reliability] → off-grid premium real-estate or expedition services market closed-loop utilities (specialized service market)
- (–) [Governance] → certification remains tied to extreme-use cases, not everyday commerce (broad linkage absent)
- (–) [Market structure] → only specialized suppliers offer integrated systems (societal effect stays minimal)
- (+) [Watchpoint] → consumer or municipal infrastructure adopts habitat-style closed-loop services at scale (would strengthen linkage)

## ART 10.082 - High-Altitude Platforms & Balloons

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

High-altitude platforms materially affect Exchange by providing recoverable, regional communications and sensing coverage where terrestrial systems are weak or disrupted. At 1st order, they support continuity for marketplaces, logistics, and services in remote or damaged regions. At 2nd order, they create new access dependencies on airspace, spectrum, and platform operators; at 3rd order, they make temporary or resilient connectivity more commercially normal. The effect is real, but still secondary to full broadband infrastructure.

Weak signals (9):

- (+) [Time and location independence] → event, rural, or disaster-zone merchants use HAP-backed connectivity routinely (service continuity broadens)
- (+) [Reliability] → logistics and public-service contracts include balloon or HAP failover links (resilience becomes purchasable)
- (+) [Prevalence] → regional observation and relay services are sold through standard APIs (pseudo-satellites commercialize)
- (+) [Flexibility] → marketplaces stay live in disrupted zones without waiting for ground rebuilds (recovery accelerates)
- (+) [Locality] → remote seasonal economies gain temporary high-quality digital access (short-term inclusion expands)
- (–) [Governance] → airspace and spectrum permissions become commercial bottlenecks (regulatory control matters)
- (–) [Market structure] → a few HAP operators mediate regional connectivity access (new intermediary appears)
- (–) [Security] → platform outages or interference hit multiple dependent services at once (shared-layer fragility grows)
- (–) [Equality] → lower-priority regions get best-effort rather than guaranteed HAP service (coverage tiers emerge)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Decentralized trust networks are transformative because they reconfigure how payments, contracts,

ownership records, access rights, and reputation can be verified without a single intermediary. At 1st order, they reduce reconciliation and enable programmable settlement and tokenized access. At 2nd order, they can weaken some bank- and platform-centric structures while creating new power around wallets, bridges, and protocols; at 3rd order, they normalize machine-executable rule enforcement and persistent audit trails across organizational boundaries. This is a major operating-model change for Exchange, even if not the only possible trust stack.

Weak signals (9):

- (+) [Low transaction costs] → marketplaces adopt on-chain escrow and automated settlement (intermediation shrinks)
- (+) [Flexibility] → access rights, memberships, and usage rights are tokenized for transfer (ownership gets more granular)
- (+) [Peer trust] → portable wallet-based reputation appears across platforms (identity and history decouple from one site)
- (+) [Time and location independence] → cross-border peer transactions settle without banking-hour dependence (exchange becomes continuous)
- (+) [Accountability] → B2B contracts release payment automatically on verified events (execution becomes programmable)
- (–) [Governance] → protocol committees and bridge operators gain bank-like influence (power recentralizes elsewhere)
- (–) [Consumer responsibility] → wallet recovery, key loss, and scam support become mainstream friction points (self-custody burden rises)
- (–) [Taxation and public revenue] → tax authorities intensify chain-analytics enforcement around micro-commerce (compliance model shifts)
- (–) [Security] → smart-contract and bridge exploits affect ordinary commercial users (trust hinges on technical safety)

## ART 11.084 - Platform Cooperatives & Fair Work

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Platform cooperatives significantly affect Exchange by changing who owns and governs the marketplaces that mediate services and work. At 1st order, they can reduce take rates and make rankings, penalties, and payouts more legible. At 2nd order, they shift bargaining power toward workers and users while raising capital and coordination constraints; at 3rd order, they offer an alternative institutional pathway to platformized exchange rather than only an operational improvement. That makes the impact significant.

Weak signals (9):

- (+) [Locality and cultural relevance] → cities or communities seed member-owned local service platforms (place-based alternatives emerge)
- (+) [Peer trust] → payout rules, fees, and ranking logic become transparent in dashboards (rules get contestable)
- (+) [Low transaction costs] → member-owned platforms attract sellers through lower take rates (intermediation margins fall)
- (+) [Individuality] → portable ratings and benefits move with workers across cooperative services (worker control rises)

- (+) [Governance] → members vote on algorithm changes and fee structures (platform rulemaking democratizes)
- (–) [Capital bottleneck] → co-ops struggle to fund marketing or scale compared with VC platforms (growth asymmetry persists)
- (–) [Coordination] → voting fatigue and factional blocs slow strategic shifts (governance frictions surface)
- (–) [Market structure] → incumbents use exclusivity, ad spend, or data advantages to suppress co-op growth (retaliation intensifies)
- (–) [Accountability] → disputes move from opaque platform edicts to contested member processes (fairness changes shape)

## ART 11.085 - Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Open data marketplaces significantly affect Exchange because they turn fragmented data into tradable infrastructure for pricing, fraud, logistics, and personalization. At 1st order, they lower access barriers for actors lacking proprietary data pools. At 2nd order, they can reduce some platform lock-in while also creating new pricing, provenance, and privacy disputes; at 3rd order, they make AI-enabled exchange more modular and contestable. That reaches the significant-impact threshold.

Weak signals (9):

- (+) [Low transaction costs] → SMEs buy small, purpose-bound datasets instead of commissioning bespoke integrations (access cost drops)
- (+) [Peer trust] → machine-readable licenses and provenance scores become visible in data listings (trust gets operationalized)
- (+) [Flexibility] → compute-to-data offerings let models run without moving raw records (sharing becomes safer)
- (+) [Individuality] → consumers or sellers earn revenue shares from contributed data streams (new asset class emerges)
- (+) [Prevalence] → sector consortia list standardized commerce datasets with API access (market infrastructure forms)
- (–) [Market structure] → a few exchanges dominate high-value datasets and usage terms (data tollgates arise)
- (–) [Accountability] → disputes center on ownership, consent scope, and dataset quality (contract complexity rises)
- (–) [Privacy] → re-identification or leakage incidents trigger market pullbacks (trust remains fragile)
- (–) [Equality] → actors with richer data still capture most revenue and model performance gains (openness only partly levels field)

## ART 11.086 - Secure & Resilient Social Platforms

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Secure and resilient social platforms materially affect Exchange through social commerce, community markets, and coordination under disruption. At 1st order, they reduce dependency on a

few centralized platforms for communication and group trust. At 2nd order, they alter moderation, identity, and hosting arrangements; at 3rd order, they support more durable niche and local markets that can survive outages or blockages. The effect is meaningful, but still secondary to core market rails like payment and identity.

Weak signals (9):

- (+) [Peer trust] → sellers carry followers, contacts, and reputation across compatible social nodes (social lock-in weakens)
- (+) [Locality and cultural relevance] → community marketplaces persist even when one host service fails (coordination becomes resilient)
- (+) [Reliability] → emergency or protest conditions do not fully stop social selling or service coordination (exchange survives disruption)
- (+) [Individuality] → users share selective identity proofs without exposing full profiles (trust gets more granular)
- (+) [Flexibility] → organizations run their own nodes while staying commercially interoperable (network diversity grows)
- (−) [Governance] → moderation and abuse disputes become fragmented across node operators (trust becomes uneven)
- (−) [Market structure] → secure-hosting and key-recovery providers become new intermediaries (control recentralizes partially)
- (−) [Security] → compromised accounts or poor key recovery disrupt seller credibility and access (identity becomes brittle)
- (−) [Equality] → technically capable communities benefit more than less organized groups (resilience is unevenly distributed)

## ART 11.087 - Collective Open Innovation Networks

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Collective open innovation networks materially affect Exchange by making invention itself more market-like: problems, expertise, experiments, and solutions become easier to match and transact. At 1st order, they reduce search and coordination costs in R&D collaboration. At 2nd order, they raise issues around credit, secrecy, and IP sharing; at 3rd order, they turn intermediate and failed work into reusable exchangeable assets. The impact is meaningful but limited to the innovation layer.

Weak signals (9):

- (+) [Low transaction costs] → organizations post structured problems and pay for validated solutions (innovation search gets marketized)
- (+) [Peer trust] → contribution trails and provenance histories determine reward splits (credit becomes auditable)
- (+) [Flexibility] → solvers, labs, and automated agents collaborate across organizational boundaries (capability matching improves)
- (+) [Individuality] → niche experts monetize narrow knowledge without joining large firms (micro-specialization pays)
- (+) [Prevalence] → public and private procurement include open-innovation challenge routes (market infrastructure normalizes)

- (–) [Governance] → disputes intensify over IP ownership of merged or AI-assisted contributions (rule complexity rises)
- (–) [Market structure] → platforms controlling validation environments gain disproportionate leverage (test access becomes chokepoint)
- (–) [Equality] → actors with more compute or lab access win more challenges (resource asymmetry persists)

## ART 11.088 - Scalable Decentralized Governance

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Decentralized governance materially affects Exchange where shared platforms, pooled resources, or community markets need binding decision mechanisms without one trusted central operator. At 1st order, it reduces some coordination overhead and makes rule changes more inspectable. At 2nd order, it introduces manipulation, turnout, and legal-accountability issues; at 3rd order, it may normalize software-mediated governance in commercial communities. The effect is real, but not as foundational as payment or identity rails.

Weak signals (9):

- (+) [Peer trust] → marketplaces publish rule changes and votes in machine-readable form (governance becomes inspectable)
- (+) [Accountability] → access rights or payouts execute automatically after formal decisions (rules become operational)
- (+) [Low transaction costs] → pooled purchasing or community asset management uses standardized governance stacks (coordination cost falls)
- (+) [Locality] → regional trade or service cooperatives adopt software-based voting and budgeting (shared control becomes viable)
- (+) [Flexibility] → delegation and role-based governance reduce organizer bottlenecks (large groups coordinate better)
- (–) [Governance] → sybil resistance, coercive blocs, and turnout problems become commercial bottlenecks (participation quality matters)
- (–) [Market structure] → governance stack providers or token-rich actors gain quiet control (formal decentralization masks concentration)
- (–) [Accountability] → legal systems struggle to map software-enforced decisions onto liability (off-chain recourse weakens)
- (–) [Equality] → digitally sophisticated participants dominate agenda-setting (inclusion remains unequal)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Digital learning networks significantly affect Exchange because service and labor markets rely heavily on signaling competence and matching skills to demand. At 1st order, portable skill credentials reduce hiring and onboarding frictions and widen pathways into service work. At 2nd order, they shift power away from some traditional gatekeepers while creating new verification and standards battles; at 3rd order, they change wage formation and competition as micro-skills become easier to compare and price. That is a significant GVN impact.

Weak signals (9):

- (+) [Low transaction costs] → service platforms accept signed micro-credentials at onboarding (screening labor drops)
- (+) [Individuality] → workers accumulate portable evidence of niche skills outside formal degrees (supply diversity grows)
- (+) [Peer trust] → reputation and credential wallets are checked automatically before task allocation (trust becomes portable)
- (+) [Prevalence] → employers and public procurement reference open skill credentials in tenders (credential rail hardens)
- (+) [Flexibility] → AI tutors are bundled into seller or worker onboarding pipelines (capability building becomes continuous)
- (–) [Governance] → credential standards become contested between platforms, educators, and labor groups (rule setting matters)
- (–) [Equality] → actors with better devices, time, or language access still gain credentials faster (digital divide persists)
- (–) [Security] → fraud, proxy-taking, and model-assisted cheating trigger stronger assessment surveillance (verification burden rises)
- (–) [Market structure] → a few credential issuers become quasi-gatekeepers for service work (new intermediaries emerge)

## ART 11.090 - Prediction-Market Forecasting Platforms

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Prediction-market platforms materially affect Exchange by improving coordination under uncertainty in pricing, inventory, launches, and risk management. At 1st order, they turn scattered beliefs into measurable probabilities that can feed operational decisions. At 2nd order, they shift authority from hierarchy toward probabilistic signals while creating manipulation and resolution-rule disputes; at 3rd order, they make forecast accuracy itself a tradable asset. The effect is useful, but not core to everyday exchange infrastructure.

Weak signals (9):

- (+) [Low transaction costs] → firms use internal or external markets to set inventory and launch timing (consensus forms faster)
- (+) [Accountability] → forecast scores are tied to project or procurement decisions (judgment becomes measurable)
- (+) [Flexibility] → platforms break broad uncertainty into linked tradable subquestions (coordination improves)
- (+) [Prevalence] → insurers, logistics firms, and marketplaces integrate market probabilities into operations (forecasting enters workflow)
- (+) [Individuality] → expert forecasters monetize calibration reputation across sectors (judgment becomes exchangeable)
- (–) [Governance] → disputes over market resolution and eligible evidence intensify (truth mechanism matters)
- (–) [Market structure] → liquidity providers and platform operators influence outcomes more than users realize (signal power centralizes)



- (–) [Security] → manipulation, information leakage, or gaming around sensitive events becomes a commercial concern (incentives distort signals)
- (–) [Equality] → thin markets in local or niche issues underperform compared with well-attended topics (coverage remains uneven)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Universal IoT interoperability is transformative for Exchange because machine-readable assets, products, spaces, and devices become far easier to connect across organizations. At 1st order, it lowers integration costs for lockers, rental assets, shelves, vehicles, smart products, and access-control systems. At 2nd order, it enables machine-to-machine exchange and wider automation while redistributing power toward certification, device-management, and update ecosystems; at 3rd order, it supports denser sharing, monitoring, and access-right automation in everyday life. This is a clear operating-model transformation.

Weak signals (9):

- (+) [Low transaction costs] → new devices join multi-vendor commercial systems with near-zero custom integration (friction collapses)
- (+) [Flexibility] → asset-sharing, smart rental, and usage billing work across brands by default (interoperability unlocks markets)
- (+) [Reliability] → signed updates and common failure reporting reduce manual troubleshooting (service quality standardizes)
- (+) [Prevalence] → marketplaces expose machine-readable device capabilities and states in listings (things become queryable)
- (+) [Time independence] → unattended access and M2M settlement become routine across sites (automation scales)
- (–) [Market structure] → certification authorities and device clouds become new chokepoints (standards still centralize power)
- (–) [Equality] → uncertified legacy devices are excluded from lucrative ecosystems (upgrade costs burden smaller actors)
- (–) [Security] → common stacks create large shared vulnerability domains (one flaw affects many markets)
- (–) [Governance] → disputes arise over mandatory update rights after ownership transfer (control boundaries get redrawn)

### ART 12.092 - Interoperable Digital Twin Ecosystems

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Interoperable twin ecosystems significantly affect Exchange because they make condition, configuration, maintenance history, and use assumptions portable between buyers, sellers, insurers, and financiers. At 1st order, they reduce information asymmetry in asset-heavy exchange. At 2nd order, they support leasing, subscription, and service contracts tied to live asset state; at 3rd order,

they create new data-format and schema power centers. That is a significant trust and transaction-cost shift.

Weak signals (9):

- (+) [Peer trust] → used assets are listed with portable condition twins rather than static PDFs (asymmetry falls)
- (+) [Low transaction costs] → financiers and insurers quote directly from shared twin data (due diligence speeds up)
- (+) [Reliability] → service providers inherit full machine or building histories across ownership changes (handoffs improve)
- (+) [Flexibility] → leasing and subscription contracts tie payments to live asset state (service models deepen)
- (+) [Accountability] → repair and modification events write back into a shared twin trail (evidence becomes cumulative)
- (–) [Market structure] → platforms controlling twin schemas gain leverage over asset ecosystems (data-format power rises)
- (–) [Governance] → liability disputes hinge on whether twin drift or physical misuse caused failure (responsibility becomes model-mediated)
- (–) [Equality] → smaller sellers cannot maintain compliance-grade twins for older assets (market access skews)
- (–) [Security] → twin tampering becomes a route to fraud in resale, insurance, or maintenance markets (new attack vector appears)

## ART 12.093 - Global Supply Chain Traceability Networks

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Global traceability networks are transformative for Exchange because they directly affect trust, provenance, recall speed, compliance, and anti-counterfeit control. At 1st order, they make product origin, handling, and composition much more visible. At 2nd order, they change bargaining power by favoring data-rich suppliers and exposing weakly documented ones; at 3rd order, they turn sustainability, authenticity, and handling claims into machine-readable transaction attributes. This is a major shift in how trust is built in the GVN.

Weak signals (9):

- (+) [Peer trust] → marketplaces filter and rank goods using verified provenance fields (trust becomes searchable)
- (+) [Reliability] → recalls and defects are isolated to precise batches or units in near real time (failure cost falls)
- (+) [Low transaction costs] → customs, finance, and insurance accept the same digital history file (reconciliation shrinks)
- (+) [Flexibility] → buyers pay premiums for handling, origin, or compliance attributes verified in-network (attributes get monetized)
- (+) [Prevalence] → digital product passports become standard in consumer and industrial categories (traceability normalizes)
- (–) [Market structure] → suppliers without traceability integration lose shelf space or bidding eligibility (data becomes gatekeeping)

- (–) [Governance] → disputes shift from “what happened” to “which node was allowed to write data” (record control matters)
- (–) [Equality] → small firms struggle with scanning, tagging, and integration overhead (compliance burden excludes)
- (–) [Security] → counterfeiters move from forging goods to forging metadata and custody events (fraud migrates upstream)

## ART 12.094 - Personal Data Portability & Trust Frameworks

Score: 10 (Impact in GVN 8)

Justification (3–5 sentences):

Personal data portability is transformative because it changes customer switching costs, control over personal history, and the competitive structure of digital exchange. At 1st order, it allows people to move preferences, records, and permissions between services more easily. At 2nd order, it lowers some platform lock-in while creating new wallet, consent, and derived-data disputes; at 3rd order, it makes individuals and their agents more active participants in data exchange rather than passive raw material. That is a major operating-model shift for digital exchange.

Weak signals (9):

- (+) [Individuality] → shoppers move purchase histories and preferences between marketplaces with one permission flow (switching cost falls)
- (+) [Peer trust] → purpose-bound consent receipts become visible in everyday service interactions (data use gets legible)
- (+) [Low transaction costs] → repeated form-filling and identity checks disappear across compatible services (onboarding friction collapses)
- (+) [Flexibility] → personal agents negotiate what data to reveal for better offers (data becomes bargaining tool)
- (+) [Prevalence] → regulators or dominant firms require import/export parity for key data classes (portability becomes baseline)
- (–) [Market structure] → wallet providers and trust intermediaries become new strategic gatekeepers (power recentralizes partially)
- (–) [Pricing fairness] → richer portable data enables sharper personalized pricing and exclusion (competition has darker edge)
- (–) [Security] → account takeover shifts from single-site compromise to wallet compromise (risk becomes more concentrated)
- (–) [Governance] → disputes grow over revocation, derivative data, and inferred attributes (ownership boundary stays contested)

## ART 12.095 - Interoperable Digital Currency Payment Networks

Score: 20 (Impact in GVN 8)

Justification (3–5 sentences):

Interoperable digital payment networks are a keystone technology for the Exchange GVN because payment is one of its central operating rails. At 1st order, they reduce settlement friction across platforms, borders, institutions, and machine agents. At 2nd order, they reconfigure the roles of banks, processors, wallets, platforms, and regulators; at 3rd order, they enable denser automation, programmable conditions, real-time settlement, and machine-to-machine commerce. Because they drastically widen time/location independence, flexibility, and transaction speed, this is a 20-level

impact.

Weak signals (9):

- (+) [Low transaction costs] → wallets route payments automatically across CBDC, bank, card, and token rails (friction falls sharply)
- (+) [Time and location independence] → cross-border settlement times collapse from days to seconds (working capital is freed)
- (+) [Flexibility] → escrow, split payout, and conditional release become routine checkout features (money becomes programmable)
- (+) [Prevalence] → marketplaces expose payment-rail choice and fee transparency to users (routing becomes visible)
- (+) [Peer trust] → identity-linked, reversible, or proof-based payment options expand in peer exchange (money and reputation fuse)
- (–) [Bank-centric regime] → interchange and correspondent-fee revenue erodes noticeably (incumbent model destabilizes)
- (–) [Governance] → disputes move from bank policy to protocol, wallet, and routing rules (control is redistributed)
- (–) [Equality] → people without trusted digital credentials or recovery tools face exclusion (new access barrier appears)
- (–) [Security] → fraud shifts from card theft to wallet recovery, key compromise, and rule exploits (risk surface changes)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Rules as code significantly affects Exchange because it turns compliance into something that can run directly inside platforms, marketplaces, and contracting systems. At 1st order, it lowers interpretation costs for tax, listing, eligibility, and procedural compliance. At 2nd order, it helps smaller actors enter regulated markets while also empowering those who control reference implementations and policy APIs; at 3rd order, it makes regulation more dynamic and immediately market-shaping. That places it in the significant-impact category.

Weak signals (9):

- (+) [Low transaction costs] → checkout and listing systems run official rule validations in real time (manual interpretation drops)
- (+) [Prevalence] → SMEs adopt compliance-by-default software rather than external legal review (entry barrier falls)
- (+) [Accountability] → decisions show which rule version and clauses were applied (enforcement gets auditable)
- (+) [Flexibility] → cross-border sellers expand because local rules are machine-queryable (jurisdiction friction declines)
- (+) [Reliability] → regulators publish test suites and change logs with implementation packages (update speed improves)
- (–) [Governance] → errors in official code or reference logic cause widespread business disruption (single-source failure matters)
- (–) [Market structure] → compliance-platform vendors become essential intermediaries (rule access gets centralized)

- (–) [Equality] → those with better integration capacity exploit machine-readable rules faster (capability gap persists)
- (–) [Security] → attacks target policy APIs, validation endpoints, or versioning processes (compliance becomes attack surface)

## ART 12.097 - Open Metaverse Interoperability Protocols

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

Open metaverse protocols materially affect Exchange by making virtual identities, goods, and interactions portable across immersive environments. At 1st order, they reduce switching costs and widen asset reuse in virtual commerce. At 2nd order, they change platform control over creators, rights, and user relationships; at 3rd order, they support more continuous cross-world social and commercial presence. The impact is meaningful, but limited to the immersive subset of the wider GVN.

Weak signals (9):

- (+) [Flexibility] → users carry identities, inventories, and payment settings across 3D worlds (switching friction drops)
- (+) [Peer trust] → asset provenance and rights travel with interoperable credentials (ownership becomes legible)
- (+) [Individuality] → creators sell once and reuse across multiple worlds (goods gain higher utilization)
- (+) [Prevalence] → service providers deliver training, events, or consultations in interoperable spaces (virtual service markets broaden)
- (+) [Low transaction costs] → cross-world checkout and royalty handling are standardized (platform fragmentation weakens)
- (–) [Market structure] → engine or wallet providers still dominate key protocol implementations (open stack recentralizes partially)
- (–) [Governance] → moderation, safety, and identity disputes span multiple worlds (rule coordination gets harder)
- (–) [Security] → cloned or rights-stripped assets create new fraud and trust issues (interoperability broadens attack surface)
- (–) [Equality] → users lacking compatible devices or bandwidth are excluded from richer exchange modes (interface gap persists)

## ART 12.098 - Content Authenticity Infrastructure

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Content authenticity infrastructure significantly affects Exchange because digital listings, reviews, advertising, identity claims, and service evidence increasingly depend on media that may be synthetic or manipulated. At 1st order, it lowers verification costs and improves trust in attributable media. At 2nd order, it shifts power toward certified capture, editing, and verification ecosystems; at 3rd order, it may become a default gate for participation in higher-trust marketplaces. That is a significant trust-layer change for Exchange.

Weak signals (9):

- (+) [Peer trust] → marketplaces visibly prefer or require credentialed images and video in listings (provenance enters ranking)
- (+) [Low transaction costs] → verification of seller media moves from manual checks to credential checks (screening labor falls)
- (+) [Reliability] → claims and disputes rely on authenticated media chains rather than screenshots (evidence gets stronger)
- (+) [Prevalence] → browsers, apps, and cameras expose provenance summaries by default (authenticity becomes ambient)
- (+) [Accountability] → AI-generated promotional content is labeled and tracked across edits (source history stays visible)
- (–) [Market structure] → certified capture and edit ecosystems gain privileged trust status (tool vendors gain power)
- (–) [Equality] → small sellers without credential-capable tools suffer ranking or trust penalties (adoption burden excludes)
- (–) [Security] → provenance spoofing or chain-break attacks become a new fraud niche (trust stack becomes target)
- (–) [Governance] → debates intensify over whether missing credentials imply low trust (non-participation gets penalized)

## ART 12.099 - Privacy-Preserving Collaboration Protocols

Score: 5 (Impact in GVN 8)

Justification (3–5 sentences):

Privacy-preserving collaboration is significant because many high-value exchange insights are locked inside datasets that cannot safely be pooled. At 1st order, it enables joint fraud, risk, logistics, and analytics computations without exposing raw data. At 2nd order, it lowers contractual and compliance overhead while creating new orchestration and safe-output governance layers; at 3rd order, it may make secure multi-party analytics a normal substrate of exchange ecosystems. That is a significant institutional shift.

Weak signals (9):

- (+) [Peer trust] → competitors jointly run fraud or chargeback analytics without pooling raw records (coordination gets safer)
- (+) [Low transaction costs] → manual redaction and bespoke legal sharing agreements decline (collaboration overhead falls)
- (+) [Reliability] → shared risk scores improve across payment, insurance, and logistics networks (blind spots shrink)
- (+) [Flexibility] → firms test joint models while keeping jurisdiction-specific data local (cross-border coordination improves)
- (+) [Prevalence] → SQL-like secure-compute interfaces are embedded in commerce platforms (technology becomes usable)
- (–) [Market structure] → orchestrators of secure collaboration networks gain strategic visibility and leverage (new intermediary emerges)
- (–) [Accountability] → participants dispute whether bad outputs came from math, policy, or source data (responsibility blurs)
- (–) [Security] → misconfiguration or side-channel failures damage trust in the whole collaboration layer (confidence can collapse quickly)
- (–) [Equality] → actors with weak data or slower infrastructure get less value from the collaboration network (benefits distribute unevenly)



## ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

Score: 3 (Impact in GVN 8)

Justification (3–5 sentences):

This infrastructure materially affects Exchange because buyers, insurers, financiers, and integrators need comparable evidence to trust novel manufacturing methods. At 1st order, it lowers qualification time for new suppliers and processes. At 2nd order, it changes who can enter markets and how quality claims are verified; at 3rd order, it may lock in favored process families and create certifier bottlenecks. The impact is real, but mostly indirect through supplier qualification and trust.

Weak signals (9):

- (+) [Peer trust] → contract-manufacturing platforms filter suppliers by machine-readable certifications (qualification gets easier)
- (+) [Low transaction costs] → buyers reuse the same digital certificates across procurement, insurance, and finance (reconciliation shrinks)
- (+) [Reliability] → benchmark test artifacts and conformance suites become routine in batch records (quality becomes comparable)
- (+) [Prevalence] → public procurement references standardized advanced-manufacturing certificates (market acceptance grows)
- (+) [Flexibility] → new suppliers win work faster because qualification cycles shorten (capacity becomes more contestable)
- (–) [Market structure] → accredited labs and certifiers become bottlenecks for market access (assurance centralizes power)
- (–) [Equality] → smaller firms struggle with recurring audit and equipment costs (compliance burden excludes)
- (–) [Governance] → disputes shift to test conditions and certificate scope rather than visible defects (trust moves procedural)
- (–) [Innovation pace] → standard suites lag the newest methods, temporarily freezing out novel entrants (certification can slow change)

## GVN 9: Remote Impact ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 – Global Broadband Connectivity

Score: 20 (Impact in GVN 9)

Justification (3–5 sentences):

Mature global broadband removes the biggest direct bottleneck in this GVN: people and organisations can observe, coordinate, transact, and teleoperate from almost any location instead of only where fixed high-quality links exist. That expands participation, regional equality, and remote service reach, but it also scales cybercrime, disinformation, platform gatekeeping, and cross-border remote labour substitution. Once reliable connectivity becomes ambient, other remote-impact layers—sensor networks, telepresence robots, immersive interfaces, and AI supervision—



compound on top of it. In a 5.5M-person society this plausibly affects the weekly life of hundreds of thousands and functions as a linchpin of remote-first operations, so 20 is justified.

Weak signals (9):

- (+) [Participation] → public services begin certifying remote access quality by service-level guarantee (distance stops excluding users)
- (+) [Location independence] → employers approve critical work from rural and temporary sites (remote presence becomes normal)
- (+) [Ease and accessibility] → consumer devices ship with automatic multi-path connectivity failover (access becomes frictionless)
- (+) [Remote-controlled robotics] → insurers underwrite teleoperation using commodity links (robotic services commercialise)
- (-) [Safety and security] → national outage reports show remote services failing with network disruptions (dependency becomes systemic)
- (-) [Market structure] → a few connectivity providers secure exclusive platform bundles (gatekeeper power hardens)
- (+) [Legal barriers] → regulators accept remote witnessing, inspection, or attendance when link quality is certified (rules adapt to bandwidth)
- (-) [Abuse of remote influence] → scam and disinformation volumes rise in newly connected groups (malicious reach scales)
- (+) [Regional equality] → specialist remote-service usage rises outside metro areas (coverage changes participation)

## ART 01.002 – Ultra-Low Latency Networks

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Mature ultra-low-latency networking makes remote influence feel immediate rather than delayed, which is critical for teleoperation, live negotiation, remote care, shared virtual spaces, and safety-critical intervention. It shifts more work and decision authority away from local presence and toward remote operators, software vendors, and network providers, while increasing dependence on timing guarantees as a new critical utility. The faster remote loops become, the more tasks migrate from asynchronous communication to real-time remote control and mixed human–AI supervision. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Ease and accessibility] → vendors market latency-bounded links for telepresence and control (real-time remote work viable)

- (+) [Remote-controlled avatars] → field tasks shift from local crews to remote operators (control loop now stable)
- (+) [Participation] → shared virtual meetings retain users for full work sessions (presence feels natural enough)
- (+) [Efficiency] → call centres, remote surgery support, or control rooms publish lower error rates (delay costs are falling)
- (-) [Safety and security] → service contracts add penalties for jitter and timing failure (timing becomes critical infrastructure)
- (-) [Market structure] → edge-node operators gain premium pricing power over sectors (latency becomes a gatekeeper)
- (+) [Legal barriers] → high-risk industries approve remote intervention with timing SLAs (regulation starts trusting distance)
- (-) [Cybersecurity risk] → timing-spoofing and edge-node attacks appear in incident reports (new attack surface emerges)
- (+) [Physical presence norm] → users report remote interfaces as 'good enough' for skilled work (cultural barrier weakens)

## ART 01.003 – Edge AI for Sensor Data

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Edge AI turns raw distant sensor feeds into actionable signals fast enough for remote action, reducing the need for local experts and making poor connectivity less of a blocker. It changes accountability—machines and remote teams increasingly decide what deserves human attention—while also creating new failure, bias, and false-alarm risks in remote operations. Once local devices can classify anomalies and trigger actions themselves, remote influence scales from a few staffed sites to large distributed estates. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Remote influence quality] → field devices trigger actions from local anomaly detection instead of raw data review (alert-to-action loop shortens)
- (+) [Efficiency] → bandwidth use per monitored site falls while response quality improves (remote monitoring gets cheaper)
- (+) [Safety and security] → regulated sectors certify on-device inference for alarms or shutoffs (local machine judgment becomes trusted)
- (+) [Ease and accessibility] → installers deploy cameras/mics/meters with pre-trained local models (advanced remote monitoring commoditises)
- (-) [Accountability] → disputes focus on false positives or missed events from edge models (liability shifts into embedded AI)

- (-) [Privacy] → organisations justify more pervasive sensing because raw data no longer leaves the edge (monitoring scope expands anyway)
- (+) [Legal barriers] → privacy or bandwidth-constrained sectors approve remote monitoring pilots (blocked domains open up)
- (+) [Labour structure] → local experts move from constant observation to exception handling (human attention reallocated)
- (+) [3rd-order adoption] → remote services standardise around local AI plus central oversight (hybrid monitoring architecture stabilises)

## ART 01.004 – Quantum & High-Precision Sensing

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

High-precision sensing improves remote influence in specialised settings where current signals are too coarse, such as infrastructure assurance, navigation in denied environments, or subtle condition monitoring. Its value concentrates in high-stakes organisations rather than everyday mass participation, so the institutional shift is real but narrower. Where adopted, it can pull regulation and insurance toward accepting more remote decisions because measurements become more trustworthy. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Remote influence quality] → remote decisions are accepted in domains that previously required on-site expert measurement (precision changes trust thresholds)
- (+) [Safety and security] → critical infrastructure or navigation pilots rely on ultra-stable sensing in degraded environments (high-stakes remote action expands)
- (+) [Legal barriers] → certification bodies publish calibration rules for continuous remote precision measurement (institutional pathway becomes visible)
- (+) [Participation] → scarce experts supervise more sites because measurements are more self-validating (expert reach multiplies)
- (-) [Market structure] → a few instrument vendors control trusted measurement baselines (precision becomes supplier power)
- (-) [Accountability] → disputes hinge on sensor calibration chains rather than local operator testimony (evidence shifts into instrumentation)

## ART 01.005 – Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Cheap, maintenance-light sensor layers greatly expand the set of distant things and events that can be noticed without sending people on site, which directly supports remote influence and intervention. They shift inspection, compliance, and asset-management work toward remote dashboards and algorithmic triage, while also raising surveillance, labour displacement, and ownership-of-data issues. As coverage becomes denser, organisations redesign processes around continuous remote awareness instead of periodic physical checks. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → asset owners replace battery-change schedules with sensor rollouts (servicing burden drops sharply)
- (+) [Location independence] → remote monitoring reaches sites where power access was the main blocker (coverage extends into neglected places)
- (+) [Ease and accessibility] → packaging, surfaces, or consumables embed passive sensing by default (instrumentation becomes almost invisible)
- (+) [Participation] → small operators adopt monitoring because upkeep no longer needs specialist rounds (capability diffuses downmarket)
- (-) [Privacy] → complaints rise when low-cost sensor tags appear in workspaces or rented properties (monitoring becomes too easy)
- (-) [Waste and maintenance] → procurement starts counting avoided battery replacement visits and waste streams (economics become measurable)
- (+) [Legal barriers] → regulators accept passive sensors as compliance evidence in remote sites (onsite checks lose necessity)
- (+) [Safety and security] → insurers price lower risk for continuously tagged assets (persistent awareness gains trust)
- (+) [3rd-order coordination] → monitoring is bundled with remote service and automated response contracts (sensing becomes part of service stacks)

## ART 01.006 – Privacy-Preserving Pervasive Sensing

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Privacy-preserving sensing makes continuous remote observation more acceptable in homes, workplaces, health settings, and public services by reducing the need to export raw personal data. That can unblock deployments that would otherwise be rejected by regulators, unions, or the public, while also normalising more pervasive monitoring under a ‘safe enough’ banner. Once trust barriers fall, remote services and optimisation systems spread faster into domains where privacy objections currently keep people physically present. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Privacy] → procurement requires on-device filtering and minimal raw-data export (social licence strengthens)
- (+) [Participation] → unions, care providers, or housing bodies approve remote monitoring pilots with privacy guarantees (deployment barrier softens)
- (+) [Ease and accessibility] → consumer products advertise local-only analytics as a default feature (trust becomes marketable)
- (+) [Cross-border coordination] → contracts allow analytics where raw data transfer was previously blocked (jurisdiction friction falls)
- (-) [Safety and security] → breach reports focus on model updates or metadata rather than raw content (threat model shifts)
- (-) [Market structure] → secure-chip and policy-stack vendors gain gatekeeper roles (trust shifts to infrastructure suppliers)
- (+) [Legal barriers] → regulators issue simplified approvals for privacy-preserving sensing classes (rules begin favouring safer architectures)
- (-) [Abuse of remote influence] → organisations expand monitoring after winning privacy legitimacy (monitoring scope grows anyway)
- (+) [Participation equality] → privacy-sensitive groups adopt remote services they had rejected before (acceptance threshold moves)

## ART 01.007 – Quantum-Resilient and Secure Communication Networks

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Stronger secure communication reduces the risk that remote influence channels are intercepted or manipulated, especially for critical control, identity, and long-lived confidential data. It matters most where remote operation is blocked by fear of coercion, espionage, or sabotage, but it is an upgrade to security rather than the main driver of remote participation. As higher-trust channels spread, more sensitive tasks move online—but so do higher-value attacks against the remaining weak links. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Safety and security] → critical remote-control contracts begin requiring post-quantum migration plans (trust threshold rises)
- (+) [Legal barriers] → regulators recognise quantum-safe or tamper-resistant channels in approvals (secure remote action legitimised)
- (+) [Cross-border coordination] → public agencies and hospitals renew long-lived remote-data links under new standards (sensitive tasks stay remote)

- (-) [Efficiency] → organisations delay rollout until interoperability certifications appear (migration friction is visible)
- (-) [Cybersecurity risk] → incident reports cite downgrade or key-management failures during transition (new vulnerability window)
- (-) [Market structure] → certified hardware vendors capture premium control of secure links (trust concentrates in few suppliers)

## ART 01.008 – Integrated Sensing and Communication (ISAC)

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

ISAC turns communications infrastructure itself into a sensing layer, so the same network that links remote actors can also reveal movement, occupancy, and environmental change. That lowers deployment friction for remote monitoring and automation, but it also deepens surveillance politics and disputes over who controls ambient situational awareness. When sensing piggybacks on connectivity rollouts, the step from communication to intervention shrinks and remote coordination becomes more pervasive. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → network upgrades are sold with built-in motion or occupancy sensing rather than separate hardware (deployment friction collapses)
- (+) [Remote influence quality] → operators act on ambient network-derived awareness between camera or site visits (communications become situational intelligence)
- (+) [Participation] → smaller facilities adopt remote monitoring when connectivity and sensing arrive together (capability piggybacks on telecom upgrades)
- (-) [Privacy] → telecom and property disputes focus on invisible radio-based sensing (surveillance concerns move into infrastructure)
- (-) [Power distribution] → network operators gain leverage over who can access ambient sensing feeds (telecom layer gains informational power)
- (+) [Legal barriers] → spectrum and privacy guidance begins covering sensing uses explicitly (governance catches up to convergence)
- (+) [3rd-order adoption] → connectivity contracts bundle sensing, analytics, and intervention services (communications turns into control infrastructure)
- (+) [Safety and security] → crowding or movement anomalies trigger remote interventions faster (shared spaces become more governable)
- (+) [Physical presence norm] → operators rely on infrastructure sensing instead of local watchers (human line-of-sight loses monopoly)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

## ART 02.009 – Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

More efficient edge compute lets telepresence devices, sensors, and robots process data locally with less power and heat, improving responsiveness and uptime in remote operations. The main effect is indirect: more tasks can be delegated to cheap field devices instead of local staff or distant data centres. As edge costs fall, remote influence spreads into places where network, battery, or privacy limits previously blocked it. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Ease and accessibility] → telepresence, sensor, or robot devices advertise all-day local AI operation (edge capability gets cheap)
- (+) [Efficiency] → service providers cut bandwidth use by processing more data locally (remote operations get cheaper)
- (+) [Safety and security] → privacy-sensitive remote services shift inference on-device (less data leaves the edge)
- (-) [Market structure] → a few chip ecosystems dominate remote-device reference designs (hardware lock-in deepens)
- (+) [Remote influence quality] → devices keep working through poor connectivity or cloud outages (local autonomy improves)
- (+) [Deployment pattern] → low-cost field hardware gains features once limited to premium systems (capability diffuses downward)

## ART 02.010 – Novel transistor technologies and materials beyond silicon CMOS

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

A step-change in general-purpose compute hardware improves almost every digital layer behind remote influence—AI inference, compression, simulation, encryption, and device autonomy. The gains are broad but diffuse, and remote impact captures only a slice of them rather than driving deployment on its own. Cheaper, cooler compute lowers the threshold for embedding remote-control intelligence into everyday devices and platforms. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).



- (+) [Ease and accessibility] → telepresence, sensor, or robot devices advertise all-day local AI operation (edge capability gets cheap)
- (+) [Efficiency] → service providers cut bandwidth use by processing more data locally (remote operations get cheaper)
- (+) [Safety and security] → privacy-sensitive remote services shift inference on-device (less data leaves the edge)
- (-) [Market structure] → a few chip ecosystems dominate remote-device reference designs (hardware lock-in deepens)
- (+) [Remote influence quality] → devices keep working through poor connectivity or cloud outages (local autonomy improves)
- (+) [Deployment pattern] → low-cost field hardware gains features once limited to premium systems (capability diffuses downward)

## ART 02.011 – Quantum Computing Platforms

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

This could improve some optimisation or planning tasks relevant to remote influence, but the pathway into this GVN is narrow and non-essential. Institutional effects would likely stay concentrated in specialist organisations rather than change how remote participation works at society scale. Any spillovers would mostly come through other, more general digital systems rather than direct adoption inside this GVN. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 02.012 – Photonic and Optical Computing

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Optical and photonic computing mainly help this GVN by easing bandwidth, latency, and energy bottlenecks in the data centres and backbones that support remote interaction. That strengthens the economics of large-scale telepresence, streaming, and AI-mediated remote operations, but users experience it indirectly. If those back-end costs fall enough, more services move from occasional remote contact to continuous remote supervision and control. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Ease and accessibility] → telepresence, sensor, or robot devices advertise all-day local AI operation (edge capability gets cheap)
- (+) [Efficiency] → service providers cut bandwidth use by processing more data locally (remote operations get cheaper)
- (+) [Safety and security] → privacy-sensitive remote services shift inference on-device (less data leaves the edge)
- (-) [Market structure] → a few chip ecosystems dominate remote-device reference designs (hardware lock-in deepens)
- (+) [Remote influence quality] → devices keep working through poor connectivity or cloud outages (local autonomy improves)
- (+) [Deployment pattern] → low-cost field hardware gains features once limited to premium systems (capability diffuses downward)

## ART 02.013 – Next-Gen Memory & Storage

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Better memory and storage make it easier to keep persistent digital twins, sensor histories, immersive media, and audit trails close to where remote decisions are made. That supports reliability, evidence, and accountability in remote operations, though it does not by itself create new remote channels. Cheaper retention of high-frequency operational data makes remote automation and post-hoc oversight more acceptable and more routine. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Ease and accessibility] → telepresence, sensor, or robot devices advertise all-day local AI operation (edge capability gets cheap)
- (+) [Efficiency] → service providers cut bandwidth use by processing more data locally (remote operations get cheaper)

- (+) [Safety and security] → privacy-sensitive remote services shift inference on-device (less data leaves the edge)
- (-) [Market structure] → a few chip ecosystems dominate remote-device reference designs (hardware lock-in deepens)
- (+) [Remote influence quality] → devices keep working through poor connectivity or cloud outages (local autonomy improves)
- (+) [Deployment pattern] → low-cost field hardware gains features once limited to premium systems (capability diffuses downward)

## ART 02.014 – Molecular Computing

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 – Causal Learning & Reasoning

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Causal reasoning improves remote influence by helping actors predict which intervention will work before acting at a distance, where trial-and-error is slower and riskier. It shifts bargaining power toward organisations that can model systems well, while also making remote policy, pricing, moderation, and control more assertive and contestable. As counterfactual tools spread, more

decisions that once required local judgment can be centralised or automated remotely. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → remote operations centres publish fewer false alarms or intervention errors (models improve action quality)
- (+) [Participation] → smaller organisations buy decision support that once required specialist analysts (advanced remote judgment diffuses)
- (+) [Ease and accessibility] → operators query systems in plain language instead of custom analytics workflows (use barrier falls)
- (-) [Power distribution] → platform owners controlling the best models gain negotiating leverage over local operators (decision power centralises)
- (-) [Accountability] → disputes emerge over who is liable for AI-guided remote decisions (governance is being renegotiated)
- (+) [Legal barriers] → regulators accept model-assisted decisions with audit trails or privacy guarantees (remote delegation normalises)
- (-) [Abuse of remote influence] → influence campaigns use the same modelling stack for optimisation (manipulation becomes more systematic)
- (+) [3rd-order scaling] → organisations expand from pilot dashboards to automated intervention loops (software starts closing the loop)
- (+) [Labour structure] → local experts are reallocated to exception handling rather than routine decisions (work reorganises around AI)

## ART 03.016 – Federated & Privacy-Preserving Learning

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Privacy-preserving learning lets remote systems improve from many sites without centralising all sensitive data, which broadens where remote services and automation can be accepted. It lowers trust and compliance barriers between organisations, but also strengthens already-large platforms that can orchestrate federated ecosystems. As more actors can collaborate without surrendering raw data, remote AI services become available in sectors that currently stay local by default. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → remote operations centres publish fewer false alarms or intervention errors (models improve action quality)
- (+) [Participation] → smaller organisations buy decision support that once required specialist analysts (advanced remote judgment diffuses)

- (+) [Ease and accessibility] → operators query systems in plain language instead of custom analytics workflows (use barrier falls)
- (-) [Power distribution] → platform owners controlling the best models gain negotiating leverage over local operators (decision power centralises)
- (-) [Accountability] → disputes emerge over who is liable for AI-guided remote decisions (governance is being renegotiated)
- (+) [Legal barriers] → regulators accept model-assisted decisions with audit trails or privacy guarantees (remote delegation normalises)
- (-) [Abuse of remote influence] → influence campaigns use the same modelling stack for optimisation (manipulation becomes more systematic)
- (+) [3rd-order scaling] → organisations expand from pilot dashboards to automated intervention loops (software starts closing the loop)
- (+) [Labour structure] → local experts are reallocated to exception handling rather than routine decisions (work reorganises around AI)

## ART 03.017 – Trustworthy AI Systems

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Trustworthy AI is a major unlock for remote impact because it makes delegated remote decisions, automated moderation, remote diagnostics, and robot supervision more auditable and governable. That can move authority away from local frontline staff toward remote control rooms, platform operators, and compliance systems, while also reducing some safety and liability objections. Once trust and fallback mechanisms improve, many organisations redesign processes around remote-first oversight rather than physical presence. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Safety and security] → contracts for remote AI require provenance logs, fallback modes, and explainability tests (trust becomes contractual)
- (+) [Legal barriers] → regulators approve higher-autonomy remote services with audit requirements (governance unlocks deployment)
- (+) [Participation] → unions or professional bodies accept AI-assisted remote work under override rights (social acceptance increases)
- (-) [Power distribution] → remote-control authority shifts to whoever owns validated model stacks (control centralises upstream)
- (-) [Accountability] → courts or insurers start testing whether model logs are enough for liability (new evidentiary norms form)
- (+) [Efficiency] → remote operations cut manual review time without higher incident rates (delegation becomes affordable)

- (-) [Abuse of remote influence] → adversarial testing becomes mandatory after manipulation attempts (attackers are probing governance layers)
- (+) [Market structure] → certified trustworthy-AI vendors win whole-sector framework deals (trusted infrastructure consolidates)
- (+) [3rd-order adoption] → organisations rewrite procedures around remote-first oversight instead of local sign-off (operating model flips)

## ART 03.018 – Automated Machine Learning (AutoML)

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

AutoML lowers the skill barrier for building remote-monitoring, prediction, and control tools, so more organisations can experiment with remote influence systems. The main effect is to speed diffusion and widen access, but also to flood the field with uneven-quality automation and lower entry barriers for manipulative uses. Faster model iteration shortens the cycle from observed remote behaviour to new interventions, reinforcing platform and automation power. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → remote operations centres publish fewer false alarms or intervention errors (models improve action quality)
- (+) [Participation] → smaller organisations buy decision support that once required specialist analysts (advanced remote judgment diffuses)
- (+) [Ease and accessibility] → operators query systems in plain language instead of custom analytics workflows (use barrier falls)
- (-) [Power distribution] → platform owners controlling the best models gain negotiating leverage over local operators (decision power centralises)
- (-) [Accountability] → disputes emerge over who is liable for AI-guided remote decisions (governance is being renegotiated)
- (+) [Legal barriers] → regulators accept model-assisted decisions with audit trails or privacy guarantees (remote delegation normalises)

## ART 03.019 – Collaborative Multi-Agent AI

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Collaborative multi-agent AI lets many digital agents, sensors, and robots act together across distance, which is close to the core of remote influence on distributed things and events. It shifts operating models toward remote mission control, fewer local staff, and new dependence on

platform-level coordination software, with obvious dual-use and coercive applications. As coordination improves, organisations can supervise much larger remote estates and launch more autonomous interventions, further normalising distance from the site of action. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Remote-controlled avatars] → one supervisor begins managing many robots or software agents simultaneously (scale of remote action jumps)
- (+) [Efficiency] → response times fall because agents self-allocate tasks in the field (coordination cost collapses)
- (+) [Participation] → smaller actors access fleet orchestration as a service (distributed capability diffuses)
- (-) [Safety and security] → incident reports involve swarm-level failure or coordination exploits (single errors now propagate)
- (-) [Power distribution] → platform orchestrators control shared maps, policies, and task markets (control centralises at middleware layer)
- (+) [Legal barriers] → regulators create rules for multi-agent supervision ratios and override rights (institutions adapting to scale)
- (+) [Labour structure] → local crews shrink while remote mission-control roles expand (work centralises by design)
- (-) [Dual use] → police, military, or criminal groups demonstrate coordinated remote actions (coercive capacity scales quickly)
- (+) [3rd-order loop] → sensor networks, robots, and payment systems become interoperable agent ecosystems (remote influence becomes automated)

## ART 03.020 – Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

This could improve some optimisation or planning tasks relevant to remote influence, but the pathway into this GVN is narrow and non-essential. Institutional effects would likely stay concentrated in specialist organisations rather than change how remote participation works at society scale. Any spillovers would mostly come through other, more general digital systems rather than direct adoption inside this GVN. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).



- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 03.021 – AI-Driven Autonomous Scientific Discovery

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 – Immersive Augmented & Virtual Reality

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Immersive AR/VR makes remote presence feel more like being there, which directly improves training, supervision, collaboration, negotiation, and remote operation of distant spaces. It can reduce travel and broaden participation, but also intensify platform dependency, behavioural

capture, and social pressure to be ‘present’ everywhere all the time. As interfaces become natural enough, more activities stop being redesigned around absence and instead assume rich remote co-presence by default. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Participation] → travel-heavy meetings, training, or inspections shift to immersive or adaptive remote sessions (remote presence gains legitimacy)
- (+) [Ease and accessibility] → users complete complex tasks with less setup and lower dropout (friction to remote action falls)
- (+) [Location independence] → employers count virtual attendance as equivalent to some on-site presence (norms change measurably)
- (-) [Power distribution] → platform vendors gain access to behaviour, gaze, or interaction data (interface owners gain leverage)
- (-) [Safety and security] → harassment, manipulation, or impersonation incidents rise in rich remote environments (social risk becomes embodied)
- (+) [Legal barriers] → sector guidance defines when immersive or adaptive interfaces satisfy presence requirements (rules start catching up)
- (+) [Efficiency] → support and training metrics improve relative to video-only channels (better embodiment pays off)
- (+) [Accessibility] → users with mobility or communication barriers report higher task completion (participation broadens)
- (+) [3rd-order adoption] → organisations redesign workflows around remote-first spatial collaboration (absence stops dictating process design)

## ART 04.023 – Brain-Computer Interfaces (BCI)

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

BCIs improve this GVN mainly by giving more people, including users with limited motor ability, access to remote control and participation channels that current interfaces restrict. The effects could be meaningful in accessibility, specialised teleoperation, and high-performance control, but adoption is likely narrower than mass-screen or voice interfaces. Where used, they could intensify data-governance and cognitive surveillance issues around remote work and remote care. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Participation] → travel-heavy meetings, training, or inspections shift to immersive or adaptive remote sessions (remote presence gains legitimacy)
- (+) [Ease and accessibility] → users complete complex tasks with less setup and lower dropout (friction to remote action falls)
- (+) [Location independence] → employers count virtual attendance as equivalent to some on-site presence (norms change measurably)
- (-) [Power distribution] → platform vendors gain access to behaviour, gaze, or interaction data (interface owners gain leverage)
- (-) [Safety and security] → harassment, manipulation, or impersonation incidents rise in rich remote environments (social risk becomes embodied)
- (+) [Legal barriers] → sector guidance defines when immersive or adaptive interfaces satisfy presence requirements (rules start catching up)

## ART 04.024 – Advanced Prosthetics & Exoskeletons

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 04.025 – Haptic and Multi-Sensory Feedback Systems

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Rich haptic feedback closes a major gap in remote influence: users can not only see distant environments but feel contact, resistance, and texture well enough to do fine physical work. That moves more skilled manual tasks into remote labour markets and remote service platforms, while creating new liability and training issues when sensed force and real force diverge. Once touch is reliable enough, teleoperation expands from monitoring and coarse control to delicate maintenance, care, and manipulation. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Remote-controlled avatars] → teleoperators complete delicate manipulation tasks without local assistants (touch closes the skill gap)
- (+) [Efficiency] → rework and breakage fall in remote maintenance or care pilots (force feedback improves accuracy)
- (+) [Participation] → remote skilled work opens to regions without the task site (manual labour becomes location-independent)
- (-) [Safety and security] → liability cases test responsibility for delayed or misleading force cues (new failure mode becomes visible)
- (-) [Labour structure] → firms source tactile telework across borders at lower wage levels (manual job markets globalise)
- (+) [Legal barriers] → standards bodies certify haptic performance thresholds for regulated teleoperation (rules begin trusting remote touch)
- (+) [Training] → simulators using the same feedback stack shorten operator training time (skill transfer accelerates)
- (-) [Dual use] → coercive or hazardous remote manipulation appears in security briefings (harmful capability becomes practical)
- (+) [3rd-order adoption] → robot makers bundle haptics as standard rather than premium (telepresence becomes more complete)

## ART 04.026 – AI Understanding of Human Intent & Context

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Intent- and context-aware AI strips friction out of remote interaction by adapting timing, modality, and assistance to what users are trying to do at a distance. It can widen participation and productivity, but it also gives platforms much greater leverage to steer attention, emotion, and behaviour in remote settings. As interfaces anticipate needs, more decisions and influence attempts happen through always-on mediated environments rather than deliberate one-off communications. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Ease and accessibility] → assistants switch modality, timing, or prompts based on user state (remote interfaces get situationally smart)
- (+) [Participation] → non-expert users complete remote tasks with less confusion or fatigue (cognitive burden drops)
- (-) [Power distribution] → platforms monetise inferred intent, emotion, or attention in remote settings (behavioural leverage deepens)
- (-) [Privacy] → procurement or labour disputes focus on gaze, posture, and affect sensing (context inference becomes contested)
- (+) [Efficiency] → support teams handle more sessions per worker without quality loss (adaptive interfaces raise throughput)
- (+) [Legal barriers] → sector rules define acceptable uses of inferred intent in remote services (governance starts formalising)
- (-) [Abuse of remote influence] → persuasion systems optimise timing and framing using live context signals (manipulation gets more precise)
- (+) [Accessibility] → remote services become workable for users with language, sensory, or literacy barriers (inclusion improves materially)
- (+) [3rd-order adoption] → interfaces quietly mediate more of everyday remote life (users stop issuing explicit commands)

## ART 04.027 – Brain-to-Brain Interfaces

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Even assuming technical maturity, the likely user base and domain fit remain narrow, so the pathway into this GVN is concrete but limited. The bigger questions are ethical and governance-related rather than whether it becomes a broad operating layer for remote impact. If it matters later, it will probably do so in specialist coordination niches before diffusing more widely. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)

- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 04.028 – Memory Prostheses

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## 5. Robotics & Physical Autonomy

### ART 05.029 – Self-Driving Vehicles

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Self-driving vehicles expand remote impact by letting people and organisations move goods, services, and even mobile workspaces without being physically present in the vehicle or at the destination. They shift transport labour, dispatch power, and urban access rules, and they create new surveillance, sabotage, and liability questions around centrally controlled fleets. As autonomous mobility becomes normal, more remote services are designed around sending vehicles and robots rather than people travelling themselves. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Location independence] → goods, tools, or mobile services arrive without staff travelling with them (movement decouples from presence)
- (+) [Efficiency] → remote dispatch replaces some local routing and standby labour (central control gets cheaper)
- (+) [Participation] → peripheral areas gain service frequency because remote fleet management lowers staffing needs (access widens geographically)
- (-) [Job displacement] → collective bargaining agendas centre on remote fleet supervision versus local driving roles (labour conflict surfaces)
- (-) [Safety and security] → authorities investigate cyber or spoofing risks in centrally controlled fleets (remote attack surface widens)
- (+) [Legal barriers] → permits allow unattended operation in more zones or times (rules concede remote mobility)
- (+) [Market structure] → platform fleet operators gain bargaining power over local service providers (mobility control centralises)
- (+) [3rd-order adoption] → other remote services are designed around autonomous vehicle availability (physical reach becomes assumed)
- (+) [Environmental efficiency] → travel reductions are measured against previous on-site attendance models (substitution becomes quantifiable)

## ART 05.030 – Drone Swarms & Aerial Robots

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Autonomous drones and field robots dramatically widen the physical reach of remote actors into hazardous, dispersed, or inaccessible environments. They transfer inspection, security, emergency response, and some coercive capacity away from local presence and toward remote supervisors, software vendors, and states or large firms. Each successful deployment lowers the cultural and regulatory barrier to more routine remote intervention, including both beneficial services and hostile uses. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Remote-controlled robotics] → organisations replace scheduled field visits with drone/robot intervention windows (distance loses operational penalty)
- (+) [Safety and security] → hazardous inspections move from local teams to remote supervisors (risk shifts away from bodies)
- (+) [Efficiency] → incident response reaches sites faster because assets are pre-positioned and remotely dispatched (time-to-action drops sharply)
- (-) [Dual use] → hostile or coercive uses appear in police, military, or criminal incident reporting (threat capability spreads)



- (-) [Job displacement] → local inspection, patrol, or routine servicing hours fall in workforce plans (site work centralises remotely)
- (+) [Legal barriers] → regulators define remote supervision ratios and beyond-line-of-sight permissions (institutions adapting to robotic presence)
- (+) [Participation] → remote operator jobs emerge outside the physical worksite region (labour geography decouples from sites)
- (-) [Power distribution] → asset owners with the best autonomy stack dominate distributed service markets (scale advantage compounds)
- (+) [3rd-order adoption] → sensing, AI, and robotic action are sold as one subscription (remote influence becomes a managed utility)

## ART 05.031 – Humanoid and General-Purpose Robots

Score: 20 (Impact in GVN 9)

Justification (3–5 sentences):

General-purpose humanoid robots are a near-direct embodiment of this GVN's goal: they let remote actors work, inspect, manipulate, and participate in human-designed environments without travelling there. They could reconfigure labour markets, service delivery, regional equality, and bargaining power, while also multiplying security, misuse, and 'ghost work' risks when one operator can project presence into many places. Once physical embodiment is rentable and networked, remote-first operating models spread into domains that today still require local human presence. In a 5.5M-person society this plausibly affects the weekly life of hundreds of thousands and functions as a linchpin of remote-first operations, so 20 is justified.

Weak signals (9):

- (+) [Physical presence norm] → customers or regulators accept robot embodiment as valid attendance in more tasks (presence gets redefined)
- (+) [Participation] → skilled people work into distant sites without relocation or travel (labour geography is rewired)
- (+) [Efficiency] → service providers publish travel-cost and downtime reductions from humanoid deployment (economics become visible)
- (-) [Job displacement] → local service and facility roles face substitution by remote or central operators (employment shifts are explicit)
- (-) [Safety and security] → trespass, sabotage, or impersonation cases involve telepresent robots (coercive remote presence becomes real)
- (+) [Legal barriers] → insurance and labour law start specifying responsibility for embodied remote work (institutions adapting to avatars)
- (-) [Power distribution] → robot-platform owners accumulate leverage over sites, operators, and data (embodiment markets centralise)
- (+) [Regional equality] → smaller towns access specialists through rentable robotic presence (service access improves materially)

- (+) [3rd-order adoption] → buildings, tools, and workflows are redesigned around robot attendance (remote-first physical operations lock in)

## ART 05.032 – Soft Robotics & Bio-Inspired Machines

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

These robots expand remote influence into niches where rigid machines or standard manipulators perform badly, such as delicate handling, confined spaces, or awkward surfaces. The economic shift is meaningful but narrower than with general-purpose robots, concentrating in specific maintenance, inspection, and care workflows. Success in those niches still matters because it broadens the set of tasks considered suitable for remote physical intervention. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)
- (-) [Market structure] → component suppliers gain leverage through proprietary subsystems (upstream dependency increases)
- (+) [Legal barriers] → certification standards start referencing the new component class (technology becomes deployable at scale)
- (+) [Training] → remote operators need less local improvisation because tools work more predictably (skill burden shifts into hardware)
- (+) [3rd-order adoption] → successful niche deployments feed confidence in broader remote robotics (adjacent tasks become thinkable)
- (-) [Dual use] → security assessments note the same components enabling harder-to-block remote actions (capability escalates quietly)

## ART 05.033 – Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Autonomous drones and field robots dramatically widen the physical reach of remote actors into hazardous, dispersed, or inaccessible environments. They transfer inspection, security, emergency

response, and some coercive capacity away from local presence and toward remote supervisors, software vendors, and states or large firms. Each successful deployment lowers the cultural and regulatory barrier to more routine remote intervention, including both beneficial services and hostile uses. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Remote-controlled robotics] → organisations replace scheduled field visits with drone/robot intervention windows (distance loses operational penalty)
- (+) [Safety and security] → hazardous inspections move from local teams to remote supervisors (risk shifts away from bodies)
- (+) [Efficiency] → incident response reaches sites faster because assets are pre-positioned and remotely dispatched (time-to-action drops sharply)
- (-) [Dual use] → hostile or coercive uses appear in police, military, or criminal incident reporting (threat capability spreads)
- (-) [Job displacement] → local inspection, patrol, or routine servicing hours fall in workforce plans (site work centralises remotely)
- (+) [Legal barriers] → regulators define remote supervision ratios and beyond-line-of-sight permissions (institutions adapting to robotic presence)
- (+) [Participation] → remote operator jobs emerge outside the physical worksite region (labour geography decouples from sites)
- (-) [Power distribution] → asset owners with the best autonomy stack dominate distributed service markets (scale advantage compounds)
- (+) [3rd-order adoption] → sensing, AI, and robotic action are sold as one subscription (remote influence becomes a managed utility)

## ART 05.034 – Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Autonomy-support infrastructure matters because remote robots scale poorly in messy spaces unless the environment itself helps with localisation, docking, access control, and safety. It shifts power toward site owners and standards-setters that decide which remote machines are allowed to operate and on what terms. As more sites become ‘robot-readable,’ remote embodiment stops being exceptional and becomes embedded in routine operations. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Ease and accessibility] → sites add robot-readable markers, docks, or safety zones as standard retrofit packages (environment starts inviting autonomy)

- (+) [Efficiency] → multiple vendors' robots share the same infrastructure with fewer local technicians (coordination cost falls)
- (+) [Legal barriers] → building codes or industrial standards begin specifying autonomy-ready features (institutionalisation becomes visible)
- (-) [Power distribution] → site owners decide which remote operators and robot brands are admitted (access becomes infrastructural power)
- (+) [Safety and security] → incident rates drop when robot traffic is channelled through managed corridors (shared rules improve trust)
- (+) [Participation] → smaller sites buy 'autonomy-ready' upgrades to access remote services (capability diffuses beyond large firms)
- (+) [3rd-order adoption] → once retrofitted, sites commission more remote tasks than originally planned (installed base pulls demand)
- (-) [Market structure] → dominant infrastructure standards disadvantage non-conforming robots (ecosystem lock-in grows)
- (+) [Physical presence norm] → workers treat remote robotic attendance as routine in equipped sites (culture adapts to mediated work)

## **ART 05.035 – Optical/Microwave Power Beaming for Persistent Robotics**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Longer-endurance power systems matter for this GVN when they let remote robots and sensors stay active without frequent local servicing. The effect is strongest in hard-to-reach or hazardous sites, while broad everyday remote participation changes only modestly. Where uptime improves, organisations can redesign operations around persistent remote presence rather than periodic visits. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)

- (-) [Market structure] → component suppliers gain leverage through proprietary subsystems (upstream dependency increases)
- (+) [Legal barriers] → certification standards start referencing the new component class (technology becomes deployable at scale)

## **ART 05.036 – Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

These robots expand remote influence into niches where rigid machines or standard manipulators perform badly, such as delicate handling, confined spaces, or awkward surfaces. The economic shift is meaningful but narrower than with general-purpose robots, concentrating in specific maintenance, inspection, and care workflows. Success in those niches still matters because it broadens the set of tasks considered suitable for remote physical intervention. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)
- (-) [Market structure] → component suppliers gain leverage through proprietary subsystems (upstream dependency increases)
- (+) [Legal barriers] → certification standards start referencing the new component class (technology becomes deployable at scale)

## **6. Additive, Agile & Digital Manufacturing**

### **ART 06.037 – Multi-Material & Hybrid 3D Printing**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

More digital, software-defined manufacturing lets designers and operators influence physical production from afar instead of being on the shop floor or near specialised suppliers. It can

reallocate bargaining power toward whoever controls digital recipes, remote diagnostics, and certification, while reducing some travel and site-specific skill bottlenecks. As factories become easier to reprogram remotely, physical production starts to behave more like a network service. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → engineers change recipes, diagnostics, or print jobs from off-site locations (production becomes software-mediated)
- (+) [Efficiency] → firms cut travel for troubleshooting, setup, or supplier coordination (remote intervention replaces visits)
- (+) [Participation] → smaller or regional plants access specialist expertise without co-locating it (capability spreads geographically)
- (-) [Power distribution] → whoever controls digital process files or simulation models gains leverage over local plants (control shifts upstream)
- (+) [Legal barriers] → auditors accept remote evidence packs for more production changes (onsite sign-off loses ground)
- (+) [3rd-order adoption] → factories move from episodic remote support to continuous remote optimisation (distance stops being exceptional)

## ART 06.038 – Digital Twin & Simulation-Driven Production

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Digital twins make distant assets legible enough to operate, optimise, and troubleshoot remotely with fewer site visits and fewer mistakes. They centralise expertise and decision rights, change maintenance contracts, and create new auditability and cybersecurity expectations for remote supervision. As models become trusted, more intervention rights shift to remote teams and automated agents instead of local operators. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Remote influence quality] → operators intervene from twin views rather than waiting for on-site inspection (situational awareness improves)
- (+) [Efficiency] → downtime and travel fall because faults are triaged remotely first (remote diagnosis becomes default)
- (+) [Participation] → scarce experts support many sites from central teams (expert reach multiplies)
- (-) [Safety and security] → cyber rules start treating twin platforms as critical control surfaces (attack stakes rise)

- (-) [Power distribution] → asset owners depend on model vendors for access to operational truth (informational leverage concentrates)
- (+) [Legal barriers] → insurers or regulators accept twin-derived evidence in maintenance and compliance (models gain institutional standing)
- (+) [3rd-order adoption] → teams rehearse interventions virtually before touching the site (remote governance becomes procedural)
- (+) [Labour structure] → local technicians shift toward exception handling and physical execution only (knowledge centralises remotely)
- (+) [Cross-organisational coordination] → suppliers and operators sync against the same live model (remote collaboration standardises)

## ART 06.039 – Reconfigurable & Agile Factories

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

More digital, software-defined manufacturing lets designers and operators influence physical production from afar instead of being on the shop floor or near specialised suppliers. It can reallocate bargaining power toward whoever controls digital recipes, remote diagnostics, and certification, while reducing some travel and site-specific skill bottlenecks. As factories become easier to reprogram remotely, physical production starts to behave more like a network service. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → engineers change recipes, diagnostics, or print jobs from off-site locations (production becomes software-mediated)
- (+) [Efficiency] → firms cut travel for troubleshooting, setup, or supplier coordination (remote intervention replaces visits)
- (+) [Participation] → smaller or regional plants access specialist expertise without co-locating it (capability spreads geographically)
- (-) [Power distribution] → whoever controls digital process files or simulation models gains leverage over local plants (control shifts upstream)
- (+) [Legal barriers] → auditors accept remote evidence packs for more production changes (onsite sign-off loses ground)
- (+) [3rd-order adoption] → factories move from episodic remote support to continuous remote optimisation (distance stops being exceptional)

## ART 06.040 – Circular & Sustainable Manufacturing

Score: 1 (Impact in GVN 9)



Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 06.041 – Bio-fabrication technologies**

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 06.042 – 4D Printed & Programmable Materials

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Programmable materials matter here because they let objects change state after remote triggering—or even without live intervention—reducing the need for local human adjustment. The biggest effect is operational simplification rather than a broad new communication channel, though it changes maintenance and design responsibilities. If widely used in devices and structures, they make remote influence more reliable because the physical world becomes easier to actuate at a distance. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → field components self-adjust after remote command or environmental trigger (fewer local visits needed)
- (+) [Safety and security] → assets survive changing conditions with less manual intervention (remote reliability improves)
- (+) [Location independence] → operators manage larger dispersed estates because objects handle small corrections themselves (human attention stretches further)
- (-) [Accountability] → failures are traced to design logic rather than local operator action (responsibility shifts upstream)
- (+) [Legal barriers] → certification starts covering adaptive material behaviour in remote assets (self-actuation becomes governable)
- (+) [3rd-order adoption] → designs assume passive or remotely triggered adaptation by default (physical systems become more governable at distance)

## ART 06.043 – Volumetric Additive Manufacturing

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

More digital, software-defined manufacturing lets designers and operators influence physical production from afar instead of being on the shop floor or near specialised suppliers. It can reallocate bargaining power toward whoever controls digital recipes, remote diagnostics, and certification, while reducing some travel and site-specific skill bottlenecks. As factories become easier to reprogram remotely, physical production starts to behave more like a network service. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Location independence] → engineers change recipes, diagnostics, or print jobs from off-site locations (production becomes software-mediated)
- (+) [Efficiency] → firms cut travel for troubleshooting, setup, or supplier coordination (remote intervention replaces visits)
- (+) [Participation] → smaller or regional plants access specialist expertise without co-locating it (capability spreads geographically)
- (-) [Power distribution] → whoever controls digital process files or simulation models gains leverage over local plants (control shifts upstream)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 – Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Better wave-control components improve antennas, optics, and signal routing, which helps remote links and telepresence hardware work more reliably in cluttered environments. The gains are real but mostly embedded inside upstream equipment rather than visible as a new operating model on their own. As coverage and device performance improve, more settings become practical for remote operation without bespoke infrastructure. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → telecom upgrades advertise thinner antennas, better indoor coverage, or lower-power links (component gains reach users indirectly)
- (+) [Ease and accessibility] → AR, wearables, or compact terminals become lighter without losing signal quality (remote interfaces get easier to wear)
- (+) [Remote influence quality] → difficult environments see fewer dead zones or shadow areas (link reliability improves where it mattered)
- (-) [Market structure] → specialised surface and optics suppliers win key integration contracts (upstream leverage increases)
- (+) [Safety and security] → controlled beam shaping is written into high-sensitivity deployment standards (signal management becomes governable)
- (+) [3rd-order adoption] → more locations become practical for dense telepresence and sensing (coverage improvements unlock adjacent services)

### ART 07.045 – Room-Temperature Superconductors

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

This mainly affects the GVN through cheaper or more capable underlying infrastructure rather than through a direct remote-impact channel. The economic benefits could be large in general, but only a small share maps specifically to remote influence and participation. Any stronger effect would depend on complementary technologies turning the broad efficiency gain into specific remote services. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 07.046 – Self-Healing & Smart Polymers**

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 07.047 – Nano-Catalysts & Advanced Coatings

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 07.048 – High-Entropy Alloys & Advanced Metals

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Better structural or motor materials improve the reliability, weight, and lifetime of remote robots, drones, wearables, and network hardware. That matters commercially, but it does not by itself shift who can influence what at a distance; it mostly improves the economics of other ARTs. If the component gains are large enough, they can accelerate broader remote robotics adoption indirectly. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)

- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)

## **ART 07.049 – Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation**

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 07.050 – Graphene and Nanotube Composites for Lightweight Strength**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Better structural or motor materials improve the reliability, weight, and lifetime of remote robots, drones, wearables, and network hardware. That matters commercially, but it does not by itself shift who can influence what at a distance; it mostly improves the economics of other ARTs. If the component gains are large enough, they can accelerate broader remote robotics adoption indirectly. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)

- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)
- (-) [Market structure] → component suppliers gain leverage through proprietary subsystems (upstream dependency increases)
- (+) [Legal barriers] → certification standards start referencing the new component class (technology becomes deployable at scale)

## **ART 07.051 – Smart Thermal Materials for Energy-Efficient Heating & Cooling**

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 07.052 – Rare-Earth-Free Magnets for Sustainable Motors**

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Better structural or motor materials improve the reliability, weight, and lifetime of remote robots, drones, wearables, and network hardware. That matters commercially, but it does not by itself shift who can influence what at a distance; it mostly improves the economics of other ARTs. If the



component gains are large enough, they can accelerate broader remote robotics adoption indirectly. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)
- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)

## **ART 07.053 – Nano-Engineered Membranes for Low-Energy Desalination**

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 07.054 – Ultra-Wide-Bandgap (UWBG) Power Semiconductors**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Higher-performance power electronics improve chargers, motor drives, wireless links, and field equipment, which makes remote systems smaller, quieter, and more reliable. The effect is a cross-cutting hardware uplift rather than a direct new mode of participation or influence. As power conversion improves, more remote devices can operate continuously in tight spaces and harsh sites. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)
- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)

## **ART 07.055 – Solid Hydrogen Storage Materials for Safe, Dense Fuel**

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Longer-endurance power systems matter for this GVN when they let remote robots and sensors stay active without frequent local servicing. The effect is strongest in hard-to-reach or hazardous sites, while broad everyday remote participation changes only modestly. Where uptime improves, organisations can redesign operations around persistent remote presence rather than periodic visits. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Efficiency] → robot uptime rises because power, materials, or specialised attachments reduce servicing demands (economics improve at the margin)
- (+) [Remote influence quality] → specialised environments become reachable without sending people (task envelope widens)

- (+) [Safety and security] → operators approve deployments in harsher or more delicate settings (risk thresholds shift)
- (+) [Participation] → smaller operators access niche remote capabilities through upgraded components (advanced tasks spread beyond pioneers)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 – Fusion Energy Reactors

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Abundant or more flexible energy helps the GVN only indirectly by lowering the risk of outages and supporting digital infrastructure and robotics. The main institutional effects belong to the energy system itself rather than to remote influence as a distinct operating model. Only if this ART materially changes local resilience or the cost of remote hardware does the linkage strengthen. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

### ART 08.057 – Small Modular Fission Reactors (SMRs)

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Abundant or more flexible energy helps the GVN only indirectly by lowering the risk of outages and supporting digital infrastructure and robotics. The main institutional effects belong to the energy system itself rather than to remote influence as a distinct operating model. Only if this ART materially changes local resilience or the cost of remote hardware does the linkage strengthen. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 08.058 – Thin-film solar cells

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Distributed power surfaces or wireless delivery extend where remote sensors, links, and actuators can be deployed without new cabling or fuel logistics. That supports location independence and lower servicing costs, especially in temporary, mobile, or hard-to-wire environments. As power becomes easier to place where needed, remote influence architectures spread beyond conventional buildings and utility footprints. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)
- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)

## ART 08.059 – Bionic Leaf Technology

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 08.060 – Grid-Scale Energy Storage

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Resilient power and storage help this GVN by keeping connectivity, sensors, platforms, and teleoperation available through outages and local disruptions. They also shift control toward operators who can maintain remote service continuity, and they matter in crisis response where physical presence is hardest. When uptime is trusted, more services are redesigned to assume remote availability instead of local fallback staffing. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)

- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)

## ART 08.061 – Solid-State Batteries

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Higher-density, safer batteries directly improve the range, runtime, and form factor of telepresence devices, drones, mobile robots, and wearables used for remote influence. That broadens which actors can deploy remote physical presence and lowers some safety and insurance barriers, while also increasing misuse potential. As endurance improves, remote operations move from short sessions to all-day or always-on services. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)
- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)
- (+) [Legal barriers] → permits and insurance products start assuming longer unattended operation (regulatory comfort increases)
- (+) [3rd-order adoption] → organisations redesign for always-on remote presence instead of periodic visits (power changes operating assumptions)
- (-) [Dual use] → hostile actors exploit longer-endurance remote devices in security incidents (malicious persistence improves)

## ART 08.062 – Green Hydrogen & Power-to-X

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Abundant or more flexible energy helps the GVN only indirectly by lowering the risk of outages and supporting digital infrastructure and robotics. The main institutional effects belong to the energy system itself rather than to remote influence as a distinct operating model. Only if this ART materially changes local resilience or the cost of remote hardware does the linkage strengthen. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## **ART 08.063 – High-Efficiency Wind Turbines**

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)



## ART 08.064 – Wireless & Space-Based Power Transfer

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Distributed power surfaces or wireless delivery extend where remote sensors, links, and actuators can be deployed without new cabling or fuel logistics. That supports location independence and lower servicing costs, especially in temporary, mobile, or hard-to-wire environments. As power becomes easier to place where needed, remote influence architectures spread beyond conventional buildings and utility footprints. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)
- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)

## ART 08.065 – Advanced geothermal technology

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)

- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 08.066 – Resilient microgrids

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Resilient power and storage help this GVN by keeping connectivity, sensors, platforms, and teleoperation available through outages and local disruptions. They also shift control toward operators who can maintain remote service continuity, and they matter in crisis response where physical presence is hardest. When uptime is trusted, more services are redesigned to assume remote availability instead of local fallback staffing. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Location independence] → remote devices stay online longer in places with weak grid access (deployment geography broadens)
- (+) [Efficiency] → servicing intervals lengthen for field sensors, robots, or temporary sites (remote uptime becomes affordable)
- (+) [Safety and security] → power redundancy is written into remote-service contracts (energy seen as part of trust stack)
- (+) [Participation] → smaller operators buy longer-endurance remote equipment instead of local staffing (capability becomes more affordable)
- (+) [Ease and accessibility] → devices ship with smaller power packs or self-powered modes (deployment friction drops)
- (-) [Market structure] → critical remote services cluster around vendors controlling the new power hardware (dependency shifts upstream)
- (+) [Legal barriers] → permits and insurance products start assuming longer unattended operation (regulatory comfort increases)
- (+) [3rd-order adoption] → organisations redesign for always-on remote presence instead of periodic visits (power changes operating assumptions)
- (-) [Dual use] → hostile actors exploit longer-endurance remote devices in security incidents (malicious persistence improves)

## 9. Bio-engineering & Life-Science Technologies

## ART 09.067 – Next-Generation Gene Editing

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.068 – mRNA Therapies & Vaccines

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)

- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.069 – Cellular Agriculture & Cultured Meat

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.070 – Organoids & Tissue Engineering

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)

- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.071 – Synthetic Biology & Designer Microbes

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.072 – Microbiome Engineering

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)

- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.073 – Precision Medicine & Genomic Diagnostics

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

Precision diagnostics modestly strengthen remote impact by letting care decisions, follow-up, and triage happen without physical co-presence more often. The stronger effects sit inside healthcare rather than the broader remote-influence operating model, and adoption remains bounded by trust and regulation. If combined with telehealth and home sensing, it could reduce some travel and widen participation for patients outside major centres. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Participation] → patients complete more specialist follow-up remotely because decisions are data-rich (travel burden drops modestly)
- (+) [Location independence] → clinicians triage and monitor with fewer in-person visits (care coordination stretches further)
- (-) [Legal barriers] → reimbursement and evidence rules still limit when remote decisions replace physical exams (institutional ceiling remains visible)
- (+) [Safety and security] → remote care tools publish lower mis-triage rates for specific cohorts (trust improves in niches)

## ART 09.074 – Organs-on-Chips & Bio-Computational Hybrids

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.075 – Biological Aging & Longevity Barriers

Score: 1 (Impact in GVN 9)

Justification (3–5 sentences):

The impact pathway into this GVN exists but is indirect: the technology may improve adjacent capabilities or research productivity without directly changing remote influence at society scale. Any institutional effects would likely be second-hand and concentrated in a few specialist organisations. If a stronger linkage emerges later, it will probably do so through other platforms that adopt outputs from this ART rather than through direct adoption. The effect is concrete enough to watch but likely stays below the material-impact anchor for the full GVN, so 1 is appropriate.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.076 – Engineered Living Materials

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.



Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 09.077 – Gene Drive Pest Control

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Gene drives are an extreme form of remote influence: actors can change distant ecological outcomes without maintaining physical presence after release. That creates major governance, accountability, and security questions about who gets to intervene in shared environments and how harms are reversed. Even limited field use would normalise a new class of remote biological control and provoke strong countermeasures and monitoring regimes. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Remote influence on ecosystems] → pest-control programmes model gene-drive release as a one-off intervention (presence decouples from ongoing action)
- (+) [Legal barriers] → draft field-trial rules specify reversibility, monitoring, and cross-border notification (governance is being built)
- (+) [Safety and security] → environmental surveillance starts tracking genetic spread after limited trials (remote biological effects become measurable)
- (-) [Accountability] → disputes focus on who owns downstream ecological outcomes after release (responsibility no longer stays local)
- (-) [Dual use] → security assessments treat gene drives as misuse-sensitive remote intervention tools (coercive pathway is acknowledged)
- (+) [3rd-order adoption] → successful narrow deployments expand political appetite for other persistent remote biological controls (new intervention logic normalises)

## ART 09.078 – Artificial Wombs & Synthetic Embryos

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## 10. Space & Aeronautical Engineering

### ART 10.079 – Satellite Mega-Constellations & Space Internet

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Alternative airborne or orbital connectivity layers matter for this GVN because they extend reach and keep remote services alive when terrestrial networks are absent, congested, or damaged. They reduce geographic exclusion and can shift bargaining power toward operators of a few strategic platforms, while also changing national-security assumptions about who controls communication. As backup and overflow capacity becomes normal, more institutions are willing to rely on remote-first operations in places they once treated as too fragile. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Location independence] → operators use non-terrestrial links as primary or backup access (coverage becomes resilient)

- (+) [Regional equality] → remote public services expand into low-density or damaged areas (infrastructure gap narrows)
- (+) [Crisis response] → emergency exercises rely on airborne/orbital communications for field coordination (remote continuity proven)
- (+) [Efficiency] → enterprises shift from dedicated on-site staff to remote support teams (reliability enables centralisation)
- (-) [Safety and security] → states classify these networks as strategic critical infrastructure (control becomes geopolitical)
- (-) [Market structure] → a small number of operators dominate last-resort connectivity contracts (dependency concentrates)
- (+) [Legal barriers] → regulators license remote operations that explicitly use resilient backup links (trust rises under disruption)
- (-) [Abuse of remote influence] → hostile actors exploit global coverage for spoofed or cross-border campaigns (malicious reach broadens)
- (+) [Remote-controlled robotics] → field robots and vessels switch between terrestrial and non-terrestrial backhaul (remote reach extends physically)

## **ART 10.080 – Space Resource Utilization (SRU)**

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 10.081 – Closed-Loop Life Support System

Score: 0 (Impact in GVN 9)

Justification (3–5 sentences):

The linkage to this GVN is weak: even in mature form, the technology does not clearly change how people influence distant things and events at society scale. Any effects would mostly arrive through broad economic spillovers rather than a distinct remote-impact pathway. A stronger linkage would require complementary technologies or regulations that are not inherent to the ART itself. Without a clearer pathway into the GVN's operating model, the score stays at 0.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Watchpoint: remote operating model] → pilots explicitly tie the ART to remote control, telepresence, or remote decision rights (linkage would become concrete)
- (+) [Watchpoint: legal adaptation] → regulators start referencing the ART in remote-service approvals (institutional pathway would open)
- (-) [Watchpoint: misuse] → security agencies classify the ART as a new remote-influence vector (harm pathway would strengthen linkage)
- (+) [Watchpoint: market signal] → vendors package the ART with remote-operation platforms rather than sector-specific tools (commercial linkage would become visible)

## ART 10.082 – High-Altitude Platforms & Balloons

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Alternative airborne or orbital connectivity layers matter for this GVN because they extend reach and keep remote services alive when terrestrial networks are absent, congested, or damaged. They reduce geographic exclusion and can shift bargaining power toward operators of a few strategic platforms, while also changing national-security assumptions about who controls communication. As backup and overflow capacity becomes normal, more institutions are willing to rely on remote-first operations in places they once treated as too fragile. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Location independence] → operators use non-terrestrial links as primary or backup access (coverage becomes resilient)
- (+) [Regional equality] → remote public services expand into low-density or damaged areas (infrastructure gap narrows)
- (+) [Crisis response] → emergency exercises rely on airborne/orbital communications for field coordination (remote continuity proven)

- (+) [Efficiency] → enterprises shift from dedicated on-site staff to remote support teams (reliability enables centralisation)
- (-) [Safety and security] → states classify these networks as strategic critical infrastructure (control becomes geopolitical)
- (-) [Market structure] → a small number of operators dominate last-resort connectivity contracts (dependency concentrates)
- (+) [Legal barriers] → regulators license remote operations that explicitly use resilient backup links (trust rises under disruption)
- (-) [Abuse of remote influence] → hostile actors exploit global coverage for spoofed or cross-border campaigns (malicious reach broadens)
- (+) [Remote-controlled robotics] → field robots and vessels switch between terrestrial and non-terrestrial backhaul (remote reach extends physically)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 – Decentralized Trust Networks (Web3 & Blockchain)

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Decentralised trust networks reduce the need for physical presence and bilateral trust when people exchange value, credentials, and commitments across distance. They can widen participation and automate rule enforcement, but they also support illicit finance, new gatekeepers, and harder-to-govern transnational influence channels. As programmable trust spreads, more remote work, contracting, and asset control happen without traditional intermediaries. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Participation] → remote workers, donors, or members use portable wallets/credentials across multiple services (trust gets unbundled from single platforms)
- (+) [Location independence] → cross-border payments or contracts settle without local intermediaries (distance loses transactional friction)
- (+) [Efficiency] → routine remote agreements trigger automatically through programmable rules (coordination overhead falls)
- (-) [Safety and security] → fraud, laundering, or exploit incidents migrate into smart-contract layers (illicit remote channels mature)
- (-) [Power distribution] → control shifts to token, wallet, oracle, or node operators (new gatekeepers emerge)
- (+) [Legal barriers] → public procurement or licensing begins recognising decentralised credentials or settlement rails (formal legitimacy expands)

- (+) [3rd-order adoption] → remote services bundle identity, payment, and governance into one stack (self-contained remote ecosystems form)
- (+) [Accountability] → audit trails are used in disputes over remote work and remote commerce (evidence shifts from paperwork to ledgers)
- (+) [Inclusion] → niche groups gain access where banks or large platforms excluded them (remote participation base widens)

## ART 11.084 – Platform Cooperatives & Fair Work

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Cooperative platforms affect this GVN by changing who captures value from remote work and remote service marketplaces, not by creating the remote channel itself. They can improve equality, transparency, and bargaining power for distributed workers, but their adoption is likely patchy and sector-specific. Where they succeed, they can make remote participation more politically durable by reducing backlash against platform extraction. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Participation] → remote workers receive portable reputation, voting, or payout rights across jobs (worker agency becomes observable)
- (+) [Equality] → platform fees and ranking rules are published to members in machine-readable form (distribution gets more legible)
- (+) [Location independence] → local co-ops recruit outside their home region without losing governance control (remote membership scales)
- (-) [Governance bottleneck] → disputes focus on voting blocs, fraud, or board capture in digital co-ops (new coordination frictions appear)
- (+) [Legal barriers] → municipalities or public buyers create procurement windows for cooperative remote platforms (institutional support appears)
- (+) [3rd-order adoption] → remote labour backlash softens where value capture is shared (operating model gains durability)

## ART 11.085 – Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Open data marketplaces let remote actors buy, share, and analyse the information needed to influence distant systems without building every data pipe themselves. They shift market power toward data-rich organisations and infrastructure providers, while also lowering barriers for smaller actors to access actionable remote situational awareness. As data becomes easier to license and

combine, more remote services and interventions become software-configurable rather than bespoke. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Efficiency] → remote service providers buy external data instead of building site-specific pipelines (time-to-deploy shrinks)
- (+) [Participation] → smaller organisations access datasets once reserved for large incumbents (informational power diffuses)
- (+) [Cross-boundary coordination] → contracts shift from bespoke sharing to standard marketplace terms (transaction friction falls)
- (-) [Safety and security] → disputes arise over re-identification, misuse, or low-quality feeds (data trust becomes operational risk)
- (-) [Power distribution] → marketplaces controlling metadata and billing gain leverage over contributors (exchange layer centralises power)
- (+) [Legal barriers] → procurement and compliance teams approve compute-to-data models for sensitive sectors (remote analytics becomes governable)
- (+) [3rd-order adoption] → remote products are configured around purchasable live data feeds (data markets become infrastructure)
- (+) [Auditability] → access logs are used to trace how remote decisions were informed (decision pipelines become more inspectable)
- (+) [Regional equality] → local actors monetise unique datasets into wider remote service markets (peripheral data becomes valuable)

## ART 11.086 – Secure & Resilient Social Platforms

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Secure and resilient social platforms sit at the core of remote influence over people and events: they are channels for mobilisation, persuasion, coordination, identity, and community without co-location. They can widen participation and continuity under disruption, but they also intensify moderation conflicts, information warfare, and platform governance battles. If trust, portability, and resilience improve, more civic, commercial, and organisational life moves into mediated spaces and becomes easier to steer remotely. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Participation] → civic, work, or mutual-aid groups keep operating through outages or censorship attempts (coordination becomes more resilient)



- (+) [Location independence] → users carry identity and contacts across services without restarting communities (social ties stop being platform-locked)
- (+) [Efficiency] → organisations shift more customer, member, and event activity into remote channels (mediated interaction becomes default)
- (-) [Safety and security] → moderation reports show coordinated manipulation adapting to more resilient networks (information conflict persists)
- (-) [Power distribution] → node hosts, reputation systems, or app-store gateways become new chokepoints (decentralisation does not remove power)
- (+) [Legal barriers] → institutions adopt secure social tools for remote hearings, committees, or crisis coordination (high-trust social use expands)
- (+) [3rd-order adoption] → more organisational rules and services are written around persistent remote communities (social infrastructure thickens)
- (+) [Equality] → geographically dispersed people maintain practical participation in local matters (distance matters less socially)
- (-) [Abuse of remote influence] → hostile actors exploit portability and resilience to avoid takedowns (counter-governance challenge grows)

## ART 11.087 – Collective Open Innovation Networks

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Open innovation networks help people influence distant problem-solving and development processes without physical co-location, especially in R&D-heavy sectors. The main shift is coordination efficiency and access to distributed expertise rather than a broad remaking of remote influence channels. Where they work well, they reinforce norms that serious collaborative work can be assembled and governed remotely. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → remote service providers buy external data instead of building site-specific pipelines (time-to-deploy shrinks)
- (+) [Participation] → smaller organisations access datasets once reserved for large incumbents (informational power diffuses)
- (+) [Cross-boundary coordination] → contracts shift from bespoke sharing to standard marketplace terms (transaction friction falls)
- (-) [Safety and security] → disputes arise over re-identification, misuse, or low-quality feeds (data trust becomes operational risk)
- (-) [Power distribution] → marketplaces controlling metadata and billing gain leverage over contributors (exchange layer centralises power)

- (+) [Legal barriers] → procurement and compliance teams approve compute-to-data models for sensitive sectors (remote analytics becomes governable)

## ART 11.088 – Scalable Decentralized Governance

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Decentralised governance systems let groups make binding decisions, allocate resources, and enforce rules at a distance with less reliance on physical meetings or local bureaucracies. They reshape legitimacy, accountability, and power distribution—sometimes democratising participation, sometimes concentrating influence in whoever designs the rules and interfaces. As remote decision rights become more operationally reliable, more organisations and communities move governance online. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Participation] → binding votes, budgets, or rule changes happen with higher remote turnout (distance barrier weakens)
- (+) [Efficiency] → organisations cut meeting and paperwork delays through structured digital decisions (coordination becomes faster)
- (+) [Location independence] → distributed groups govern shared assets without regular co-location (governance detaches from place)
- (-) [Power distribution] → proposal design and interface defaults shape outcomes more than assemblies realise (code authors gain leverage)
- (-) [Safety and security] → governance attacks focus on identity, bribery, or vote capture (new integrity risks emerge)
- (+) [Legal barriers] → bylaws, public consultations, or procurement rules accept remote execution traces (institutions start trusting digital governance)
- (+) [3rd-order adoption] → remote economic and civic systems begin embedding their own governance layer (self-governing remote ecosystems spread)
- (+) [Accountability] → disputes cite on-chain or logged decision trails instead of informal records (legibility increases)
- (+) [Equality] → members outside urban centres influence decisions more consistently (participation becomes less place-bound)

## ART 11.089 – Digital Learning Networks and Skill Credentialing

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Digital learning and verifiable skill credentials broaden who can take part in remote work and remote influence ecosystems by making competence legible without local gatekeepers. That matters

for participation and labour-market access, though it changes who can join remote systems more than it changes the remote systems themselves. As credential portability improves, remote labour pools become deeper and more competitive across geography. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Participation] → remote workers present portable credentials instead of local references (entry barriers decline)
- (+) [Location independence] → employers hire across regions using verifiable skill proofs (labour markets delink from place)
- (+) [Ease and accessibility] → AI tutors reduce training time for remote-service roles (capability formation accelerates)
- (-) [Power distribution] → credential platforms and assessment models shape who is considered employable (new gatekeepers emerge)
- (+) [Legal barriers] → regulators or public buyers accept digital credentials for remote work categories (formal recognition expands)
- (+) [3rd-order adoption] → remote-service ecosystems deepen because training and verification are bundled (supply of capable participants scales)

## ART 11.090 – Prediction-Market Forecasting Platforms

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Prediction markets improve remote influence by giving distributed actors a shared, continuously updated signal about likely outcomes before they intervene. They can centralise attention around measurable probabilities and reduce some decision friction, but they remain niche relative to the main channels of remote participation and control. Where adopted, they can tighten remote coordination loops by making assumptions explicit and scoreable. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → organisations reference live probabilities before remote interventions or public messaging (decision loops tighten)
- (+) [Participation] → distributed experts contribute forecast signals without being inside the same institution (tacit judgment becomes legible)
- (+) [Accountability] → teams compare intervention outcomes against prior market forecasts (remote decisions become scoreable)

- (-) [Safety and security] → manipulation, thin liquidity, or information leaks appear in governance reviews (integrity remains contested)
- (+) [Legal barriers] → risk, policy, or procurement processes formally incorporate calibrated forecast feeds (markets enter operations)
- (+) [3rd-order adoption] → shared probability dashboards reduce coordination lag across distant actors (uncertainty becomes more actionable remotely)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 – Universal IoT Interoperability Standards

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Interoperability standards are a major unlock because remote influence on things scales badly when every device, actuator, and sensor needs a custom integration. Common standards shift competition toward services and analytics, while also making it easier for regulators, insurers, and buyers to accept remote operation as routine. Once heterogeneous environments become machine-legible, remote control spreads from isolated pilots to whole buildings, fleets, and infrastructures. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Ease and accessibility] → device onboarding times collapse because new equipment self-describes through common schemas (integration friction drops sharply)
- (+) [Remote-controlled things] → mixed-vendor homes, buildings, and fleets are managed from one control layer (remote action scales across heterogeneity)
- (+) [Participation] → smaller operators adopt remote automation without bespoke middleware projects (capability diffuses downmarket)
- (-) [Safety and security] → vulnerabilities in common standards become sector-wide events (shared protocol risk appears)
- (+) [Legal barriers] → regulators and insurers cite standard interfaces in approvals (institutional trust rises with interoperability)
- (-) [Market structure] → standard-setting winners shape access and data rights across ecosystems (governance shifts to protocol layer)
- (+) [Efficiency] → maintenance and troubleshooting move from site-specific guesswork to standard diagnostics (support becomes more remote)
- (+) [3rd-order adoption] → once installed, users connect more devices and actuators than originally planned (network effects pull more remote control)

- (+) [Physical presence norm] → more tasks are accepted as remotely manageable because device behaviour is legible (culture adapts to machine transparency)

## ART 12.092 – Interoperable Digital Twin Ecosystems

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Interoperable twin ecosystems make remote oversight portable across vendors and organisations, so remote decision rights are less trapped inside single-tool silos. That changes contracts, accountability, and cross-organisational coordination, though it is still a layer beneath the end-user experience. As twin portability improves, more assets remain ‘remotely governable’ throughout their lifecycle. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Remote influence quality] → operators intervene from twin views rather than waiting for on-site inspection (situational awareness improves)
- (+) [Efficiency] → downtime and travel fall because faults are triaged remotely first (remote diagnosis becomes default)
- (+) [Participation] → scarce experts support many sites from central teams (expert reach multiplies)
- (-) [Safety and security] → cyber rules start treating twin platforms as critical control surfaces (attack stakes rise)
- (-) [Power distribution] → asset owners depend on model vendors for access to operational truth (informational leverage concentrates)
- (+) [Legal barriers] → insurers or regulators accept twin-derived evidence in maintenance and compliance (models gain institutional standing)
- (+) [3rd-order adoption] → teams rehearse interventions virtually before touching the site (remote governance becomes procedural)
- (+) [Labour structure] → local technicians shift toward exception handling and physical execution only (knowledge centralises remotely)
- (+) [Cross-organisational coordination] → suppliers and operators sync against the same live model (remote collaboration standardises)

## ART 12.093 – Global Supply Chain Traceability Networks

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Traceability networks let distant actors influence supply, compliance, and product flows through verified data rather than local inspection or paperwork alone. They strengthen remote auditing and market enforcement, but the main impact sits in selected sectors rather than the whole remote-

impact operating model. As provenance data becomes more live and machine-readable, commercial influence shifts toward whoever can see and certify flows in real time. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Efficiency] → remote audits replace some site visits and paper reconciliation (verified data substitutes presence)
- (+) [Safety and security] → recalls or incident responses identify affected batches faster (remote situational awareness improves)
- (+) [Cross-boundary coordination] → suppliers and buyers use the same history file in disputes (shared facts accelerate action)
- (-) [Power distribution] → dominant traceability hubs gain leverage over smaller suppliers (visibility becomes market power)
- (+) [Legal barriers] → customs, ESG, or product rules start requiring machine-readable provenance (traceability becomes compulsory infrastructure)
- (+) [3rd-order adoption] → remote compliance and sourcing decisions become continuous rather than episodic (flows become governable at distance)

## ART 12.094 – Personal Data Portability & Trust Frameworks

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Portable personal-data and trust frameworks make remote participation easier because users can prove identity, attributes, and permissions without repeated physical checks or bespoke integrations. They lower friction and strengthen user control in some contexts, but they also create new gatekeepers around wallets, schemas, and trust services. As portability grows, more services become credibly remote-first because onboarding and consent no longer depend on local paperwork. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Participation] → users grant time-bound data and credential access without repeated manual onboarding (remote entry gets easier)
- (+) [Location independence] → services accept portable proofs instead of local paperwork or branch visits (distance loses administrative penalty)
- (+) [Privacy] → selective disclosure becomes a visible procurement requirement (trust grows through less over-sharing)
- (-) [Safety and security] → wallet theft, recovery failures, or phishing become major governance topics (identity control is now digital infrastructure)

- (-) [Power distribution] → wallet providers and trust registries gain gatekeeper roles (user control depends on infrastructure choices)
- (+) [Legal barriers] → authorities recognise reusable digital proofs in remote services (rules accept portable trust)
- (+) [3rd-order adoption] → more services become remote-first once compliant onboarding is solved (administration stops forcing presence)
- (+) [Equality] → people with fragmented records enter formal remote systems more easily (identity portability widens inclusion)
- (+) [Efficiency] → support teams spend less time on document chasing and manual verification (transaction cost falls visibly)

## ART 12.095 – Interoperable Digital Currency Payment Networks

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Interoperable digital payments matter because remote influence increasingly rides on the ability to pay, reward, fine, subscribe, donate, and settle across distance with low friction. They widen participation in cross-border remote work and services, but they also lower barriers for scams, coercive microtransactions, and platform lock-in around payment rails. As payment interoperability improves, more interactions that still require local intermediaries become directly remote and programmable. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Participation] → remote workers and sellers receive funds across rails with fewer delays (distance stops blocking settlement)
- (+) [Location independence] → subscriptions, donations, micropayments, and fines work across borders more smoothly (economic influence gets programmable)
- (+) [Efficiency] → reconciliation and FX handling move into network rules (manual payment coordination declines)
- (-) [Safety and security] → scams, coercive billing, or fraudulent charge routing rise in oversight reports (remote abuse scales financially)
- (-) [Power distribution] → routing nodes and liquidity providers gain leverage over access and fees (new intermediaries become strategic)
- (+) [Legal barriers] → public and regulated sectors accept interoperable digital payments for remote services (formal adoption deepens)
- (+) [3rd-order adoption] → more interactions become instantly chargeable or rewardable online (business models shift remote-first)
- (+) [Regional equality] → peripheral workers join remote markets that were previously payment-fragile (participation becomes more viable)



- (+) [Accountability] → machine-readable payment trails are used in disputes over remote transactions (economic control becomes more inspectable)

## ART 12.096 – Machine-Readable Regulation (Rules as Code)

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Machine-readable regulation reduces one of this GVN's core inhibitors: rules that still assume physical presence, manual interpretation, or local paperwork. It makes remote compliance and automated decision-making easier to scale, while also concentrating influence in whoever writes and updates the executable rule logic. Once law becomes easier to query by software, many remote services move from 'exception' to 'standard process'. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Legal barriers] → agencies publish executable rules alongside prose guidance (software can act without manual interpretation)
- (+) [Efficiency] → remote-service providers update workflows quickly after rule changes (compliance lag shortens)
- (+) [Participation] → smaller actors use standard rule packages instead of hiring bespoke legal interpretation (entry costs fall)
- (-) [Power distribution] → whoever encodes and maintains rule logic gains quiet influence over implementation (governance moves into software layer)
- (-) [Safety and security] → edge cases and contestability disputes focus on coded interpretations (formalism meets real-world ambiguity)
- (+) [Physical presence norm] → requirements once tied to signatures, counters, or office visits are converted to digital checks (bureaucracy detaches from place)
- (+) [3rd-order adoption] → remote services expand once compliance becomes machine-routine (rules stop throttling scale)
- (+) [Auditability] → decision traces show which clauses were applied automatically (remote action becomes more legible)
- (+) [Coordination] → organisations align faster because they run the same encoded rules (shared interpretation reduces friction)

## ART 12.097 – Open Metaverse Interoperability Protocols

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Open metaverse protocols matter because they make immersive remote presence and shared virtual influence portable across platforms rather than trapped in closed worlds. They can widen

participation and reduce lock-in, but they also expand the volume of mediated social life that platforms and automated agents can shape. As identities, assets, and spaces interoperate, remote co-presence becomes more persistent and economically meaningful. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Participation] → users carry identity, inventory, and accessibility settings across immersive spaces (remote presence stops resetting)
- (+) [Location independence] → work, training, and events span multiple virtual environments without rebuilding tools (co-presence becomes portable)
- (+) [Ease and accessibility] → creators reuse assets and spaces across platforms (entry cost to remote worlds falls)
- (-) [Power distribution] → standard owners and gateway platforms still shape visibility and monetisation (interoperability does not remove hierarchy)
- (-) [Safety and security] → moderation, harassment, and impersonation problems follow users across spaces (risk becomes portable too)
- (+) [Legal barriers] → employers, schools, or agencies adopt interoperable immersive spaces for formal use (institutional trust rises)
- (+) [3rd-order adoption] → persistent remote communities and markets span many environments (virtual presence gains economic weight)
- (+) [Market formation] → services build once for many worlds rather than one silo (ecosystem thickens faster)
- (+) [Physical presence norm] → some collaboration and event categories stop defaulting to travel (shared virtuality changes expectations)

## ART 12.098 – Content Authenticity Infrastructure

Score: 10 (Impact in GVN 9)

Justification (3–5 sentences):

Authenticity infrastructure addresses an explicit fault line in this GVN: remote influence becomes more powerful and more dangerous when convincing media can be forged cheaply. Provenance tools reshape trust, moderation, journalism, compliance, and legal evidence, while also shifting power toward certified devices, platforms, and identity providers. If attribution becomes easier, some remote channels gain legitimacy and others lose reach, altering the balance between beneficial and manipulative remote influence. That is transformative in how the GVN is realised and can plausibly clear the >€1B / hundreds-of-thousands threshold, so 10 fits; 20 would require it to be indispensable across most remote-impact domains.

Weak signals (9):

- (+) [Safety and security] → browsers, apps, or newsroom tools surface provenance checks by default (verification becomes routine)

- (+) [Abuse of remote influence] → public institutions start filtering submissions or media by credential status (deepfake defence moves into operations)
- (+) [Legal barriers] → courts, regulators, or employers recognise signed provenance in evidence rules (trusted remote media gains standing)
- (-) [Power distribution] → certified devices, editing tools, and identity issuers gain authority over what counts as authentic (trust centralises technically)
- (-) [Evasion] → influence operators circulate content stripped of credentials to test platform policies (counter-adaptation becomes visible)
- (+) [Participation] → legitimate remote creators and witnesses gain credibility without physical co-presence (trust can travel digitally)
- (+) [Efficiency] → moderation teams triage high-volume content faster with provenance signals (attention burden decreases)
- (+) [3rd-order adoption] → organisations redesign workflows around 'credentialed-by-default' media inputs (remote communication regains procedural trust)
- (+) [Market structure] → procurement requires authenticity support in capture and publishing tools (credential infrastructure becomes baseline)

## ART 12.099 – Privacy-Preserving Collaboration Protocols

Score: 5 (Impact in GVN 9)

Justification (3–5 sentences):

Privacy-preserving collaboration lets separated organisations coordinate and learn from shared patterns without centralising all their sensitive data, which supports remote decision-making across boundaries. It lowers some trust barriers but raises dependence on specialised cryptographic infrastructure and governance. As secure collaboration gets easier, more remote services are built from pooled insight rather than siloed local judgement. The combined direct, institutional, and feedback effects plausibly land in the €100M–€1B or 50–500M person-hour range, so 5 is appropriate.

Weak signals (9):

- (+) [Cross-boundary coordination] → organisations compute shared indicators without centralising raw records (collaboration becomes politically possible)
- (+) [Privacy] → procurement and data-sharing agreements specify secure computation rather than manual redaction (machine-enforced trust rises)
- (+) [Efficiency] → approval cycles shorten because fewer bespoke data-transfer negotiations are needed (coordination friction falls)
- (-) [Power distribution] → specialised secure-compute providers gain leverage as neutral intermediaries (trust migrates to protocol operators)
- (+) [Legal barriers] → regulators accept privacy-preserving analytics in sensitive sectors (remote joint action gets formal cover)

- (+) [3rd-order adoption] → more remote services are based on pooled signals from many institutions (silo boundaries weaken operationally)
- (+) [Auditability] → logs show who queried what and under which privacy constraints (joint remote decisions become more inspectable)
- (+) [Participation] → smaller actors join collaborations without surrendering full data control (capability diffuses beyond incumbents)
- (-) [Security risk] → incident reports focus on implementation flaws and side-channel leakage (cryptographic trust still needs operations)

## **ART 12.100 – Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure**

Score: 3 (Impact in GVN 9)

Justification (3–5 sentences):

Certification and conformance infrastructure matter when remote influence depends on trusting distant machines, processes, and measurements without sending experts on site every time. It changes procurement, liability, insurance, and cross-site comparability, but mostly in industrial and regulated domains rather than mass everyday life. As remote assurance becomes standardised, more operations can be approved and supervised from afar. That reaches the material-impact anchor (~€10–100M or 5–50M person-hours) but not a full operating-model transformation, so 3 fits.

Weak signals (6):

Signal density: LOW (linkage bounded; additional signals would be speculative).

- (+) [Location independence] → engineers change recipes, diagnostics, or print jobs from off-site locations (production becomes software-mediated)
- (+) [Efficiency] → firms cut travel for troubleshooting, setup, or supplier coordination (remote intervention replaces visits)
- (+) [Participation] → smaller or regional plants access specialist expertise without co-locating it (capability spreads geographically)
- (-) [Power distribution] → whoever controls digital process files or simulation models gains leverage over local plants (control shifts upstream)
- (+) [Legal barriers] → auditors accept remote evidence packs for more production changes (onsite sign-off loses ground)
- (+) [3rd-order adoption] → factories move from episodic remote support to continuous remote optimisation (distance stops being exceptional)

## **GVN 10: Automation of Work ART Impact**

### **1. Sensing, Measurement & Connectivity**

## ART 01.001 - Global Broadband Connectivity

Score: 10 (Impact in GVN 10)

Justification: Mature ubiquitous broadband makes remote supervision, software updates, telemaintenance, and data-rich coordination of machines routine across urban and rural sites. First-order it expands where autonomous equipment can operate; second-order it concentrates power in connectivity/platform providers, enables tighter workforce surveillance, and supports robot-as-a-service and shared-machine markets; third-order it accelerates decentralized production and thinner local management layers. In a 5.5M-person society this can plausibly shift well above €1B of logistics, field-service, and production activity and affect weekly work patterns of hundreds of thousands, so it is transformative but not a unique linchpin.

Weak signals (9):

- (+) [Remote machine supervision] → [robot fleets managed from centralized control rooms] (cuts local expert travel)
- (+) [Shared-use machinery] → [robot-as-a-service contracts bundle connectivity by default] (broadens machine access)
- (+) [Rural/remote worksites] → [autonomous equipment tenders require satellite backhaul] (extends automation footprint)
- (+) [24/7 operations] → [night shifts run with off-site supervisors only] (supports continuous service)
- (+) [Decentralized production] → [microfactories connect to cloud MES without private fiber] (enables local manufacture)
- (+) [Skill gaps] → [remote maintenance centers close more tickets than field teams] (lowers local competence barrier)
- (–) [Security vulnerabilities] → [fleet ransomware incidents propagate via connectivity stacks] (exposes autonomy dependence)
- (–) [Job status/privacy] → [labor agreements contest constant task telemetry] (signals surveillance intensification)
- (–) [Market structure] → [telecom-platform bundles lock SMEs into one robot ecosystem] (concentrates bargaining power)

## ART 01.002 - Ultra-Low Latency Networks

Score: 5 (Impact in GVN 10)

Justification: Mature ultra-low-latency networks make real-time teleoperation fallback, synchronized fleet control, and time-critical cyber-physical coordination much more dependable. First-order they reduce the need to keep expertise physically co-located with machines; second-order they favor edge-cloud and telecom operators that can certify timing guarantees and create new liability boundaries around network performance; third-order they support remote service models in ports, hospitals, warehouses, and utilities. This fits the €100M–1B / 50–500M person-hour band, but a higher 10 would require safety-certified real-time automation far beyond specialized sites.

Weak signals (9):

- (+) [Teleoperation fallback] → [ports and mines certify millisecond remote-assist modes] (shrinks on-site staffing)
- (+) [Fine-grained control] → [robot cells move vision/control workloads to nearby edge nodes] (improves response stability)
- (+) [Shared autonomy] → [one operator handles more exception interventions per hour] (widens supervisory span)
- (+) [Safety] → [warehouse standards add network-latency thresholds for mobile robots] (makes timing auditable)
- (+) [Service automation] → [remote maintenance tasks enter routine operations] (expands real-time automation)
- (+) [Public-space autonomy] → [city permits cite bounded-latency service requirements] (normalizes networked robots)
- (–) [Infrastructure cost] → [SME automation projects stall outside edge-covered zones] (shows uneven access)
- (–) [Cyber-physical risk] → [latency spikes appear in near-miss reports] (links jitter to accidents)
- (–) [Power concentration] → [edge-cloud providers win exclusive industrial control contracts] (shifts control upstream)

## ART 01.003 - Edge AI for Sensor Data

Score: 20 (Impact in GVN 10)

Justification: Mature edge AI embeds situational judgment directly into machines, cameras, meters, and controllers, letting them react locally in messy, bandwidth-limited, privacy-sensitive environments without waiting for humans or clouds. First-order this is one of the clearest enablers of replacing human inspection, exception handling, and routine supervision; second-order it shifts expertise from workers into devices, changes liability toward model providers, and makes surveillance both easier and more politically defensible; third-order it drives a feedback loop in which cheaper, more autonomous equipment spreads into ever more sectors. In a 5.5M-person society this can plausibly move well above €1B annually and reshape weekly work for hundreds of thousands, making it a keystone technology for the challenger regime.

Weak signals (9):

- (+) [Human oversight bottleneck] → [machines close more anomalies locally without operator review] (embeds judgment on-site)
- (+) [Harsh environments] → [dust- and noise-tolerant edge vision retrofits spread beyond pilots] (widens feasible autonomy)
- (+) [24/7 service] → [facilities add unattended shifts after edge-AI upgrades] (turns uptime into substitution)
- (+) [Skill gaps] → [OEMs market “expert-in-the-box” controllers to SMEs] (reduces specialist dependence)
- (+) [Privacy protection] → [procurements require on-device processing for workplace sensing] (eases adoption resistance)
- (+) [Decentralized production] → [microfactories operate through connectivity outages without performance loss] (supports local autonomy)
- (–) [Liability] → [incident investigations hinge on local model logs and confidence scores] (forces new accountability rules)

- (–) [Market structure] → [robot vendors lock customers into proprietary model-update services] (concentrates control)
- (–) [Security/dual-use] → [tampered edge models cause physical misclassification events] (shows sabotage pathway)

## ART 01.004 - Quantum & High-Precision Sensing

Score: 3 (Impact in GVN 10)

Justification: Mature quantum and high-precision sensing improves autonomous inspection, navigation, and process control where conventional sensing is too coarse, sparse, or unreliable. Its strongest impact is in high-value niches—utilities, underground sites, critical manufacturing, and safety-heavy environments—where it can displace expert measurement trips and tighten autonomous tolerances; broader labor-market and ownership effects remain bounded. The likely impact sits in the €10M–100M band, and a higher 5 would require these sensors to become standard in everyday commercial automation rather than premium deployments.

Weak signals (7):

- (+) [Precision inspection] → [autonomous maintenance contracts specify quantum-grade detection thresholds] (replaces expert measurement trips)
- (+) [GNSS-denied autonomy] → [indoor and mining robots adopt cold-atom inertial modules] (extends autonomous navigation)
- (+) [Safety margins] → [plants narrow manual check intervals after continuous subtle sensing] (reduces inspection labor)
- (+) [Quality assurance] → [high-value manufacturers use quantum clocks in closed loops] (improves autonomous precision)
- (–) [Certification] → [insurers require calibration evidence before unmanned approvals] (shows governance dependence)
- (–) [Asset concentration] → [only premium sectors justify high-precision sensor retrofits] (keeps impact bounded)
- (–) [Security] → [tamper-detection clauses appear for precision sensor chains] (signals trust sensitivity)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 10)

Justification: Mature micro/nano sensor networks make dense, continuous awareness of machines, buildings, inventories, and work environments cheap enough to replace many periodic checks and manual walkthroughs. Second-order they shift value from hardware toward analytics and fleet management, enable tighter monitoring of workers, and support lower management layers through automatic threshold-based responses; third-order they reinforce predictive maintenance and unattended operation as the default. That is a significant GVN effect, though not enough on its own to count as a linchpin.

Weak signals (9):



- (+) [Sparse measurement bottleneck] → [facilities move from sample checks to full-surface monitoring] (supports unattended operation)
- (+) [Early fault detection] → [maintenance KPIs shift from failures to anomaly catches] (reduces emergency labor)
- (+) [Safety] → [hazardous sites authorize smaller on-site crews after dense sensing] (automation absorbs exposure)
- (+) [Shared machine access] → [leased equipment ships with disposable sensor skins] (simplifies multi-user monitoring)
- (+) [Lower hierarchies] → [frontline decisions trigger automatically from sensor thresholds] (reduces managerial mediation)
- (+) [Compliance] → [continuous-sensing evidence replaces parts of manual audits] (turns measurement into automation)
- (–) [Privacy] → [labor disputes cite sensor “specks” as covert monitoring] (tests social acceptability)
- (–) [Information bottleneck] → [edge-analytics vendors capture growing share of sensor spend] (shifts value from hardware)
- (–) [Waste/externalities] → [procurements add sensor recovery requirements] (signals material side effects)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

Score: 5 (Impact in GVN 10)

Justification: This ART directly addresses one of the GVN’s explicit inhibitors: privacy and social acceptability of machine observation in workplaces, services, and public-facing settings. First-order it unlocks automation where raw video, audio, or biometric capture would otherwise be blocked; second-order it changes compliance, labor relations, and audit models; third-order it allows pervasive sensing to spread into sectors that currently resist robotization. That makes it a strong enabler in the €100M–1B range, though not a keystone because privacy-safe sensing still needs capable autonomous systems behind it.

Weak signals (9):

- (+) [Acceptability] → [service-robot tenders require on-device redaction by default] (makes sensing politically viable)
- (+) [Privacy protection] → [works councils approve sensor rollouts with local-only processing clauses] (unblocks workplace automation)
- (+) [Regulation] → [compliance audits accept aggregated outputs instead of raw video] (lowers governance burden)
- (+) [Human-free monitoring] → [retail and health sites expand autonomous sensing after trust safeguards] (widens sensitive-sector use)
- (+) [Cross-border operations] → [multisite firms standardize privacy-preserving fleet analytics] (supports scale across jurisdictions)
- (–) [Opacity] → [operators complain raw evidence is unavailable after incidents] (shows accountability trade-off)
- (–) [Power asymmetry] → [platform vendors control privacy settings through closed dashboards] (centralizes governance power)
- (–) [Worker surveillance] → [productivity scoring survives despite anonymized raw feeds] (privacy does not end control)

- (+) [Insurance] → [insurers price lower cyber/privacy premiums for edge-private systems] (rewards safer automation)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

Score: 3 (Impact in GVN 10)

Justification: Quantum-resilient secure networking matters most where automated systems carry long-lived sensitive data or command high-consequence assets, such as utilities, ports, defense-adjacent logistics, and critical infrastructure. Its main effect on this GVN is second-order: it preserves trust in remote operation, machine coordination, and audit trails, while raising transition costs and vendor concentration risks; the direct labor-replacement effect is limited. The plausible impact is material but bounded, so 3 is more defensible than 5.

Weak signals (7):

- (+) [Critical automation] → [utilities and ports mandate post-quantum upgrades for robot control links] (extends trust in remote autonomy)
- (+) [Long-lived evidence] → [autonomous-system logs are re-encrypted during asset refreshes] (protects liability records)
- (+) [Machine identity] → [secure key rotation becomes standard in fleet management] (hardens autonomous coordination)
- (–) [Upgrade burden] → [legacy robot fleets miss tenders due to cryptography noncompliance] (reveals transition friction)
- (–) [Market structure] → [security-certified vendors gain gatekeeper status in automation stacks] (raises entry barriers)
- (–) [Operational risk] → [downgrade or spoofing attempts target command channels] (shows adversarial pressure)
- (+) [Insurance/compliance] → [cyber cover distinguishes PQ-secure autonomous assets] (prices integrity explicitly)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 - Integrated Sensing and Communication (ISAC)

Score: 5 (Impact in GVN 10)

Justification: ISAC turns communication infrastructure into a shared environmental awareness layer, lowering the sensing burden on each robot and making dense machine activity easier to coordinate. First-order it improves navigation, collision avoidance, and occupancy monitoring; second-order it reshapes facility retrofits, privacy disputes, and vendor lock-in; third-order it helps structured spaces become autonomy-native. The impact is significant, but it depends on adoption in specific environments rather than being a universal prerequisite.

Weak signals (9):

- (+) [Situational awareness] → [warehouses add communication nodes that also track motion zones] (combines connectivity and sensing)

- (+) [Safety] → [public-space robot permits accept network-based sensing redundancy] (reduces line-of-sight limits)
- (+) [Facility retrofits] → [new factories specify ISAC-ready ceilings and walls] (reshapes autonomy infrastructure)
- (+) [Lower machine cost] → [AGV vendors drop some standalone sensors in ISAC sites] (shifts burden to environment)
- (+) [Coordination] → [multi-robot fleets use shared radio maps for traffic management] (improves dense choreography)
- (+) [Shared spaces] → [landlords market autonomy-ready coverage as building amenity] (turns infrastructure into access gate)
- (-) [Privacy] → [occupancy-tracking complaints rise where comms gear doubles as sensor grid] (signals social resistance)
- (-) [Cybersecurity] → [spoofed-reflection attacks appear in red-team tests] (shows dual-use risk)
- (-) [Vendor power] → [single-network providers lock sites into proprietary control layers] (concentrates infrastructure control)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 10 (Impact in GVN 10)

Justification: Mature compute-in-memory and neuromorphic hardware makes always-on local perception and control cheap enough for mass deployment in robots, sensors, wearables, and embedded industrial systems. First-order this reduces the power, thermal, and latency costs that currently keep autonomy dependent on cloud links or expensive GPUs; second-order it shifts bargaining power toward chip/toolchain ecosystems and changes safety verification practices; third-order it expands autonomy into smaller firms and smaller devices. In aggregate that is transformative for how automation is realized, though not as singularly central as the AI and robotics stack itself.

Weak signals (9):

- (+) [Edge autonomy] → [robot controllers ship with in-memory accelerators by default] (cuts power and latency)
- (+) [24/7 operation] → [autonomous sensors stay active without cooling upgrades] (widens unattended deployment)
- (+) [SME adoption] → [low-power vision kits replace GPU boxes in small facilities] (lowers capex barrier)
- (+) [Battery-constrained machines] → [microdrones add local perception instead of cloud links] (expands mobile automation)
- (+) [Skill gaps] → [OEM toolchains hide chip complexity from integrators] (spreads use beyond experts)
- (+) [Privacy] → [on-device perception replaces raw-stream uploads] (eases data concerns)
- (-) [Vendor lock-in] → [robot software stacks optimize for one chip ecosystem] (concentrates ecosystem power)
- (-) [Verification] → [safety audits add tests for event-based inference] (governance catches up)

- (–) [Maintenance] → [field failures trace to analog drift or retraining mismatches] (shows reliability burden)

## ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

Score: 5 (Impact in GVN 10)

Justification: Better transistors beyond CMOS would diffuse through the automation stack by lowering heat, shrinking controllers, and making long-lived always-on electronics more practical at the edge. The direct effect is diffuse rather than visible, but second-order it lowers the cost floor for sensors, actuators, and autonomous devices while changing supply-chain and manufacturing power in semiconductors. That is significant for the GVN, but a higher 10 would require these devices to change deployment economics across most robot classes rather than improving them incrementally.

Weak signals (9):

- (+) [Always-on control] → [cheap machine controllers gain persistent local inference] (widens low-cost autonomy)
- (+) [Thermal limits] → [robot joints and sensor heads integrate more compute] (moves intelligence into hardware)
- (+) [Long-life electronics] → [industrial sensors advertise decade-scale unattended operation] (cuts service labor)
- (+) [Miniaturization] → [autonomy modules fit into tools and attachments] (spreads automation to smaller form factors)
- (+) [Capex barrier] → [SME-grade automation kits match prior premium performance] (broadens access)
- (+) [Embedded power efficiency] → [mobile robots increase runtime without larger batteries] (improves utilization)
- (–) [Supply concentration] → [few fabs control next-gen device volumes] (creates upstream dependence)
- (–) [Certification] → [safety-rated electronics standards are rewritten for new devices] (shows ecosystem transition)
- (–) [Reliability] → [integrators delay adoption over drift and durability questions] (keeps impact below transformative)

## ART 02.011 - Quantum Computing Platforms

Score: 1 (Impact in GVN 10)

Justification: Quantum computing could improve certain planning, optimization, and simulation tasks around automation, but the linkage to replacing human labor in mainstream work systems remains indirect. The main pathway is third-order—better logistics, scheduling, materials, and verification for a subset of high-value sectors—rather than direct deployment inside the GVN's core operating model. It is worth monitoring, but likely stays below the material-anchor range unless quantum routines become routine inside everyday automation software.

Weak signals (5):

- (+) [Planning bottlenecks] → [industrial software adds premium quantum-optimization modules] (would create direct workflow linkage)
- (+) [Robot scheduling] → [fleet platforms benchmark quantum solvers against dispatch teams] (tests substitution value)
- (+) [Materials for autonomy] → [robot OEMs cite quantum-discovered components in roadmaps] (links compute to hardware advances)
- (–) [Access inequality] → [only large firms can afford quantum-assisted automation tools] (keeps impact narrow)
- (–) [Operational integration] → [quantum outputs remain advisory rather than executable] (limits labor replacement)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

Score: 3 (Impact in GVN 10)

Justification: Photonic and optical computing mainly affects automation through heavier AI and data-movement workloads in control centers, edge servers, and high-end machines rather than direct labor substitution. It can materially lower latency, cooling, and bandwidth constraints in automation-heavy environments, but second-order labor and governance effects remain narrower than for AI software or robotics. The likely impact is material yet bounded, and a higher 5 would require broad rollout into ordinary edge and factory systems rather than data-center-centric use.

Weak signals (7):

- (+) [AI-heavy automation] → [vision-control servers shift to optical interconnects] (relieves data-movement bottlenecks)
- (+) [Thermal limits] → [control rooms shrink cooling footprints after optical upgrades] (cuts operating cost)
- (+) [Dense coordination] → [large robot sites adopt photonic backplanes for orchestration] (supports synchronized fleets)
- (+) [Edge performance] → [premium robot cells advertise optical accelerators] (moves tech toward deployment)
- (–) [Capital intensity] → [only large sites justify photonic retrofits] (keeps diffusion narrow)
- (–) [Integration burden] → [electro-optic conversion remains a project bottleneck] (limits full-stack gains)
- (–) [Vendor concentration] → [few suppliers dominate optical compute modules] (raises dependency risk)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

Score: 5 (Impact in GVN 10)

Justification: Better non-volatile memory and hierarchical storage helps autonomous systems keep more context, state, logs, and digital twin data near where work happens. First-order that reduces startup delays, data movement, and recovery times; second-order it strengthens auditability,

software rollback, and remote management while concentrating value in memory/controller ecosystems; third-order it makes large fleets and persistent local autonomy easier to operate safely. The impact is significant, though less decisive than perception, reasoning, or embodiment.

Weak signals (9):

- (+) [Persistent machine state] → [robots resume tasks after outages without manual reinitialization] (reduces downtime labor)
- (+) [Digital twins] → [asset controllers keep larger local histories by default] (supports autonomous diagnosis)
- (+) [Auditability] → [incident replay logs are retained on-device instead of centrally] (improves accountability)
- (+) [Remote sites] → [machines operate longer with delayed backhaul uploads] (widens off-grid autonomy)
- (+) [Maintenance] → [service teams use local state snapshots for fewer visits] (cuts troubleshooting travel)
- (+) [24/7 operations] → [reboot and recovery times fall sharply in automated lines] (improves utilization)
- (–) [Vendor lock-in] → [fleet software ties analytics to proprietary memory formats] (concentrates ecosystem power)
- (–) [Cyber risk] → [larger local data stores become new attack targets] (raises edge-security burden)
- (–) [Integration cost] → [legacy assets cannot exploit new memory tiers] (slows broad diffusion)

## ART 02.014 - Molecular Computing

Score: 0 (Impact in GVN 10)

Justification: Even in a mature state, molecular computing is far more likely to matter inside specialized biochemical or sensing contexts than across the mainstream robotics, machinery, and digital-control systems central to this GVN. There is no clear near-systemic pathway from this ART to broad replacement of human labor, or to the key second-order shifts in ownership, autonomy governance, or job structure described in the GVN. It only rises above 0 if molecular controllers become standard inside autonomous bioprocessing systems or smart materials used widely in work automation.

Weak signals (4):

- (+) [Bioprocess automation] → [molecular logic modules are sold as in-line controllers] (would create direct factory linkage)
- (+) [Harsh-environment sensing] → [chemical computers are used where electronics fail] (opens niche autonomous tasks)
- (+) [Robot materials] → [self-regulating coatings incorporate molecular logic] (moves control into materials)
- (–) [Standards and safety] → [industrial certification starts covering molecular controllers] (signals routinized deployment)

Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

Score: 10 (Impact in GVN 10)

Justification: Causal AI matters because replacing human labor in less-structured work depends on answering “what happens if I act” rather than only recognizing patterns. First-order it improves autonomous decision quality in planning, process control, and exception handling; second-order it makes machine decisions more auditable while shifting power to whoever owns the causal models and assumptions; third-order it widens automation into white-collar and supervisory domains that currently still rely on human judgment. That is transformative at society scale, though not as uniquely foundational as trusted autonomy and physical robots.

Weak signals (9):

- (+) [Human judgment bottleneck] → [automation vendors advertise counterfactual planning, not just prediction] (moves beyond pattern matching)
- (+) [Process tuning] → [plants let AI change setpoints within causal guardrails] (reduces operator intervention)
- (+) [Root-cause analysis] → [incident reviews cite machine-generated causal graphs] (makes actions auditable)
- (+) [White-collar automation] → [dispatch and procurement tools test “what-if” actions automatically] (replaces managerial analysis)
- (+) [Training] → [operators supervise goals and constraints, not rule trees] (reshapes skill mix)
- (+) [Performance] → [autonomous systems recover faster after process shifts] (proves intervention reasoning value)
- (–) [Liability] → [lawsuits challenge hidden assumptions in causal models] (shows confounder risk)
- (–) [Power asymmetry] → [platforms own causal models smaller firms cannot inspect] (concentrates decision power)
- (+) [Regulation] → [safety cases require intervention-effect evidence] (formalizes explainable autonomy)

#### ART 03.016 - Federated & Privacy-Preserving Learning

Score: 5 (Impact in GVN 10)

Justification: This ART eases a major automation bottleneck: useful training data are often fragmented across firms, sites, and devices that do not want to pool raw records. First-order it improves models for distributed machines and services; second-order it lowers legal and trust barriers, broadens SME access to shared models, and changes who controls model improvement; third-order it can accelerate cross-sector diffusion of automation without centralizing everything. That is significant, but not transformative unless shared learning becomes the default coordination layer for most automation ecosystems.

Weak signals (9):



- (+) [Fragmented data] → [multiple firms train shared maintenance models without centralizing logs] (unlocks pooled learning)
- (+) [SME access] → [small operators join federated robot-learning consortia] (reduces scale disadvantage)
- (+) [Privacy protection] → [works councils approve local-only model updates] (eases workplace data conflict)
- (+) [Multisite operations] → [fleet vendors advertise cross-site learning with no raw upload] (supports distributed automation)
- (+) [Sector coordination] → [industry bodies publish common federated benchmarks] (normalizes shared model improvement)
- (+) [Device personalization] → [assistive and service machines adapt locally but share updates] (keeps context near users)
- (–) [Model imbalance] → [remote or low-volume sites see poorer performance gains] (shows uneven benefit distribution)
- (–) [Governance] → [disputes arise over who owns federated model improvements] (tests bargaining power)
- (–) [Security] → [poisoned updates appear in fleet-learning incident reports] (shows new attack surface)

## ART 03.017 - Trustworthy AI Systems

Score: 20 (Impact in GVN 10)

Justification: Trustworthy AI is a direct answer to several explicit inhibitors in the GVN: safety fears, liability uncertainty, resistance to autonomous decisions, and the need for human oversight. First-order it makes high-stakes autonomous systems deployable; second-order it rewrites certification, insurance, labor agreements, and audit practices; third-order it allows automation to move from fenced, repetitive tasks into mainstream services, public spaces, and mixed human-machine work. Because broad automation is bottlenecked by trust, safety, and governance as much as by raw capability, this is a keystone 20.

Weak signals (9):

- (+) [Safety] → [insurers require certified fallback modes in autonomous fleets] (ties trust to deployment)
- (+) [Auditability] → [procurements demand model lineage and incident replay] (makes autonomy contractable)
- (+) [Human oversight] → [one supervisor covers more machines under assurance dashboards] (widens span of control)
- (+) [Regulatory barriers] → [approvals shift from pilots to standing licenses] (signals institutional trust)
- (+) [Worker acceptance] → [union deals trade redeployment for transparent escalation rules] (reduces resistance)
- (+) [24/7 service] → [unattended operations expand beyond fenced sites] (trust unlocks scale)
- (–) [Liability] → [courts treat missing monitoring traces as negligence] (hardens accountability)
- (–) [Cybersecurity] → [red-team certification becomes mandatory for autonomy vendors] (reflects adversarial exposure)

- (–) [Market structure] → [few assurance-certified AI vendors dominate tenders] (raises concentration risk)

## ART 03.018 - Automated Machine Learning (AutoML)

Score: 10 (Impact in GVN 10)

Justification: AutoML reduces a major labor and skill bottleneck around automation itself: the scarcity of people who can build, tune, maintain, and document models and agents. First-order it speeds deployment of predictive and control systems; second-order it shifts model-building power toward platforms and away from specialists, while also making unsafe or biased automation easier to scale if guardrails are weak; third-order it accelerates diffusion into SMEs and service sectors. That is transformative for the operating model, though the core machine intelligence still comes from broader AI and robotics stacks.

Weak signals (9):

- (+) [Skill gaps] → [non-ML teams deploy production models through guided platforms] (widens deployer base)
- (+) [Experiment cycle] → [automation pilots move from months to weeks] (speeds iteration)
- (+) [SME adoption] → [robotics integrators sell prebuilt AutoML pipelines] (lowers expertise threshold)
- (+) [Maintenance] → [model rollback and retraining become standard managed services] (reduces specialist burden)
- (+) [Agent creation] → [firms generate task-specific decision agents from logs] (automates software creation)
- (+) [Documentation] → [platforms auto-produce compliance and model cards] (makes scaling easier)
- (–) [Unsafe optimization] → [reward-design failures trigger costly field behavior incidents] (shows governance dependence)
- (–) [Platform power] → [few AutoML vendors dominate industrial AI stacks] (concentrates capability control)
- (–) [Labor effects] → [demand shifts from data scientists to governance reviewers] (reshapes expert roles)

## ART 03.019 - Collaborative Multi-Agent AI

Score: 20 (Impact in GVN 10)

Justification: Collaborative multi-agent AI is one of the clearest realizations of the challenger regime: many machines and software agents coordinating work without constant human micromanagement. First-order it replaces dispatchers, schedulers, supervisors, and some frontline labor by letting fleets allocate tasks, share maps, and maintain coverage; second-order it changes management hierarchies, bargaining power, and accountability for failures; third-order it enables pooled machine ecosystems and dense autonomous activity across sites. Because scalable automation of work increasingly depends on coordinated swarms and software societies rather than isolated robots, this is a keystone 20.

Weak signals (9):

- (+) [Distributed tasks] → [fleets auto-allocate work without dispatcher micromanagement] (flattens operational hierarchy)
- (+) [Resilience] → [sites keep operating after individual robot failures] (coordination beats single-point dependence)
- (+) [Labor substitution] → [one supervisor oversees mixed fleets across multiple sites] (scales machine labor)
- (+) [Shared assets] → [industrial parks schedule robots across tenants] (enables pooling models)
- (+) [Facility design] → [traffic and storage rules become software-defined] (spaces adapt to agents)
- (+) [24/7 service] → [night operations rely on autonomous coordination, not shift leads] (replaces managerial labor)
- (–) [Governance] → [disputes arise over which agent caused cascading losses] (tests accountability)
- (–) [Cybersecurity] → [swarm-behavior tampering enters threat models] (shows systemic attack surface)
- (–) [Power concentration] → [fleet-orchestration platforms capture more value than hardware] (shifts market control)

## ART 03.020 - Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 10)

Justification: Quantum-accelerated AI could eventually improve a subset of very hard planning or search problems, but its pathway into everyday automation remains indirect and narrow. The most plausible impact is on high-end optimization services rather than on the broad replacement of human labor that defines this GVN. It is worth tracking, but likely remains below the material-anchor range unless quantum routines become commonplace inside mainstream automation platforms.

Weak signals (5):

- (+) [Planning bottlenecks] → [AI vendors advertise quantum-assisted dispatch modules] (would create operational linkage)
- (+) [Combinatorial tasks] → [large logistics sites benchmark quantum solvers in live routing] (tests practical advantage)
- (+) [Premium automation stacks] → [cloud robotics contracts include quantum optimization add-ons] (signals market entry)
- (–) [Access inequality] → [only top-tier firms can afford quantum-assisted tools] (keeps impact narrow)
- (–) [Workflow fit] → [quantum outputs remain advisory rather than executable] (limits labor substitution)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

Score: 3 (Impact in GVN 10)

Justification: This ART affects the GVN mainly through a third-order feedback loop: it can speed the development of better robots, materials, controls, and process recipes that then automate work more effectively. First-order impact on actual work automation is limited, but second-order it can concentrate innovation power and compress R&D cycles, helping automation leaders pull away. That is material at society level, but a higher 5 would require autonomous discovery systems to become a dominant driver of deployable automation solutions rather than a specialized R&D accelerator.

Weak signals (7):

- (+) [Innovation cycle] → [robot firms shorten hardware iteration loops with AI-led design] (speeds capability improvement)
- (+) [Process automation] → [plants adopt AI-discovered operating recipes with minimal human tuning] (reduces engineering labor)
- (+) [Materials bottlenecks] → [automation OEMs cite AI-found actuator or battery materials] (links discovery to deployment)
- (+) [R&D staffing] → [research teams shift from manual screening to AI-supervised labs] (changes innovation labor mix)
- (–) [Knowledge concentration] → [few firms control discovery platforms and resulting IP] (deepens asymmetry)
- (–) [Verification burden] → [regulators demand extra validation for AI-generated design steps] (slows diffusion)
- (+) [Open innovation] → [shared challenge platforms accept AI-generated solutions routinely] (shows normalisation)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

Score: 5 (Impact in GVN 10)

Justification: Immersive AR/VR does not replace labor as directly as robots or AI, but it materially changes how automation is deployed, supervised, and learned. First-order it reduces expert travel, eases teleoperation fallback, and accelerates training; second-order it supports remote concentration of expertise and tighter monitoring of frontline work; third-order it helps decentralized production and service automation spread beyond places with local specialists. That places it in the significant band, but not the transformative band unless remote embodied work becomes routine across many sectors.

Weak signals (9):

- (+) [Remote expertise] → [maintenance centers resolve more faults through first-person AR support] (cuts travel and downtime)
- (+) [Training bottlenecks] → [robot technician training hours shift from classrooms to simulators] (scales skill formation)
- (+) [Teleoperation fallback] → [hazardous sites keep fewer specialists on location] (supports thin local staffing)

- (+) [Digital twins] → [AR overlays become standard in commissioning and reconfiguration] (tightens design-to-operation loop)
- (+) [Service automation] → [field workers supervise more machines per person via immersive dashboards] (widens span of control)
- (+) [Decentralized production] → [small sites buy remote expert subscriptions instead of resident engineers] (lowers competence threshold)
- (–) [Deskilling] → [operators follow overlays without deep process understanding] (shifts expertise upstream)
- (–) [Privacy] → [labor agreements limit always-on first-person capture] (shows surveillance resistance)
- (–) [Vendor lock-in] → [OEMs tie service procedures to proprietary immersive platforms] (concentrates control)

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 1 (Impact in GVN 10)

Justification: BCIs could improve teleoperation, accessibility, and high-bandwidth control in a few work settings, but they are far more complementary to human labor than central to replacing it. Their strongest GVN pathway is niche: enabling some workers to operate machines more effectively at a distance or despite physical limits. That is concrete enough to watch, but too bounded to reach the material anchor without much broader adoption than seems plausible here.

Weak signals (5):

- (+) [Teleoperation] → [hazardous-task pilots test neural control for remote manipulators] (would widen operator bandwidth)
- (+) [Labor inclusion] → [disabled operators manage machines through BCI interfaces] (expands supervisory workforce)
- (+) [Skill transfer] → [premium control rooms add BCI options for high-cognitive-load tasks] (tests productivity gains)
- (–) [Acceptability] → [unions demand strict limits on neural data use] (shows privacy barrier)
- (–) [Cost concentration] → [BCI control remains confined to elite applications] (keeps impact narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 3 (Impact in GVN 10)

Justification: Exoskeletons and advanced prosthetics mainly augment rather than replace human labor, so their largest effect is second-order: they can delay automation in some tasks by making human work cheaper, safer, or more feasible. At the same time they can extend participation, reduce injuries, and change the boundary between what is mechanized and what is still done by people. The impact is material but bounded, and a higher 5 would require augmentation to systematically reshape automation economics across major sectors.

Weak signals (7):

- (+) [Physical strain] → [warehouses and care facilities adopt exosuits before full robotization] (changes substitution timing)
- (+) [Injury risk] → [worker-comp premiums fall for assisted manual handling roles] (prices augmentation value)
- (+) [Labor inclusion] → [firms recruit workers with mobility limits into assisted roles] (extends participation)
- (+) [Task boundary] → [automation plans postpone robot investment after exoskeleton trials] (shows complement-vs-substitute effect)
- (–) [Professional identity] → [workers resist being “mechanized” without pay changes] (tests acceptability)
- (–) [Market structure] → [assistive gear is leased with proprietary analytics services] (shifts control to vendors)
- (–) [Privacy] → [fatigue and posture telemetry becomes a labor dispute topic] (surveillance follows augmentation)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 3 (Impact in GVN 10)

Justification: Rich haptics improves remote manipulation and human-in-the-loop automation in tasks where visual control alone is too crude, such as delicate maintenance, care, or hazardous handling. That can reduce local staffing and increase the reliability of partial automation, but it does not by itself create autonomous work systems. The effect is material in some sectors, and a higher 5 would require teleoperation-enhanced workflows to become a dominant bridge technology across many occupations.

Weak signals (7):

- (+) [Telemanipulation] → [remote handling error rates fall after haptic retrofits] (makes remote work credible)
- (+) [Hazard reduction] → [sites replace local intervention teams with remote operators] (moves labor off-site)
- (+) [Quality control] → [delicate service tasks are newly automated or teleoperated] (widens task envelope)
- (+) [Training] → [simulators add touch-rich task certification] (formalizes mediated skill)
- (–) [System cost] → [only high-value tasks justify multi-sensory kits] (keeps diffusion bounded)
- (–) [Reliability] → [feedback lag or drift appears in incident reports] (shows control fragility)
- (–) [Deskilling] → [local craft knowledge is replaced by platformized remote scripts] (shifts power upstream)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 10 (Impact in GVN 10)

Justification: This ART is highly relevant because replacing human labor increasingly depends on handling ambiguous, social, and contextual work rather than only repetitive routines. First-order it lets machines infer user needs, timing, and acceptable action in services, teamwork, and mixed human-machine environments; second-order it intensifies privacy risks and manipulative management while broadening access for some users; third-order it opens entire new classes of service and coordination work to automation. That is transformative, though not keystone because many automation gains remain possible without deep social-context inference.

Weak signals (9):

- (+) [Service automation] → [frontline bots handle unscripted requests with fewer escalations] (moves beyond rigid workflows)
- (+) [Mixed environments] → [robot fleets adapt speed and behavior to human cues] (improves coexistence)
- (+) [Cognitive load] → [tools change interface mode automatically by operator state] (reduces manual coordination burden)
- (+) [Accessibility] → [machines tailor interaction for different communication styles] (widens usable automation)
- (+) [White-collar work] → [meeting, dispatch, and support tools infer intent without explicit commands] (replaces clerical mediation)
- (–) [Surveillance] → [employer systems score affect and attention during work] (expands behavioral monitoring)
- (–) [Manipulation] → [customer-service AI is accused of steering vulnerable users] (tests social legitimacy)
- (–) [Bias] → [regulators investigate misread intent across demographic groups] (shows fairness risk)
- (+) [Procurement] → [service contracts require human-context performance metrics] (signals mainstreaming)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 0 (Impact in GVN 10)

Justification: Even in a mature state, brain-to-brain interfaces sit too far from the GVN's core machine, factory, and autonomous-service logic to justify a meaningful systemic score. Their plausible pathways are niche communication or coordination enhancements, not broad labor substitution or the main institutional shifts described in the GVN. It only rises above 0 if BBIs become a practical medium for operating or coordinating machines at scale.

Weak signals (4):

- (+) [Tacit coordination] → [remote-operation labs test BBI links for team control] (would create work-automation linkage)
- (+) [Skill transfer] → [high-risk domains trial neural cue sharing between operators] (tests coordination value)



- (–) [Ethics/governance] → [workplace rules begin covering neural sharing at work] (signals institutional entry)
- (–) [Practicality] → [BBI stays confined to experimental or therapeutic use] (keeps linkage weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

Score: 1 (Impact in GVN 10)

Justification: Memory prostheses mainly improve human capability rather than replacing labor, so their largest effects on this GVN are indirect. They could extend the working life of skilled operators, reduce certain error types, and alter training or supervision patterns, but they do not strongly change the operating model of autonomous machines. That is concrete but limited.

Weak signals (5):

- (+) [Skill retention] → [high-reliability roles test implant-assisted recall support] (could reduce retraining burden)
- (+) [Supervision] → [operators with memory aids manage more complex exception queues] (extends human oversight)
- (+) [Workforce aging] → [firms use memory aids to retain expert staff longer] (may delay substitution)
- (–) [Inequality] → [enhanced supervisors command premium control-room roles] (reshapes labor hierarchy)
- (–) [Acceptability] → [labor law debates whether neural memory support counts as monitoring] (signals governance friction)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

Score: 10 (Impact in GVN 10)

Justification: Self-driving vehicles directly substitute for driving labor and also alter scheduling, asset utilization, maintenance, and service availability across logistics, transit, and mobile service sectors. Second-order effects include job displacement, insurance redesign, curb and depot redesign, and concentration of value in fleet software and remote operations centers; third-order effects spill into land use, delivery expectations, and 24/7 mobility services. In a 5.5M society this can clearly exceed the transformative anchor, but it is not the sole linchpin of automation across all work.

Weak signals (9):

- (+) [Driver substitution] → [freight contracts shift from per-driver to per-vehicle uptime pricing] (replaces labor cost basis)

- (+) [24/7 service] → [depots schedule overnight driverless runs routinely] (raises asset utilization)
- (+) [Remote supervision] → [one control room oversees fleets across multiple regions] (widens supervisory span)
- (+) [Facility redesign] → [depots add no-driver staging, fueling, and maintenance layouts] (reshapes logistics sites)
- (+) [Local service labor] → [municipal shuttles and maintenance vehicles run without onboard staff] (spreads beyond freight)
- (–) [Job disruption] → [collective bargaining focuses on redeployment and remote-operator roles] (shows labor-market shock)
- (–) [Liability] → [insurers create distinct no-driver risk classes] (formalizes governance shift)
- (–) [Security] → [hijack or spoofing drills become part of fleet audits] (shows cyber-physical risk)
- (–) [Tax base] → [transport tax and licensing models are revised for driverless fleets] (signals systemic fiscal effects)

## ART 05.030 - Drone Swarms & Aerial Robots

Score: 10 (Impact in GVN 10)

Justification: Coordinated aerial robots can replace or thin human labor in inspection, mapping, monitoring, inventory, security, and some delivery functions across large or hazardous spaces. Second-order effects include new airspace governance, remote concentration of expertise, new surveillance conflicts, and misuse/security pathways; third-order they enable persistent machine presence where human attention is scarce. That is transformative at society scale, though still bounded by airspace and weather compared with more general labor-automation technologies.

Weak signals (9):

- (+) [Hazard reduction] → [utilities replace rope-access inspections with autonomous aerial swarms] (removes dangerous field labor)
- (+) [Coverage] → [large sites move from periodic flyovers to continuous aerial monitoring] (supports persistent machine presence)
- (+) [Remote expertise] → [one operator supervises multiple missions across sites] (widens control span)
- (+) [24/7 response] → [nighttime inventory and perimeter checks become routine] (extends service availability)
- (+) [Data-rich maintenance] → [repair work is dispatched from drone-generated anomaly maps] (replaces manual patrols)
- (–) [Airspace governance] → [BVLOS permits shift from pilots to standing operational licenses] (signals institutional normalization)
- (–) [Privacy] → [community complaints rise over persistent workplace or neighborhood overflight] (tests acceptability)
- (–) [Security/dual-use] → [anti-drone defenses become standard around automated sites] (reflects misuse risk)
- (–) [Market structure] → [few swarm-software vendors dominate inspection contracts] (concentrates control)

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 20 (Impact in GVN 10)

Justification: This is the most direct embodiment of the GVN's goal: machines that can work in human-designed spaces and use human tools without constant redesign of the environment. First-order they can replace labor across logistics, cleaning, retail backrooms, light manufacturing, maintenance, and some care/support tasks; second-order they reshape labor contracts, professional identity, and ownership models while intensifying liability and safety governance; third-order they make shared machine labor markets and flatter organizational structures much more plausible. Because they drastically increase the reach of the challenger regime across multiple sectors, they are a keystone 20.

Weak signals (9):

- (+) [Labor substitution] → [firms procure humanoids for routine multistep tasks, not just demos] (signals real task replacement)
- (+) [Human-designed environments] → [robots use existing tools and doors without site redesign] (proves general-purpose fit)
- (+) [24/7 service] → [night shifts in warehouses and facilities become robot-heavy] (expands nonhuman labor hours)
- (+) [Shared access] → [general-purpose robots are leased by task-hour to SMEs] (broadens adoption base)
- (+) [Lower hierarchies] → [one remote supervisor manages mixed-site robot crews] (replaces local coordination labor)
- (−) [Job disruption] → [union negotiations focus on minimum staffing and retraining guarantees] (shows broad displacement pressure)
- (−) [Safety/liability] → [incident rules differentiate contact-force and autonomy-fault cases] (hardens accountability)
- (−) [Market structure] → [few platforms control behavior libraries and updates] (concentrates upstream power)
- (−) [Professional identity] → [service roles resist replacement in human-facing settings] (tests social legitimacy)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 10 (Impact in GVN 10)

Justification: Soft and bio-inspired robots unlock automation in spaces where rigid machines are too dangerous, clumsy, or inflexible, especially around fragile goods, cluttered environments, and close human contact. First-order that expands the reachable task set; second-order it changes safety, hygiene, and maintenance regimes and may reduce repetitive strain work without fully removing human roles; third-order it helps automation spread into care, food handling, and variable-object logistics. This is transformative for the breadth of automation, though not as economy-wide a linchpin as general-purpose humanoids.

Weak signals (9):

- (+) [Fragile-object handling] → [food and pharma lines replace manual picking with compliant grippers] (opens formerly hard tasks)
- (+) [Human-close work] → [care and hospitality pilots use soft assistants beyond demos] (widens service automation)
- (+) [Safety] → [procurements specify compliant contact-rated manipulators] (reduces human-machine collision risk)
- (+) [Variable environments] → [robots handle mixed parcels and irregular goods without custom fixtures] (cuts setup labor)
- (+) [Strain reduction] → [injury-heavy manual tasks shift to soft robotic aids] (substitutes repetitive labor)
- (–) [Durability] → [wear and material fatigue dominate service logs] (shows maintenance constraint)
- (–) [Certification] → [new hygiene and contact standards emerge for soft actuators] (governance catches up)
- (–) [Vendor control] → [motion libraries become proprietary subscription assets] (shifts value upstream)
- (–) [Role displacement] → [labor agreements target “safe but deskilling” robot deployments] (signals social tension)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 10 (Impact in GVN 10)

Justification: Long-endurance autonomous platforms directly replace human presence in remote, hazardous, or inaccessible work, which is central to the GVN’s efficiency and danger-reduction values. Second-order they centralize expertise, reduce travel and assembly of specialist teams, and raise governance issues around unattended operation, liability, and dual use; third-order they make continuous machine presence normal in sectors that today rely on periodic human intervention. That is transformative, though less universal than general-purpose robots in everyday indoor labor.

Weak signals (9):

- (+) [Hazardous work] → [inspection contracts shift from crew-days to autonomous mission hours] (replaces field presence)
- (+) [Continuous monitoring] → [sites move from scheduled visits to persistent robotic coverage] (changes operating model)
- (+) [Remote expertise] → [control centers handle air, ground, and underwater assets together] (concentrates supervision)
- (+) [Travel reduction] → [maintenance budgets reallocate from mobilization to autonomous uptime] (cuts human deployment cost)
- (+) [Precision/repeatability] → [regulators accept autonomous survey data for compliance filings] (normalizes machine evidence)
- (–) [Security/dual-use] → [counter-autonomy defenses appear around critical sites] (shows misuse risk)
- (–) [Liability] → [operators are held responsible for delayed intervention during edge cases] (tests accountability model)
- (–) [Infrastructure dependence] → [missions fail after communication or localization outages] (reveals support fragility)
- (–) [Market structure] → [few mission-software vendors dominate rugged autonomy contracts] (concentrates ecosystem control)

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 20 (Impact in GVN 10)

Justification: This ART can make automation economically viable at scale by moving complexity out of each machine and into buildings, streets, depots, and public spaces. First-order it lowers the cost and competence requirements for robot deployment; second-order it rewrites property, access, and standards politics because infrastructure owners gain control over machine participation; third-order it creates self-reinforcing autonomy-native zones where machine labor outcompetes human labor more rapidly. Because it drastically increases the reach and affordability of the automation regime, it is a keystone 20.

Weak signals (9):

- (+) [Facility redesign] → [new buildings include robot docks, markers, and service lanes] (bakes autonomy into space)
- (+) [Lower robot cost] → [simple machines outperform expensive models in instrumented sites] (moves burden into infrastructure)
- (+) [Shared use] → [multi-tenant sites offer autonomy-ready access as paid amenity] (enables pooled fleets)
- (+) [24/7 operations] → [infra-managed traffic rules allow dense night robot activity] (supports round-the-clock machine work)
- (+) [Regulatory barriers] → [building and public-space codes add autonomy-readiness classes] (institutionalizes the shift)
- (–) [Access inequality] → [small firms are excluded from vendor-specific autonomy zones] (turns infrastructure into gatekeeper)
- (–) [Market structure] → [facility owners capture more value than robot operators] (shifts bargaining power)
- (–) [Safety/accountability] → [incident reports blame rule-conflicts between robots and site infrastructure] (shows layered liability)
- (–) [Professional identity] → [service workers lose discretion inside tightly choreographed spaces] (reduces human autonomy)

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

Score: 3 (Impact in GVN 10)

Justification: Power beaming directly addresses endurance constraints for some robotic tasks, but mainly in line-of-sight, infrastructure-rich, or remote-hazard contexts. It can reduce servicing labor and extend persistent monitoring, yet its deployment pattern is narrow and heavily governed by safety rules. The impact is material in specific sectors, but a higher score would require broad use across ordinary logistics and service automation.

Weak signals (7):

- (+) [Mission duration] → [remote sites install beam towers to keep robots aloft or active] (cuts battery-swap labor)

- (+) [Hazard reduction] → [inspection missions run for weeks without human servicing visits] (extends unattended presence)
- (+) [Infrastructure model] → [energy-as-a-service contracts bundle beaming with robotic patrols] (creates new access pathway)
- (+) [Response time] → [facilities keep persistent airborne sentries rather than on-call crews] (changes coverage economics)
- (–) [Safety governance] → [radiation exclusion rules are written into site permits] (reveals deployment constraints)
- (–) [Weather dependence] → [downtime clusters around fog and occlusion events] (keeps impact bounded)
- (–) [Vendor concentration] → [few tower-network providers control robotic endurance infrastructure] (shifts power upstream)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Score: 3 (Impact in GVN 10)

Justification: Dry-adhesion systems matter where automation is limited by working at height, on smooth surfaces, or in delicate attachment/detachment tasks. They can reduce specialized access labor and enable new mobile-maintenance niches, but the effect is narrower than broader robotics advances. The likely impact is material but bounded.

Weak signals (7):

- (+) [Work at height] → [building and vessel inspections shift from rope crews to climbing robots] (replaces risky access labor)
- (+) [Delicate surfaces] → [maintenance tenders prohibit drilling or suction but allow dry-adhesion tools] (opens new robot tasks)
- (+) [Repeat attachment cycles] → [clean-room and glass handling lines adopt adhesive grippers] (reduces manual repositioning)
- (+) [Remote maintenance] → [asset owners buy wall-climbing robot services instead of scaffolding] (changes cost structure)
- (–) [Surface limitations] → [dust and roughness dominate failure reports] (keeps deployment niche)
- (–) [Consumable burden] → [pad cleaning and replacement become major service item] (limits labor savings)
- (–) [Safety] → [insurers require dual-fall-protection for climbing robots] (shows trust barrier)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 5 (Impact in GVN 10)

Justification: Mature multi-material additive manufacturing reduces assembly steps, supplier coordination, and specialized manual integration by producing more functional parts in one pass. Second-order it supports local, small-batch, and customized production, shifts value toward digital design and feedstock control, and can weaken traditional economies of scale; third-order it reinforces decentralized automation. That is a significant fit with the GVN's challenger regime, though not broad enough to be a linchpin.

Weak signals (9):

- (+) [Assembly labor] → [parts are procured as single printed assemblies instead of multi-supplier kits] (cuts joining work)
- (+) [Customization] → [SME factories run profitable short batches with minimal setup] (supports flexible automation)
- (+) [Local production] → [critical spares are printed near point of use] (reduces logistics dependence)
- (+) [Skill mix] → [process engineers replace some manual assembly roles] (moves value to digital design)
- (+) [24/7 production] → [printers run unattended overnight with in-line monitoring] (extends machine labor hours)
- (+) [Shared access] → [regional print hubs serve multiple firms through digital queues] (broadens machine access)
- (–) [Certification] → [buyers demand material-trace and print-parameter evidence] (governance hardens)
- (–) [IP/power] → [OEMs restrict printable design files to licensed ecosystems] (concentrates control)
- (–) [Waste/externalities] → [rejected multimaterial prints dominate early scrap analysis] (shows hidden costs)

## ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 10 (Impact in GVN 10)

Justification: Digital twins are central to the challenger regime's emphasis on flexible, data-rich, lower-hierarchy production. First-order they reduce downtime, speed changeovers, and let machines be optimized remotely; second-order they shift expertise into models and vendors, alter accountability, and reduce the need for on-site trial-and-error; third-order they make decentralized, continuously adjusted production more viable. That is a transformative change in how automation is realized.

Weak signals (9):

- (+) [Downtime reduction] → [plants require live twins for critical assets in procurement] (makes model-based control normal)
- (+) [Remote expertise] → [commissioning and tuning are done off-site through twins] (cuts travel and local staffing)
- (+) [Changeovers] → [new product variants are rehearsed in simulation before line edits] (shrinks reconfiguration risk)
- (+) [Lower hierarchies] → [operators act on model recommendations instead of managerial escalation] (shifts authority into software)



- (+) [Decentralized production] → [small sites rely on central twin teams rather than resident specialists] (lowers competence barrier)
- (+) [Predictive maintenance] → [service contracts guarantee outcomes based on twin diagnostics] (turns expertise into platform service)
- (–) [Liability] → [disputes hinge on whether model drift was disclosed] (tests accountability)
- (–) [Vendor power] → [twin platforms become mandatory gateways for machine updates] (concentrates ecosystem control)
- (–) [Cyber risk] → [model tampering is treated as operational sabotage] (raises security stakes)

## ART 06.039 - Reconfigurable & Agile Factories

Score: 10 (Impact in GVN 10)

Justification: Reconfigurable factories map directly onto the GVN's challenger vision of smaller batches, customized output, reduced hierarchy, and decentralized production. First-order they lower setup labor and make automated production viable in more product categories; second-order they shift value into modular equipment ecosystems and digital recipes while reducing the need for deeply specialized line-specific staff; third-order they shorten the path from design intent to physical output. That is transformative, though not the single key linchpin of the wider automation regime.

Weak signals (9):

- (+) [Setup costs] → [changeovers drop from days to hours or minutes] (makes small-batch automation economical)
- (+) [Flexible output] → [plants switch between product families without major rebuilds] (supports volatile demand)
- (+) [Local production] → [regional microfactories win work previously sent to mass plants] (decentralizes manufacturing)
- (+) [Skill gaps] → [operators load digital recipes instead of manual line retuning] (lowers competence threshold)
- (+) [Capacity fluidity] → [modular cells are leased across sites as demand shifts] (turns machines into shared assets)
- (+) [24/7 service] → [reconfiguration occurs during unattended night windows] (extends machine utilization)
- (–) [Cybersecurity] → [misconfigured recipes cause cross-line disruptions] (shows software dependence)
- (–) [Market structure] → [module vendors lock firms into proprietary interfaces] (concentrates power)
- (–) [Labor disruption] → [specialist line-setup roles shrink sharply] (signals occupational displacement)

## ART 06.040 - Circular & Sustainable Manufacturing

Score: 3 (Impact in GVN 10)

Justification: Circular manufacturing affects the GVN through more automated sorting, qualifying, and reprocessing of materials rather than through direct broad labor replacement. It can reduce disposal and handling labor, create new automated material flows, and shift market power toward traceability and feedstock qualification platforms. The effect is real but bounded; a higher 5 would require circular systems to become a major driver of automated local production across many sectors.

Weak signals (7):

- (+) [Waste handling] → [sorting and requalification lines replace manual salvage processes] (automates material recovery)
- (+) [Local feedstocks] → [microfactories use recycled streams with automated recipe adjustment] (supports decentralized production)
- (+) [Traceability] → [buyers require digital material passports for remanufactured parts] (normalizes data-rich circular flows)
- (+) [Labor mix] → [manual disassembly roles shrink as robotic sorting scales] (changes recycling work)
- (–) [Contamination risk] → [feedstock-quality failures dominate reprocessing incident logs] (shows technical fragility)
- (–) [Certification burden] → [recycled-content claims need automated proof systems] (adds governance cost)
- (–) [Economics] → [capital approval stalls outside high-throughput regions] (keeps impact bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.041 - Bio-fabrication technologies

Score: 1 (Impact in GVN 10)

Justification: Bio-fabrication can automate specialized biological production, but its direct relationship to the broader automation-of-work GVN is narrow and sector specific. The main effect would be concentrated in biotech manufacturing and lab operations rather than across general machinery, logistics, or services. It is worth tracking, but the plausible impact remains limited.

Weak signals (5):

- (+) [Lab labor] → [tissue-production lines run with fewer manual handling steps] (would create direct automation effect)
- (+) [Remote operation] → [biofabrication suites shift to dashboard-based supervision] (moves work off the bench)
- (+) [Quality control] → [in-line sensing replaces manual microscopy checks] (automates verification)
- (–) [Specialized staffing] → [sterility failures still require scarce expert intervention] (limits labor substitution)
- (–) [Capital intensity] → [only premium facilities can justify automated biofabrication cells] (keeps impact narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

Score: 3 (Impact in GVN 10)

Justification: Programmable materials reduce assembly, adjustment, and some maintenance labor by letting components self-deploy or self-change rather than being mechanically reworked by people. That is useful in access-constrained or high-variation settings, but the direct GVN effect remains narrower than conventional robotics or agile factories. The impact is material, but not broad enough for a higher score without much wider use in everyday industrial and service equipment.

Weak signals (7):

- (+) [Assembly burden] → [products ship flat and self-deploy on site] (cuts installation labor)
- (+) [Maintenance access] → [components self-adjust to wear or temperature changes] (reduces manual tuning)
- (+) [Remote sites] → [hard-to-access assets adopt self-reconfiguring parts] (supports unattended operation)
- (+) [Design shift] → [engineers specify state changes instead of mechanisms] (moves work into digital materials design)
- (−) [Reliability] → [unexpected state changes appear in field-failure reports] (shows trust barrier)
- (−) [Recycling/externalities] → [buyers question end-of-life handling for programmable composites] (limits scale)
- (−) [Cost] → [use remains concentrated in premium or access-constrained tasks] (keeps impact bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

Score: 3 (Impact in GVN 10)

Justification: Volumetric additive manufacturing compresses the labor and time from design file to physical part, especially in small-batch, customized, or geometrically complex production. That can reduce handling, support removal, and setup work, but the broader operating-model impact remains narrower than more general additive or reconfigurable-manufacturing technologies. The result is a material but bounded contribution.

Weak signals (7):

- (+) [Prototype cycle] → [design teams print validated parts in minutes instead of hours] (compresses iteration labor)
- (+) [Unattended production] → [compact print cells run overnight without operator intervention] (extends machine-only hours)
- (+) [Inventory] → [sites replace stocked specialty parts with on-demand volumetric prints] (cuts coordination and storage)
- (+) [Geometry bottlenecks] → [internal-channel parts shift from machining to one-step printing] (reduces assembly steps)

- (–) [Certification] → [buyers require new proof rules for layerless parts] (governance slows adoption)
- (–) [Feedstock dependence] → [material choice remains narrow in procurement] (limits broad substitution)
- (–) [Scale] → [technology stays concentrated in labs and specialty shops] (keeps impact bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 10)

Justification: Metamaterials matter to this GVN mainly by improving sensing, coverage, and compact wave-handling hardware in automated environments. They can lower the footprint of antennas, improve difficult radio coverage, and sharpen machine perception, but their labor effects remain indirect and infrastructure-specific. The impact is material, yet a higher score would require widespread use across everyday automation sites rather than select communications and sensing applications.

Weak signals (7):

- (+) [Connectivity bottlenecks] → [robotic sites add reconfigurable surfaces instead of extra base stations] (improves coverage economically)
- (+) [Compact sensing] → [machines adopt flat lenses or beam shapers in constrained form factors] (supports smaller autonomous devices)
- (+) [Facility retrofits] → [autonomy-ready buildings market smart wave-control panels] (turns materials into enablers)
- (+) [Safety] → [sensing reliability improves in cluttered industrial spaces] (reduces blind spots)
- (–) [Durability] → [weathering and tolerance drift dominate exposed-surface maintenance] (keeps impact bounded)
- (–) [Supply chain] → [specialized fabrication remains concentrated in few vendors] (raises dependency risk)
- (–) [Privacy] → [radio-sensing upgrades trigger occupancy-tracking objections] (tests acceptability)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 07.045 - Room-Temperature Superconductors

Score: 3 (Impact in GVN 10)

Justification: Room-temperature superconductors would lower losses and improve compact high-current systems, which could benefit motors, power delivery, sensing, and cooling across automation-heavy sites. But the relationship to this GVN is mostly indirect through better

infrastructure and hardware economics rather than direct operating-model change. The impact could be material, yet a higher score would require automation-specific system redesigns to diffuse broadly.

Weak signals (7):

- (+) [Motor performance] → [premium robotic systems adopt superconducting actuators or links] (tests direct hardware payoff)
- (+) [Facility power] → [high-density automation sites redesign busways around low-loss conductors] (supports large fleets)
- (+) [Sensing precision] → [new autonomous platforms use stronger compact magnetic systems] (widens capability envelope)
- (+) [Thermal limits] → [control rooms shrink cooling and cabling footprints] (improves dense deployment)
- (–) [Mechanical robustness] → [strain and joining issues dominate service reports] (keeps impact bounded)
- (–) [Supply concentration] → [high-performance materials remain scarce and premium-priced] (limits diffusion)
- (–) [Safety] → [new current and field standards delay broad use] (governance lags capability)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 - Self-Healing & Smart Polymers

Score: 5 (Impact in GVN 10)

Justification: Self-healing and adaptive polymers reduce downtime, inspection, and replacement labor across robots, sensors, wearables, and automated infrastructure. Second-order they improve safety and unattended operation while shifting value toward material suppliers and lifecycle analytics; third-order they make long-lived autonomous assets more viable in hard-to-access settings. That is a significant GVN contribution, though not a primary driver of automation on its own.

Weak signals (9):

- (+) [Maintenance burden] → [robot skins, seals, and cable jackets shift to self-healing materials] (cuts service calls)
- (+) [Remote assets] → [inspection intervals are extended after smart-polymer retrofits] (supports unattended operation)
- (+) [Human-safe automation] → [soft-contact surfaces retain performance after repeated wear] (improves reliability near people)
- (+) [Predictive maintenance] → [materials broadcast degradation before visible failure] (automates lifecycle decisions)
- (+) [Cost-effectiveness] → [buyers compare lifetime repair reduction, not just upfront price] (changes procurement logic)
- (+) [Harsh environments] → [autonomous equipment operates longer in abrasive or humid sites] (widens deployment)
- (–) [Recycling] → [end-of-life separation becomes a procurement concern] (shows externality trade-off)

- (–) [Performance drift] → [partial healing is blamed for hidden quality failures] (tests trust)
- (–) [Supply power] → [specialty polymer vendors capture maintenance-data relationships] (shifts market control)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 3 (Impact in GVN 10)

Justification: These materials help automation mainly by making equipment cleaner, more durable, lower-friction, and more stable under unattended operation. The labor effect comes through reduced cleaning, tuning, and replacement work rather than direct task automation. That yields a material but bounded impact.

Weak signals (7):

- (+) [Maintenance] → [coated robotic components show longer intervals between cleaning or replacement] (cuts routine labor)
- (+) [Process stability] → [automated lines maintain quality with fewer manual adjustments] (supports unattended production)
- (+) [Harsh environments] → [anti-corrosion and anti-fouling coatings spread to remote assets] (widens viable deployment)
- (+) [Safety] → [low-friction or easier-clean surfaces reduce manual intervention around hazards] (lowers exposure)
- (–) [Durability] → [coating wear becomes the dominant service issue] (keeps impact bounded)
- (–) [Supply risk] → [scarce catalyst inputs create recurring availability shocks] (limits scaling)
- (–) [Health/environment] → [nanomaterial handling rules slow widespread rollout] (adds governance friction)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 3 (Impact in GVN 10)

Justification: Stronger, more heat-tolerant metals make automated systems more durable in harsh settings and can reduce service, replacement, and downtime labor. Their impact on the GVN is real but mostly indirect through reliability and maintenance economics rather than through the operating model itself. A higher score would require these metals to become decisive in mainstream robot and factory adoption.

Weak signals (7):

- (+) [Harsh-environment automation] → [robot vendors shift critical joints and tools to HEAs] (extends asset life)
- (+) [Maintenance cycles] → [replacement intervals lengthen for high-load machine components] (cuts service labor)

- (+) [Precision under stress] → [high-vibration or thermal sites widen autonomous operating windows] (supports reliable automation)
- (+) [Weight/performance] → [machines use smaller parts without losing safety margins] (improves economics)
- (–) [Cost] → [premium-alloy prices confine uptake to mission-critical assets] (keeps impact bounded)
- (–) [Certification] → [long-duration testing delays broad procurement] (slows diffusion)
- (–) [Supply concentration] → [specialty alloy producers become bottlenecks] (raises dependency risk)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 10)

Justification: CO<sub>2</sub> capture materials affect automation of work only indirectly, mainly by enabling automated carbon-management operations or preserving license to operate for carbon-intensive automated industries. They do not strongly alter the core labor-substitution logic of the GVN. The linkage is concrete but limited.

Weak signals (5):

- (+) [Automated compliance] → [capture units run with minimal on-site staffing under sensor control] (would create direct labor linkage)
- (+) [Industrial continuity] → [automated plants keep output by pairing with modular capture] (preserves machine-heavy operations)
- (+) [Traceability] → [buyers require machine-verifiable carbon-removal data in contracts] (turns compliance into automation)
- (–) [Energy burden] → [capture retrofits stall where power use offsets automation savings] (limits broader effect)
- (–) [Capital allocation] → [projects are approved for compliance, not labor transformation] (keeps linkage weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

Score: 5 (Impact in GVN 10)

Justification: Lighter, tougher, more conductive composites materially improve drones, mobile robots, wearables, and instrumented structures used in automated work. Second-order they reduce downtime, embed self-monitoring into hardware, and alter supply chains for strategic autonomy components; third-order they widen the sectors where mobile automation is economical. That is significant, though still a hardware enabler rather than a keystone shift.

Weak signals (9):



- (+) [Mobile robotics] → [drone and robot runtimes rise after composite frame adoption] (improves utilization)
- (+) [Condition monitoring] → [structural health is read directly from conductive composite parts] (automates inspection)
- (+) [Payload limits] → [lighter frames let robots carry more tools or sensors] (broadens task envelope)
- (+) [Service life] → [fatigue-related failures drop in high-cycle autonomous assets] (cuts replacement labor)
- (+) [Weight-sensitive sectors] → [inspection and delivery platforms switch to nano-composite airframes] (supports scale-out)
- (+) [Safety] → [impact-tolerant parts reduce downtime after minor collisions] (improves resilience)
- (–) [Manufacturing complexity] → [quality variance at joints dominates early claims] (slows broad uptake)
- (–) [Health/regulation] → [nanoparticle handling rules reshape factory workflows] (adds governance burden)
- (–) [Supply power] → [few advanced-material suppliers control key composite grades] (creates dependency)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 3 (Impact in GVN 10)

Justification: Smart thermal materials improve automation by stabilizing temperatures, reducing cooling loads, and extending operation where thermal management is a bottleneck. The main effect is on uptime and passive control rather than direct substitution of human labor. That is material, but not broad enough for a higher score without much deeper penetration into everyday robotic and industrial systems.

Weak signals (7):

- (+) [Thermal bottlenecks] → [robot cabinets and batteries adopt passive thermal-regulation layers] (cuts cooling and maintenance)
- (+) [24/7 operations] → [sites reduce thermal shutdowns during peak conditions] (supports continuous machine work)
- (+) [Remote assets] → [autonomous equipment tolerates wider weather ranges] (widens deployment geography)
- (+) [Facility efficiency] → [dense automation sites retrofit thermal films before HVAC expansion] (lowers capex barrier)
- (–) [Durability] → [cycling-induced degradation appears in service logs] (tests lifetime claims)
- (–) [Fire/compliance] → [materials face strict safety qualification before broad rollout] (slows diffusion)
- (–) [Supply constraints] → [high-performance variants stay premium and selective] (keeps impact bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

Score: 5 (Impact in GVN 10)

Justification: Motors and actuators are core inputs to robotics and automation, so more resilient magnet supply directly affects deployment costs, scaling speed, and geopolitical vulnerability. First-order this lowers supply-chain bottlenecks for machine labor; second-order it widens the supplier base and may reduce concentration around scarce inputs; third-order it makes mass rollout of autonomous fleets more robust. That is significant, though the operating-model impact remains indirect.

Weak signals (9):

- (+) [Motor supply bottleneck] → [robot and AGV vendors redesign around rare-earth-free motor grades] (stabilizes scaling)
- (+) [Capex planning] → [buyers compare actuator contracts on supply resilience, not only torque] (changes procurement logic)
- (+) [Fleet expansion] → [autonomy rollouts accelerate after magnet-supply constraints ease] (removes hidden deployment brake)
- (+) [Industrial policy] → [public tenders favor non-rare-earth motors for resilience] (institutionalizes the shift)
- (+) [Market structure] → [more motor suppliers qualify for automation programs] (reduces dependency concentration)
- (+) [Maintenance] → [corrosion-resistant magnet grades extend replacement intervals] (cuts service burden)
- (–) [Performance trade-offs] → [high-end applications keep rare-earth magnets for peak density] (limits universality)
- (–) [Thermal stability] → [buyers demand extra verification in heat-heavy deployments] (keeps trust hurdle alive)
- (–) [Control complexity] → [software compensation becomes a new vendor lock-in point] (shifts value into control stack)

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

Score: 1 (Impact in GVN 10)

Justification: Better desalination membranes mainly influence water infrastructure, with only a limited indirect effect on this GVN through more automated utility operations or industrial water availability. They do not strongly alter the machinery, AI, labor, or governance dynamics central to automation of work. The linkage is concrete but weak.

Weak signals (5):

- (+) [Automated utilities] → [desalination plants cut operator staffing after membrane upgrades] (would create direct labor linkage)
- (+) [Remote industry] → [water-constrained automated sites become viable with modular desalination] (supports niche deployment)

- (+) [Maintenance] → [cleaning intervals lengthen enough to shift service contracts] (reduces manual intervention)
- (–) [Concentrate handling] → [disposal remains human-intensive despite membrane gains] (limits automation effect)
- (–) [Sector confinement] → [benefits stay inside water infrastructure budgets] (keeps GVN linkage narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 5 (Impact in GVN 10)

Justification: Better power semiconductors matter directly to electric motors, chargers, drives, converters, and high-density control systems that underpin automated work. First-order they reduce size, heat, and loss in robotic and autonomy infrastructure; second-order they improve reliability while concentrating value in advanced module suppliers; third-order they support denser, quieter, more distributed automated systems. That is significant for the GVN even if it is not as visible as software or robotics.

Weak signals (9):

- (+) [Drive efficiency] → [robot and AGV vendors ship smaller cooler power modules] (lowers deployment footprint)
- (+) [Fast charging] → [autonomous fleets shorten downtime without larger chargers] (improves utilization)
- (+) [Dense automation] → [sites add more electrified machines before upgrading cooling] (raises feasible machine density)
- (+) [Remote reliability] → [power-electronics failures fall in harsh-environment autonomous assets] (cuts maintenance travel)
- (+) [Noise/space limits] → [compact converters enable automation in constrained buildings] (widens site compatibility)
- (+) [Monitoring] → [modules expose health diagnostics to predictive-maintenance software] (improves unattended operation)
- (–) [Supply concentration] → [few vendors control certified high-power modules] (creates dependency)
- (–) [Packaging durability] → [thermal cycling dominates warranty claims] (tests lifetime economics)
- (–) [Qualification] → [buyers require new electrical safety profiles for novel devices] (slows diffusion)

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 1 (Impact in GVN 10)

Justification: Solid hydrogen storage could help a subset of heavy or remote autonomous machines operate longer with less manual refueling complexity, but the overall GVN linkage is narrow. Its main relevance is in edge cases where batteries are inadequate and safe fuel handling is the bottleneck. That is worth watching, yet still limited.

Weak signals (5):

- (+) [Remote autonomy] → [mining and field robots adopt swappable solid-hydrogen cartridges] (would reduce refueling labor)
- (+) [Heavy-duty fleets] → [autonomous off-road machines pilot solid-storage modules] (tests niche fit)
- (+) [Safety burden] → [operators replace high-pressure handling with cartridge logistics] (could simplify fueling)
- (–) [Thermal management] → [heat-demand during discharge dominates service design] (limits convenience gains)
- (–) [Economics] → [storage modules remain premium versus batteries or liquid fuels] (keeps impact narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

Score: 3 (Impact in GVN 10)

Justification: Fusion would lower some long-run energy constraints around 24/7 automation, electrified fleets, and compute-heavy control centers, but it does not directly change the GVN's operating model. Its strongest effects are second- and third-order: cheaper, steadier power for machine-heavy sectors and less need for fuel logistics and human energy operations. That is material but too indirect for a higher score.

Weak signals (7):

- (+) [24/7 automated industry] → [energy-intensive automated clusters reserve fusion-backed power contracts] (supports nonstop operation)
- (+) [Fuel logistics] → [remote automated sites prefer fusion-supplied grids over diesel chains] (reduces human resupply work)
- (+) [High-temperature processes] → [automated plants pair machine-heavy lines with fusion heat] (stabilizes output economics)
- (+) [Remote maintenance] → [robotic hot-cell operations become normalized in fusion plants] (feeds autonomy know-how back)
- (–) [Capital allocation] → [fusion power remains concentrated in large infrastructure nodes] (keeps automation linkage indirect)
- (–) [Grid dependence] → [automation benefits arrive through price effects, not direct redesign] (limits operating-model shift)
- (–) [Licensing] → [slow reactor approvals delay wider economic spillover] (holds impact below 5)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 3 (Impact in GVN 10)

Justification: SMRs could support automated factories, mines, data centers, and microgrids with reliable local power and heat, especially where fuel logistics or grid weakness constrain round-the-clock machine use. But the impact on this GVN remains mostly infrastructural rather than directly labor-substitutive. It is material, not transformative.

Weak signals (7):

- (+) [Remote automation] → [mines and industrial parks pair SMR plans with labor-light operating models] (links power to machine-intensive sites)
- (+) [24/7 service] → [automated facilities cite SMRs in expansion cases] (stabilizes nonstop operation)
- (+) [Fuel logistics] → [remote sites replace frequent fuel deliveries with long-refuel infrastructure] (reduces support labor)
- (+) [Microgrids] → [SMRs are proposed as anchor assets in autonomy-heavy local grids] (supports resilient operations)
- (–) [Capital intensity] → [only large assets justify bundled automation-plus-SMR plans] (keeps effect bounded)
- (–) [Security/governance] → [nuclear obligations add specialist staffing back into some sites] (offsets labor reductions)
- (–) [Licensing] → [permitting timelines remain the dominant bottleneck] (limits speed of impact)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.058 - Thin-film solar cells

Score: 3 (Impact in GVN 10)

Justification: Thin-film solar helps the GVN by making local electricity generation easier on distributed sites, buildings, vehicles, and some machines, reducing dependence on central infrastructure and installers. That supports remote sensing, microfactories, and some autonomous fleets, but the direct labor-automation linkage remains bounded. A higher score would require thin films to become a standard power layer across many automated assets.

Weak signals (7):

- (+) [Distributed sensing] → [remote sensor and gateway deployments switch to laminated solar skins] (supports unattended infrastructure)
- (+) [Site autonomy] → [warehouse roofs and walls power more local robotic loads] (reduces dependence on grid upgrades)
- (+) [Mobile assets] → [thin-film surfaces extend runtime for low-power autonomous devices] (widens niche autonomy)
- (+) [Installation labor] → [manufacturers pre-integrate power skins during production] (shifts work off-site)

- (–) [Durability] → [microcracking and moisture ingress dominate warranty claims] (keeps effect bounded)
- (–) [Output variability] → [critical automation still requires major buffering systems] (limits direct substitution value)
- (–) [Economics] → [use clusters in special surfaces rather than core factory power] (holds impact below 5)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.059 - Bionic Leaf Technology

Score: 1 (Impact in GVN 10)

Justification: Bionic leaf systems could create distributed low-carbon chemical feedstocks, but the pathway to mainstream automation-of-work effects is weak and indirect. Their main relevance would be in specialized chemical or remote-energy contexts rather than in the core machinery and labor dynamics of the GVN. The linkage is worth monitoring, but remains limited.

Weak signals (5):

- (+) [Remote autonomy] → [off-grid automated sites test leaf-panels for local fuel generation] (would create operational linkage)
- (+) [Chemical supply] → [microfactories pair bionic-leaf panels with robotic process skids] (tests local feedstock model)
- (+) [Maintenance] → [panels run with mostly automated sensing and cleaning] (could reduce support labor)
- (–) [Throughput] → [output remains too low for machine-intensive operations] (keeps impact narrow)
- (–) [Use-case confinement] → [deployments stay in demonstration or specialty chemistry] (limits GVN relevance)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

Score: 5 (Impact in GVN 10)

Justification: Long-duration storage is significant because automation gains are only fully realized when electrified facilities, robots, and control systems can operate continuously without fragile timing dependence on the wider grid. Second-order it changes tariff structures, backup staffing, and investment patterns, and third-order it makes 24/7 local automation and microfactories more robust. That fits the significant band, though not as a direct labor-substitution technology.

Weak signals (9):

- (+) [24/7 operations] → [automated sites shift from curtailment to storage-backed night production] (extends machine labor hours)
- (+) [Electrified fleets] → [robot and AGV charging is scheduled against local storage state] (stabilizes uptime)

- (+) [Backup labor] → [sites retire diesel and manual outage procedures after storage installs] (reduces support work)
- (+) [Microfactories] → [small production sites operate through grid-price spikes using storage] (supports decentralized automation)
- (+) [Power quality] → [sensitive automated lines cite storage in scrap reduction metrics] (improves reliability)
- (+) [Tariff structure] → [energy contracts reward flexible machine-heavy operations] (changes machine-economics calculus)
- (–) [Safety] → [fire and gas-handling audits become major deployment gate] (shows governance burden)
- (–) [Capital access] → [only larger firms can finance multi-day storage buffers] (creates uneven adoption)
- (–) [Ownership] → [utilities or platform operators capture dispatch control over site storage] (shifts bargaining power)

## ART 08.061 - Solid-State Batteries

Score: 10 (Impact in GVN 10)

Justification: Better batteries directly expand the reach, safety, and economics of mobile automation in robots, drones, warehouse vehicles, and autonomous road transport. First-order they reduce downtime, charging complexity, and fire/insurance friction; second-order they reshape fleet design, charging infrastructure, and the balance between local and remote deployment; third-order they let mobile machine labor spread into more sites and shifts. That is clearly transformative for the GVN.

Weak signals (9):

- (+) [Mobile autonomy] → [robot and AGV runtimes rise without larger battery enclosures] (improves asset utilization)
- (+) [Safety] → [insurers lower premiums for indoor fleets after solid-state rollout] (reduces deployment friction)
- (+) [Charging downtime] → [autonomous fleets shorten charge windows without overheating] (supports continuous operation)
- (+) [Space constraints] → [smaller packs let robots work in tighter footprints] (widens site compatibility)
- (+) [Remote sites] → [field robots operate longer between human servicing visits] (cuts support labor)
- (+) [Fleet economics] → [buyers shift from pilot fleets to full replacements after battery upgrades] (shows scaling threshold crossed)
- (–) [Supply power] → [few cell suppliers dominate automation-grade packs] (creates strategic dependence)
- (–) [Cold-condition limits] → [operators keep fallback fleets in harsh climates] (keeps impact below keystone)
- (–) [Recycling] → [long-life packs expose gaps in automated end-of-life handling] (adds systemic burden)

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 3 (Impact in GVN 10)



Justification: Green hydrogen matters to this GVN mainly where heavy autonomous equipment or long-duration industrial operation outstrips battery practicality. It can reduce fuel logistics and enable lower-carbon machine-heavy operations, but the direct automation effect is narrower than for batteries or digital-control technologies. The impact is material but bounded.

Weak signals (7):

- (+) [Heavy-duty autonomy] → [ports, mines, or farms test hydrogen-fueled autonomous equipment] (opens battery-hard use cases)
- (+) [Fuel logistics] → [remote automated sites switch to local hydrogen production or delivery] (reduces resupply labor)
- (+) [Traceability] → [buyers require carbon-certified machine fuels in service contracts] (turns energy data into governance)
- (+) [Microgrids] → [hydrogen buffers support uninterrupted automated operations] (improves endurance)
- (–) [Safety governance] → [hydrogen handling rules add staffing and monitoring overhead] (offsets labor savings)
- (–) [Economics] → [low utilization keeps power-to-X unattractive for most automation fleets] (limits breadth)
- (–) [Infrastructure] → [fueling networks lag behind vehicle and robot pilots] (holds impact below 5)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

Score: 1 (Impact in GVN 10)

Justification: Better wind power lowers long-run energy costs for machine-heavy systems but does not strongly alter the operating model of automation of work. The pathway is real yet indirect and mostly mediated through electricity prices and local generation strategies. That keeps the score low.

Weak signals (5):

- (+) [Energy-intensive automation] → [robot-heavy sites sign direct wind power agreements] (would improve machine economics)
- (+) [Remote operations] → [wind-backed microgrids are paired with autonomous infrastructure] (supports isolated automation)
- (+) [Maintenance automation] → [wind assets themselves become highly robot-serviced] (creates sector-specific labor substitution)
- (–) [Variability] → [automation gains depend on storage more than turbine efficiency] (limits direct linkage)
- (–) [Grid mediation] → [benefits arrive as generic power pricing, not workflow redesign] (keeps impact weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 10)

Justification: Wireless and space-based power transfer could aid certain remote or mobile autonomous operations, but the pathway to broad work automation remains niche. Most gains would show up in specialized sites, emergency response, or hard-to-connect systems rather than across the main GVN operating model. The linkage is worth watching, but narrow.

Weak signals (5):

- (+) [Remote autonomy] → [mobile robots receive usable power without heavy cables or fuel runs] (would enable niche persistence)
- (+) [Disrupted areas] → [temporary automated sites are powered by beamed-energy receivers] (tests resilience value)
- (+) [Logistics] → [operators replace generator resupply with receiver deployment] (could cut support labor)
- (–) [Safety] → [beam-exclusion rules dominate permitting and staffing] (limits routine use)
- (–) [Economics] → [systems stay cost-competitive only in exceptional access-constrained cases] (keeps impact narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

Score: 3 (Impact in GVN 10)

Justification: Advanced geothermal can support machine-heavy local industry with steady power and heat in places where grid weakness or fuel logistics constrain automation. But its effect on this GVN remains infrastructural and location-dependent rather than directly labor-substitutive. The plausible impact is material, not transformative.

Weak signals (7):

- (+) [Round-the-clock automation] → [industrial parks market geothermal-backed uptime for automated production] (supports nonstop operation)
- (+) [Remote sites] → [deep-heat projects are paired with labor-light mines or plants] (links energy to automation)
- (+) [Local resilience] → [microgrid plans use geothermal as anchor for autonomous facilities] (improves continuity)
- (+) [Heat-intensive processes] → [automated plants pair geothermal heat with robotic operations] (changes operating economics)
- (–) [Capital intensity] → [only a few sites justify drill costs despite automation benefits] (keeps impact bounded)
- (–) [Permitting] → [subsurface risk rules dominate timelines] (slows diffusion)
- (–) [Location fit] → [automation spillovers remain geographically concentrated] (limits GVN-wide effect)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

Score: 5 (Impact in GVN 10)

Justification: Resilient microgrids are significant because machine-intensive sites depend on steady local power and rapid recovery more than many traditional workplaces do. First-order they reduce downtime and support islanded operation; second-order they automate energy management and alter who controls operational continuity; third-order they enable distributed production and service sites that do not need central-grid reliability to automate. That is significant, though not itself a direct labor-replacement technology.

Weak signals (9):

- (+) [Downtime risk] → [automated sites add island-capable local grids before adding more machines] (power becomes automation precondition)
- (+) [24/7 service] → [robot-heavy facilities keep operating through wider-grid outages] (supports continuity)
- (+) [Local control] → [energy dispatch is automated through same dashboards as operations] (integrates utility and workflow management)
- (+) [Distributed production] → [microfactories pair robotics with site-level generation and storage] (supports decentralization)
- (+) [Black-start capability] → [recovery drills prioritize machine resumption over manual fallback] (changes resilience model)
- (+) [Skilled labor bottleneck] → [sites rely on remote microgrid support instead of resident specialists] (lowers local competence need)
- (–) [Cybersecurity] → [grid-control interfaces become part of autonomy threat models] (raises systemic risk)
- (–) [Ownership] → [utilities or platform firms retain dispatch rights over customer microgrids] (shifts bargaining power)
- (–) [Capex inequality] → [only larger sites can afford full resilience stacks] (creates uneven automation gains)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

Score: 1 (Impact in GVN 10)

Justification: Gene editing has a concrete but limited pathway into this GVN through automated breeding, engineered production organisms, and a few labor-saving agricultural or biomanufacturing applications. Those are real, but they are far from the core machine/autonomy operating model of work automation described here. The effect is worth watching but remains narrow.

Weak signals (5):

- (+) [Bioprocess automation] → [edited strains are adopted for highly automated production lines] (would strengthen direct linkage)

- (+) [Agricultural labor] → [gene-edited crops are paired with labor-light robotic farming models] (tests substitution synergy)
- (+) [Design cycle] → [automated edit-design platforms reduce manual breeding work] (moves biology toward programmable workflows)
- (–) [Governance] → [approval and containment burdens keep use in narrow sectors] (limits breadth)
- (–) [Public legitimacy] → [social contestation blocks deployment even where automation value exists] (holds impact down)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

Score: 0 (Impact in GVN 10)

Justification: Better mRNA therapies may improve population health and workforce resilience, but there is no clear GVN-specific pathway from that to the automation-of-work operating model. The technology neither directly automates work nor clearly resolves the main institutional or technical bottlenecks of autonomous machine deployment. It only rises above 0 if mRNA platform manufacturing itself becomes a large labor-automation domain within the assessed economy.

Weak signals (4):

- (+) [Biomanufacturing automation] → [mRNA plants reach very low labor-per-dose ratios] (would create sector-specific linkage)
- (+) [Workforce resilience] → [employers justify automation delays using health-productivity gains] (tests second-order labor effect)
- (–) [Domain separation] → [mRNA remains mainly a health intervention, not a work-automation lever] (keeps linkage weak)
- (–) [Manufacturing scope] → [automation gains stay inside pharma facilities] (limits GVN relevance)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

Score: 3 (Impact in GVN 10)

Justification: Cellular agriculture can materially automate parts of food production by shifting output from animal husbandry and slaughter toward tightly monitored, machine-heavy production systems. Second-order it changes land use, rural labor demand, regulation, and ownership of food capacity; third-order it could normalize highly automated biofactories in a major consumer sector. That is material, but not broad enough to score higher for this general GVN.

Weak signals (7):

- (+) [Food-processing labor] → [cultivated-protein plants report low labor-per-kilo versus slaughter lines] (shows substitution)

- (+) [Continuous monitoring] → [production is run through sensor-rich bioreactor dashboards] (moves work into automation)
- (+) [Rural restructuring] → [investment shifts from farms to urban or peri-urban bioplants] (changes labor geography)
- (+) [Traceability] → [buyers demand digital proof of feedstock, contamination, and batch quality] (turns governance into software)
- (–) [Capital access] → [only large players can finance automated facilities] (concentrates ownership)
- (–) [Regulation] → [approvals and labeling disputes slow scaling] (holds impact below 5)
- (–) [Workforce transition] → [displaced agricultural labor lacks clear routes into new roles] (tests social adaptation)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

Score: 1 (Impact in GVN 10)

Justification: Organoids and tissue engineering can automate parts of testing and specialized biological production, but their relationship to the broader automation-of-work GVN is narrow. The main effects fall inside R&D and clinical-biotech workflows rather than mainstream industrial or service labor substitution. That keeps the score low.

Weak signals (5):

- (+) [Lab automation] → [organoid workflows move from benchcraft to robotic handling] (would create direct labor effect)
- (+) [Testing cycles] → [firms replace manual assay stages with automated tissue platforms] (cuts specialist handling)
- (+) [Quality control] → [machine-vision and sensor scoring replace manual review] (turns biology into dashboard work)
- (–) [Variability] → [batch drift keeps human expert oversight central] (limits substitution)
- (–) [Sector confinement] → [use remains concentrated in pharma and advanced clinics] (keeps GVN linkage narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

Score: 3 (Impact in GVN 10)

Justification: Designer microbes can automate chemical and material production by moving work from multi-step, human-tuned process chains into programmable fermentation-like systems. Second-order they alter who owns production recipes, reduce some hazardous manual processing, and enable smaller distributed plants; third-order they can widen machine-led production into new feedstocks and geographies. That is material, but still narrower than the main robotics/AI regime.

Weak signals (7):

- (+) [Process labor] → [fermentation plants cut manual tuning after engineered-microbe rollout] (shifts work into automation)
- (+) [Distributed production] → [containerized bioplants appear near waste or feedstock sources] (supports decentralization)
- (+) [Hazard reduction] → [chemical routes with fewer high-heat human operations gain share] (reduces exposure)
- (+) [Recipe power] → [value shifts from physical plant to coded microbial strains] (changes ownership structure)
- (–) [Containment] → [biosecurity controls add specialist staffing back into operations] (offsets labor savings)
- (–) [Feedstock purity] → [variability still triggers human interventions] (keeps impact bounded)
- (–) [Market concentration] → [few IP owners control top-performing production organisms] (concentrates bargaining power)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 - Microbiome Engineering

Score: 1 (Impact in GVN 10)

Justification: Microbiome engineering could reduce certain manual dosing, cleaning, or contamination-control tasks in agriculture, water, or health settings, but the linkage to the overall automation-of-work GVN is weak. Its effects are mostly indirect and domain-specific. The score stays low.

Weak signals (5):

- (+) [Maintenance reduction] → [soil or water systems shift from routine manual treatments to monitored microbiome control] (would create niche automation value)
- (+) [Invisible-state monitoring] → [simple tests let non-experts manage microbial conditions] (lowers expertise burden)
- (+) [Stability] → [engineered communities replace repeated corrective interventions] (reduces routine labor)
- (–) [Unpredictability] → [effects remain temporary and human troubleshooting stays central] (limits automation payoff)
- (–) [Governance] → [containment and ecological-risk rules slow operational use] (keeps linkage narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

Score: 0 (Impact in GVN 10)

Justification: Precision medicine may automate parts of healthcare decision support, but it has no strong general pathway into the GVN's operating model of replacing work with machines across the economy. The main impact is sector-specific diagnostics, not broad automation of work. It only

risks above 0 if genomics platforms become a major automation driver in health labor systems at economy-wide scale.

Weak signals (4):

- (+) [Clinical workflow automation] → [genomic decision platforms drastically cut clinician review time] (would create sector-specific linkage)
- (+) [Credentialing] → [automation of diagnostic interpretation changes staffing models] (tests labor substitution)
- (–) [Sector confinement] → [benefits stay inside healthcare pathways] (keeps GVN relevance low)
- (–) [Governance burden] → [human confirmation remains mandatory for high-stakes decisions] (limits automation effect)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

Score: 1 (Impact in GVN 10)

Justification: These platforms can automate experimentation and some bio-sensing workflows, but their effect on the broader automation-of-work GVN is still narrow. They matter more as specialized R&D and testing tools than as drivers of general labor substitution. The impact is concrete but limited.

Weak signals (5):

- (+) [Testing labor] → [drug and safety screening shifts from manual assays to chip platforms] (would cut niche labor)
- (+) [Continuous sensing] → [biochips stream machine-readable outputs into automated pipelines] (turns experiments into software workflows)
- (+) [Remote operation] → [lab teams supervise chips through dashboards, not benches] (moves work off-site)
- (–) [Stability] → [chip-to-chip variability keeps expert interpretation central] (limits substitution)
- (–) [Use-case scope] → [deployments remain concentrated in advanced labs] (keeps linkage weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

Score: 3 (Impact in GVN 10)

Justification: This ART matters mainly through second-order labor-market effects: if people remain healthier and more capable for longer, the economics and politics of automation shift. It can delay some substitution by preserving human labor supply, while also enabling older workers to supervise machines longer and reducing absenteeism or fatigue-related variability. That is material at society scale, but indirect.



Weak signals (7):

- (+) [Labor supply] → [retirement and late-career work patterns shift after longevity uptake] (changes substitution pressure)
- (+) [Supervisory roles] → [older expert workers remain in remote-control and oversight jobs longer] (extends human oversight pool)
- (+) [Injury/fatigue] → [productivity gaps between human and machine labor narrow in some tasks] (alters automation ROI)
- (+) [Training investment] → [firms lengthen expected returns on human skill development] (may slow some substitution)
- (–) [Inequality] → [enhanced longevity is concentrated in high-income occupations] (reshapes bargaining power)
- (–) [Automation delay] → [capital spending on robots is postponed where human performance stays high] (tests countervailing effect)
- (–) [Insurance/productivity policy] → [labor rules are rewritten around longer healthy working lives] (signals systemic shift)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 - Engineered Living Materials

Score: 3 (Impact in GVN 10)

Justification: Engineered living materials affect this GVN through self-repair, self-monitoring, and lower-maintenance structures, which can reduce inspection and replacement labor. The strongest link is to automated infrastructure and building maintenance rather than to core machine decision-making or task execution. That makes the impact material but bounded.

Weak signals (7):

- (+) [Maintenance labor] → [self-healing coatings or blocks reduce routine repair crews] (cuts manual upkeep)
- (+) [Condition monitoring] → [materials emit machine-readable health indicators] (automates inspection)
- (+) [Remote infrastructure] → [hard-to-access assets adopt living materials first] (supports unattended operation)
- (+) [Lifecycle economics] → [procurement shifts toward longevity and regeneration metrics] (changes asset logic)
- (–) [Operating envelope] → [temperature and moisture constraints limit real-world use] (keeps impact bounded)
- (–) [Governance] → [biosecurity and durability rules slow approvals] (adds adoption friction)
- (–) [Maintenance complexity] → [periodic nutrient or activation cycles create new service tasks] (offsets savings)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

Score: 1 (Impact in GVN 10)

Justification: Gene drives could reduce repetitive pest-control labor in some agricultural and public-health contexts, but the pathway into the broader automation-of-work GVN is weak and highly governance constrained. The technology substitutes biological persistence for repeated human effort, yet not in a way that strongly reshapes the main automation regime. The score therefore stays low.

Weak signals (5):

- (+) [Repetitive control labor] → [spraying or trapping budgets shrink after controlled releases] (would show labor substitution)
- (+) [Remote areas] → [hard-to-service zones are prioritized for gene-drive deployment] (tests access-driven value)
- (+) [Governance tooling] → [continuous genetic monitoring becomes machine-mediated] (turns oversight into data operations)
- (–) [Public legitimacy] → [social authorization remains harder than technical deployment] (limits broad use)
- (–) [Reversibility/accountability] → [field programs stall over liability rules] (keeps impact narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

Score: 0 (Impact in GVN 10)

Justification: Whatever their profound ethical implications, these technologies do not have a clear, meaningful pathway into the GVN's core automation-of-work operating model. Any labor-market effects would be demographic, sector-specific, and too indirect to justify a material score here. They only rise above 0 if they become a major platform for automated livestock, conservation, or reproductive-industrial systems with broad labor consequences.

Weak signals (4):

- (+) [Livestock systems] → [automated breeding platforms integrate artificial-gestation modules] (would create direct linkage)
- (+) [Controlled reproduction] → [synthetic embryo workflows move into industrialized animal production] (tests sectoral automation effect)
- (–) [Ethical governance] → [rules keep deployments tightly bounded to research or care] (keeps linkage weak)
- (–) [Domain separation] → [uses remain far from mainstream work automation] (limits GVN relevance)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

Score: 10 (Impact in GVN 10)

Justification: Satellite constellations directly support the GVN by extending connectivity, positioning, and machine-readable situational awareness into remote, mobile, and infrastructure-poor settings where terrestrial automation otherwise stalls. Second-order they concentrate power in a few network operators, widen remote supervision, and intensify surveillance and cyber-dependence; third-order they help normalize distributed autonomous operations across logistics, agriculture, utilities, and field services. That is transformative but still an enabler rather than the single keystone of automation.

Weak signals (9):

- (+) [Remote automation] → [farms, mines, and utilities deploy autonomous equipment with satellite backhaul by default] (extends automation footprint)
- (+) [Shared situational awareness] → [fleet platforms consume constellation-derived alerts in real time] (improves distributed coordination)
- (+) [Skill gaps] → [sites rely on remote support instead of local specialists] (lowers place-based competence barrier)
- (+) [Decentralized production] → [microfactories in peripheral areas use satcom for cloud coordination] (supports local manufacture)
- (+) [Resilience] → [operations continue after terrestrial outages via LEO fallback links] (reduces infrastructure fragility)
- (–) [Surveillance] → [worker and asset tracking expands with always-on orbital connectivity] (intensifies monitoring power)
- (–) [Cybersecurity] → [fleet threat models include orbital network compromise or spoofing] (shows dependence risk)
- (–) [Market structure] → [a few constellation providers bundle connectivity and analytics] (concentrates control)
- (–) [Regulation] → [cross-border data and spectrum disputes shape autonomous service areas] (signals institutional friction)

### ART 10.080 - Space Resource Utilization (SRU)

Score: 0 (Impact in GVN 10)

Justification: Space resource utilization may eventually matter for material supply, but its path into the GVN's automation-of-work operating model is too indirect and uncertain to score meaningfully here. Any impact would arrive through long-run commodity effects rather than through the direct labor, control, or governance dynamics at issue. It only rises above 0 if SRU-derived materials become a major bottleneck reliever for automation hardware supply within the assessed economy.

Weak signals (4):

- (+) [Automation hardware inputs] → [robotics supply roadmaps begin assuming space-derived strategic metals] (would create direct relevance)
- (+) [Material resilience] → [buyers treat SRU materials as hedge against terrestrial shortages] (tests second-order pathway)
- (–) [Domain separation] → [space mining remains disconnected from mainstream manufacturing] (keeps linkage weak)
- (–) [Timing] → [commercial return volumes stay too small to affect automation costs] (limits GVN impact)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

Score: 0 (Impact in GVN 10)

Justification: Closed-loop life support is highly relevant for habitats and extreme environments, but it does not map cleanly onto the GVN's mainstream automation-of-work model. Terrestrial spillovers into water, air, or waste management could exist, yet they are too indirect and niche to justify a meaningful score. It only rises above 0 if these systems become widely repurposed into automated terrestrial facilities.

Weak signals (4):

- (+) [Extreme-site automation] → [closed-loop habitat systems are reused in mines or offshore sites] (would create direct linkage)
- (+) [Utility automation] → [terrestrial facilities adopt life-support-like integrated resource control] (tests spillover value)
- (–) [Sector confinement] → [use remains tied to space or extreme habitats] (keeps relevance weak)
- (–) [Cost] → [terrestrial operators avoid the complexity of full-loop systems] (limits adoption)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

Score: 3 (Impact in GVN 10)

Justification: High-altitude platforms help this GVN by delivering interim connectivity, sensing, and navigation support in remote or disrupted areas, thereby enabling labor-light operations where terrestrial infrastructure is weak. Their strongest effects are enabling rather than core, and deployment is likely episodic or regional. That makes the impact material but bounded.

Weak signals (7):

- (+) [Disrupted-area automation] → [temporary HAP coverage enables autonomous logistics after outages] (supports resilient operations)
- (+) [Remote monitoring] → [sites buy stratospheric sensing as service for machine coordination] (widens non-terrestrial support layer)

- (+) [Rapid deployment] → [operators use HAPs before building local towers for autonomous sites] (lowers time-to-automation)
- (+) [Agriculture/utilities] → [large rural operators combine HAP links with autonomous fleets] (extends coverage economically)
- (–) [Airspace governance] → [flight permissions dominate service availability] (keeps effect bounded)
- (–) [Seasonality] → [coverage gaps appear with stratospheric weather shifts] (limits continuity)
- (–) [Payload limits] → [high-data automation still falls back to ground infrastructure] (holds impact below 5)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

Score: 5 (Impact in GVN 10)

Justification: Decentralized trust networks matter mainly through the GVN's second-order dynamics: shared machine ownership, machine-to-machine contracting, auditable usage rights, and reduced reconciliation across firms. They can support robot-as-a-service, autonomous supply coordination, and tamper-evident logs, while also creating new fraud, governance, and concentration risks in middleware. That makes them significant institutional infrastructure, though not a core technical prerequisite.

Weak signals (9):

- (+) [Shared machine access] → [robot-hour markets settle usage and access rights automatically] (supports pooled automation)
- (+) [Machine-to-machine trade] → [autonomous devices execute conditional service payments] (reduces human intermediation)
- (+) [Auditability] → [buyers require tamper-evident job and maintenance logs] (makes machine work contractable)
- (+) [Cross-firm coordination] → [multi-party production workflows rely on shared event ledgers] (cuts reconciliation labor)
- (+) [Decentralized production] → [small firms join common automation marketplaces without one host] (lowers platform dependence)
- (–) [Governance] → [smart-contract bugs cause production or payment disputes] (tests rule-automation risk)
- (–) [Market concentration] → [few infrastructure providers dominate chain access and tooling] (recreates centralization)
- (–) [Security] → [bridge or wallet failures disrupt autonomous service flows] (shows operational fragility)
- (–) [Labor power] → [platform rules become harder to contest once encoded] (changes bargaining dynamics)

## ART 11.084 - Platform Cooperatives & Fair Work

Score: 5 (Impact in GVN 10)

Justification: This ART can materially change who owns, governs, and benefits from automation even if it does not directly create the machines. It is highly relevant to the GVN's second-order layer: shared machine access, bargaining power, labor displacement management, and alternative governance of platform-mediated work; third-order it could shape whether automation concentrates or diffuses. That is significant, but not transformative in the same way as autonomy technologies themselves.

Weak signals (9):

- (+) [Shared machinery] → [worker- or user-owned robot fleets appear in local service markets] (changes ownership model)
- (+) [Bargaining power] → [co-ops negotiate data rights and algorithm changes collectively] (makes platform rules contestable)
- (+) [Access] → [SMEs use cooperative automation pools instead of vendor lock-in leases] (broadens machine availability)
- (+) [Transition fairness] → [redeployment funds are tied to automation gains in co-op charters] (shares productivity benefits)
- (+) [Governance transparency] → [members vote on ranking, pricing, and penalty rules] (changes platform power)
- (–) [Capital constraints] → [co-op platforms struggle to finance rapid automation expansion] (limits scale)
- (–) [Decision friction] → [member voting slows technical upgrades and reconfiguration] (creates agility trade-off)
- (–) [Internal politics] → [dominant member blocs shape rules to their own benefit] (tests fairness claims)
- (–) [Competitive pressure] → [investor-owned rivals undercut co-ops with faster automation rollouts] (stresses viability)

## ART 11.085 - Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 10)

Justification: Open data marketplaces can unlock fragmented operational data that otherwise slows machine learning, automation benchmarking, and cross-firm coordination. Second-order they change bargaining power around data ownership, lower entry barriers for smaller automation adopters, and create new compliance and trust infrastructure; third-order they speed diffusion of data-driven automation. That is significant even though the technology is not itself an autonomous worker.

Weak signals (9):

- (+) [Fragmented information] → [firms buy shared maintenance and workflow datasets instead of collecting everything themselves] (cuts data bottlenecks)
- (+) [SME access] → [small operators license high-quality training data through marketplaces] (reduces scale disadvantage)

- (+) [Compute-to-data] → [automation vendors train models where data sits] (lowers legal sharing friction)
- (+) [Quality competition] → [datasets are sold with performance and provenance scores] (turns data into infrastructure)
- (+) [Cross-sector learning] → [shared event data improves generic robot models] (speeds diffusion)
- (–) [Market power] → [few intermediaries set access fees and terms] (concentrates control)
- (–) [Privacy] → [worker or customer re-identification concerns trigger restrictions] (tests legitimacy)
- (–) [Data inequality] → [large firms monetize datasets while smaller ones become buyers only] (widens asymmetry)
- (+) [Governance] → [buyers require machine-readable usage rights in procurement] (normalizes programmable data exchange)

## ART 11.086 - Secure & Resilient Social Platforms

Score: 1 (Impact in GVN 10)

Justification: Secure social platforms mainly affect this GVN through continuity of coordination among distributed workers, operators, and communities during outages or contested governance situations. They do not directly automate work, though they can support remote supervision and collective response around automation systems. The linkage is concrete but peripheral.

Weak signals (5):

- (+) [Distributed supervision] → [operators coordinate incident response through resilient channels during outages] (supports continuity)
- (+) [Worker organization] → [automation-affected workers use resilient platforms for bargaining] (shapes second-order politics)
- (+) [Remote services] → [field teams maintain coordination when vendor systems fail] (provides fallback)
- (–) [Operational integration] → [platforms remain separate from machine-control systems] (limits direct impact)
- (–) [Use-case scope] → [benefits stay mostly social and organizational] (keeps linkage weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.087 - Collective Open Innovation Networks

Score: 5 (Impact in GVN 10)

Justification: These networks matter through a third-order acceleration pathway: they can shorten the time needed to solve automation bottlenecks, spread reusable solutions, and coordinate invention across firms and regions. Second-order they change who can participate in innovation, who captures value, and how evidence is shared; third-order they can speed the overall transition toward more automated operating models. That is significant, though indirect.

Weak signals (9):



- (+) [Innovation bottlenecks] → [automation challenges are solved through open cross-firm calls faster than in-house R&D] (speeds problem solving)
- (+) [Skill scarcity] → [small firms source niche automation expertise through shared networks] (widens access to capability)
- (+) [Evidence reuse] → [failed automation trials are logged and reused across participants] (reduces repeated mistakes)
- (+) [Decentralized production] → [local actors adapt global automation templates quickly] (supports diffusion)
- (+) [Human-AI collaboration] → [automated agents participate in open innovation workflows] (scales solution search)
- (–) [IP concentration] → [platform operators claim broad rights over contributed solutions] (shifts value capture)
- (–) [Quality control] → [automation proposals require heavier validation after high-profile failures] (adds governance burden)
- (–) [Participation inequality] → [well-resourced actors dominate challenge wins and reputation] (recreates hierarchy)
- (+) [Procurement] → [public buyers source automation solutions via open challenge platforms] (institutionalizes the model)

## ART 11.088 — Scalable Decentralized Governance

Score: 3 (Impact in GVN 10)

Justification: Decentralized governance does not directly automate tasks, but it can materially affect shared machine fleets, pooled infrastructure, data commons, and platform-mediated work. Its strongest effects are second-order: reducing coordination friction and making rule changes more explicit, while also introducing manipulation, identity, and participation risks. The impact is material but bounded.

Weak signals (7):

- (+) [Shared assets] → [robot pools or industrial commons adopt code-based voting and budgeting] (supports pooled automation)
- (+) [Rule transparency] → [participants can inspect and contest machine-governance parameters] (changes accountability)
- (+) [Cross-site coordination] → [distributed facilities approve changes through common governance stacks] (reduces manual administration)
- (+) [Resource allocation] → [maintenance budgets or machine priorities are set by formalized rules] (automates governance work)
- (–) [Manipulation] → [identity and voting attacks target shared automation systems] (tests robustness)
- (–) [Voter fatigue] → [participants delegate decisions to a few power brokers] (recreates hierarchy)
- (–) [Legal fit] → [real-world liability still overrides decentralized rule execution] (limits full impact)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 — Digital Learning Networks and Skill Credentialing

Score: 5 (Impact in GVN 10)

Justification: Skill gaps are an explicit inhibitor in the GVN, so scalable learning and credentialing have a strong second-order effect on whether automation can actually spread and whether displaced workers can move into adjacent roles. First-order they lower training costs for operators, technicians, and redeployed workers; second-order they change who certifies competence and who controls access to new jobs; third-order they can speed diffusion of automation into smaller firms and regions. That is significant, though not directly labor-substitutive.

Weak signals (9):

- (+) [Skill gaps] → [automation roles accept portable digital credentials in hiring] (lowers entry friction)
- (+) [Reskilling] → [displaced workers move through short modular automation pathways] (speeds labor reallocation)
- (+) [SME adoption] → [small firms train technicians through platform-based practice labs] (reduces local training bottleneck)
- (+) [Remote support] → [credentialed operators supervise machines across many sites] (supports centralized expertise)
- (+) [Standards] → [machine-vendor ecosystems recognize common skill badges] (turns training into infrastructure)
- (+) [Transition politics] → [public automation programs tie subsidies to retraining outcomes] (institutionalizes adaptation)
- (–) [Credential inflation] → [platform badges become gatekeepers to mid-level technical work] (reshapes bargaining power)
- (–) [Quality] → [employers question weak or automated assessments after job failures] (tests trust)
- (–) [Platform concentration] → [few learning networks dominate access to automation careers] (centralizes pathway control)

## ART 11.090 — Prediction-Market Forecasting Platforms

Score: 3 (Impact in GVN 10)

Justification: Prediction markets matter mainly through the second- and third-order layer: they can improve decisions about automation investments, labor transitions, regulation, and operational risk. They do not automate work directly, but they can change coordination quality under uncertainty and thereby affect which automation paths are chosen. That is material but bounded.

Weak signals (7):

- (+) [Investment decisions] → [large firms use internal markets to time automation capex] (turns uncertainty into signals)
- (+) [Policy response] → [public agencies use forecasting markets around displacement risks] (improves transition planning)
- (+) [Operational risk] → [forecast markets are tied to maintenance or outage expectations] (supports proactive management)

- (+) [Coordination] → [multiple teams align on market-based probabilities instead of committee estimates] (reduces planning friction)
- (–) [Manipulation] → [thin markets are gamed around major automation procurements] (tests credibility)
- (–) [Verification disputes] → [settlement arguments slow adoption in operational settings] (limits routine use)
- (–) [Participation inequality] → [insiders dominate markets and shape narratives] (skews signal quality)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

Score: 10 (Impact in GVN 10)

Justification: Interoperability standards are highly relevant because they reduce the integration cost and coordination friction of heterogeneous machine fleets, which is a major practical barrier to scaling automation beyond pilots. First-order they make devices and software plug together more cheaply; second-order they shift bargaining power away from bespoke integrators and toward whichever actors control certification and profiles; third-order they allow more decentralized and shared machine ecosystems to emerge. That is transformative, though not a keystone because de facto proprietary standards could still carry part of the transition.

Weak signals (9):

- (+) [Integration bottleneck] → [buyers specify interoperability profiles instead of custom adapters] (cuts deployment friction)
- (+) [SME adoption] → [small firms connect mixed-vendor robots without bespoke projects] (broadens access)
- (+) [Shared machinery] → [leased machines move between sites with minimal reconfiguration] (supports pooling models)
- (+) [Maintenance] → [common update and diagnostics pathways replace vendor-specific service routines] (reduces support burden)
- (+) [Lower hierarchies] → [operators manage mixed fleets through common dashboards] (simplifies control)
- (+) [Decentralized production] → [local factories integrate new devices quickly using common schemas] (supports flexible scaling)
- (–) [Certification power] → [a few bodies or vendors dominate conformance tools] (reshapes gatekeeping)
- (–) [Security] → [common protocol flaws trigger fleetwide vulnerabilities] (shows systemic risk)
- (–) [Legacy drag] → [old assets remain isolated despite new standards] (slows full transformation)

## ART 12.092 — Interoperable Digital Twin Ecosystems

Score: 10 (Impact in GVN 10)

Justification: Interoperable twin ecosystems directly support the GVN's move toward flexible, remotely managed, lower-hierarchy operations by keeping asset state, history, and simulation portable across firms and tools. First-order they cut duplicate modeling and speed diagnosis; second-order they change accountability, vendor lock-in, and who controls operational knowledge; third-order they support distributed production and service networks that can coordinate around common machine-readable asset views. That is transformative.

Weak signals (9):

- (+) [Cross-firm coordination] → [asset twins travel between designers, operators, and service vendors] (cuts duplicate modeling)
- (+) [Remote expertise] → [external teams diagnose assets through shared twin standards] (reduces local specialist dependence)
- (+) [Lifecycle continuity] → [buyers require portable twins at procurement handover] (makes portability contractable)
- (+) [Change management] → [config updates are simulated before physical deployment] (reduces operational risk)
- (+) [Shared production] → [multi-site plants coordinate around common twin schemas] (supports decentralized operations)
- (+) [Auditability] → [compliance reports reference twin-derived histories] (turns models into evidence)
- (–) [Liability] → [disputes center on which twin version represented reality] (tests accountability)
- (–) [Vendor control] → [platforms restrict advanced functions despite nominal portability] (recreates lock-in)
- (–) [Data quality] → [sensor gaps undermine trust in portable twin decisions] (limits impact ceiling)

## ART 12.093 — Global Supply Chain Traceability Networks

Score: 5 (Impact in GVN 10)

Justification: Traceability networks support the GVN by making decentralized, automated, lower-touch production and logistics more governable across distance and low trust. First-order they reduce manual reconciliation and root-cause search; second-order they change bargaining power over provenance data and compliance claims; third-order they support local manufacturing and automated procurement while also tightening surveillance of suppliers and workers. That is significant.

Weak signals (9):

- (+) [Paperwork burden] → [buyers accept machine-readable provenance instead of manual documentation] (cuts reconciliation labor)
- (+) [Quality failures] → [automated root-cause tracing replaces lengthy human investigations] (speeds corrective action)

- (+) [Decentralized production] → [small local producers join larger networks through portable trace data] (supports distributed manufacturing)
- (+) [Compliance] → [robotized warehouses update custody events automatically] (turns handling into data infrastructure)
- (+) [Counterfeit control] → [authenticity checks are integrated into autonomous receiving] (improves trust at handoff)
- (–) [Data asymmetry] → [dominant buyers demand deeper supplier transparency than they reciprocate] (reshapes bargaining power)
- (–) [Scanning burden] → [weak tagging and read quality create new manual exceptions] (limits automation gains)
- (–) [Privacy] → [worker and subcontractor activity becomes more tightly traceable] (extends surveillance)
- (+) [Insurance] → [insurers price lower risk for fully traceable automated supply flows] (rewards structured transparency)

## ART 12.094 — Personal Data Portability & Trust Frameworks

Score: 3 (Impact in GVN 10)

Justification: Personal data portability matters where automation depends on using identity, preference, or credential data without tripping privacy and trust barriers. It can ease some service automation, onboarding, and credential-sharing frictions, but the broader labor-substitution effect is limited. The impact is material, but not central.

Weak signals (7):

- (+) [Service automation] → [users grant purpose-bound data to bots without full account linking] (supports trusted automation)
- (+) [Credential portability] → [workers move verified qualifications between platforms instantly] (reduces onboarding labor)
- (+) [Selective disclosure] → [machines check eligibility without full personal-data access] (eases privacy concerns)
- (+) [Cross-platform work] → [operators reuse settings and permissions across multiple services] (cuts repeated setup)
- (–) [Usability] → [recovery and consent fatigue keep users on default provider rails] (limits shift)
- (–) [Power asymmetry] → [large platforms shape wallet standards to preserve influence] (recreates lock-in)
- (–) [Governance] → [liability for revoked or stale permissions complicates automation] (slows operational use)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.095 — Interoperable Digital Currency Payment Networks

Score: 3 (Impact in GVN 10)

Justification: Payment interoperability can materially support machine-to-machine transactions, robot-as-a-service, and cross-platform autonomous service exchange, which are relevant second-

order enablers for this GVN. But it does not directly create automation capability, and many automated systems can still operate on existing payment rails. The impact is material but bounded.

Weak signals (7):

- (+) [Machine-to-machine trade] → [robots or software agents pay for services without human invoicing] (reduces transaction labor)
- (+) [Shared machinery] → [usage-based robot leasing settles across different payment systems] (supports pooled access)
- (+) [Cross-border operations] → [autonomous services settle instantly across jurisdictions] (cuts administrative friction)
- (+) [Conditional work] → [payments release automatically on machine-verified completion] (makes autonomous contracting easier)
- (–) [Compliance burden] → [KYC and reporting still require human intervention in edge cases] (limits full automation)
- (–) [Fraud/security] → [wallet compromise becomes a route into machine-economy disruption] (shows new attack surface)
- (–) [Governance] → [payment-network rule disputes slow shared automation platforms] (keeps effect bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

Score: 10 (Impact in GVN 10)

Justification: Regulation is an explicit inhibitor in the GVN, and rules-as-code can materially reduce the cost, delay, and ambiguity of making automated systems compliant and auditable. First-order it lets machines and deployment platforms check requirements automatically; second-order it shifts power toward whoever encodes and updates rules while also making enforcement more automatic; third-order it can speed diffusion of automation into sectors where compliance complexity currently blocks adoption. That makes it transformative for the operating model, even though it is governance infrastructure rather than a machine technology.

Weak signals (9):

- (+) [Regulatory barriers] → [permits and compliance checks are executed through rule APIs] (cuts interpretation lag)
- (+) [Deployment speed] → [automation vendors ship jurisdiction-specific compliance profiles] (reduces customization burden)
- (+) [Auditability] → [inspectors accept machine-generated compliance traces] (makes automation evidence legible)
- (+) [SME adoption] → [small operators buy ready-made compliance engines instead of consultants] (lowers entry barrier)
- (+) [Policy change response] → [sites update workflows quickly after rule revisions] (shortens adaptation cycle)
- (+) [Liability clarity] → [incident reviews reference executed rule versions] (formalizes accountability)

- (–) [Over-automation of enforcement] → [minor breaches trigger rigid system shutdowns] (shows governance brittleness)
- (–) [Encoding power] → [few intermediaries control canonical digital rule libraries] (concentrates institutional power)
- (–) [Edge cases] → [human review remains necessary where rules are ambiguous] (keeps it below keystone)

## ART 12.097 — Open Metaverse Interoperability Protocols

Score: 1 (Impact in GVN 10)

Justification: Open metaverse protocols may help remote training, collaboration, and some digital work environments, but their direct role in replacing human labor with machines is peripheral. The main effect is as an optional interaction layer around automation, not as a core driver of the GVN. That keeps the score low.

Weak signals (5):

- (+) [Remote training] → [industrial skill sims become portable across vendors and devices] (would support automation onboarding)
- (+) [Digital twins] → [portable 3D spaces are used for machine supervision and rehearsal] (tests operational value)
- (+) [Cross-platform collaboration] → [service teams move among virtual workspaces without losing context] (reduces coordination friction)
- (–) [Workflow fit] → [most operators still prefer simpler dashboards over immersive environments] (limits broad effect)
- (–) [Bandwidth/compute] → [use stays confined to premium training and design cases] (keeps linkage narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 — Content Authenticity Infrastructure

Score: 3 (Impact in GVN 10)

Justification: Provenance infrastructure can materially improve trust in remote inspection, machine-generated reports, AI-captured evidence, and autonomous incident records. Its main effect is second-order: lowering verification labor and tightening accountability, while also creating new compliance obligations around credentialed content. The impact is real but bounded.

Weak signals (7):

- (+) [Remote inspection] → [buyers accept credentialed video as evidence for maintenance decisions] (cuts verification labor)
- (+) [AI-generated records] → [autonomous systems attach provenance to logs and media by default] (makes machine evidence usable)
- (+) [Liability] → [insurers require authenticated media in incident claims] (turns provenance into governance)



- (+) [Supply coordination] → [credentialed content is prioritized in distributed service platforms] (reduces trust friction)
- (–) [Adoption gaps] → [unauthenticated but accurate media still dominates many workflows] (limits effect)
- (–) [False trust] → [credentialed media is mistaken for ground truth rather than traceability] (shows misuse risk)
- (–) [Tool concentration] → [few capture/edit vendors control provenance roots] (creates gatekeeping power)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.099 — Privacy-Preserving Collaboration Protocols

Score: 5 (Impact in GVN 10)

Justification: These protocols are significant because many automation opportunities are blocked by the inability to combine sensitive operational data across firms, sites, or public agencies. First-order they enable joint analytics and model building without centralizing raw data; second-order they lower trust barriers while shifting value into cryptographic infrastructure and governance; third-order they make cross-organization automation ecosystems more feasible. That is significant, though not transformative on its own.

Weak signals (9):

- (+) [Fragmented operations] → [firms compute joint maintenance or demand insights without sharing raw logs] (unlocks collaboration)
- (+) [Sensitive sectors] → [health, utilities, and public services use secure analytics for automation planning] (widens high-friction adoption)
- (+) [SME participation] → [smaller actors join shared optimization networks safely] (reduces data-scale disadvantage)
- (+) [Cross-border coordination] → [multijurisdictional automation projects use privacy-preserving compute layers] (eases legal friction)
- (+) [Model quality] → [joint models outperform siloed ones in operational deployments] (proves value pathway)
- (+) [Human-free governance] → [safe-output checks are embedded in automated workflows] (cuts approval overhead)
- (–) [Performance cost] → [latency and compute overhead confine use to high-value cases] (keeps impact bounded)
- (–) [Key management] → [credential failures block shared automation runs] (shows operational fragility)
- (–) [Platform power] → [a few secure-compute providers dominate collaboration hubs] (concentrates ecosystem control)

## ART 12.100 — Manufacturing-Specific Standards, Conformance Testing & Certification Infrastructure

Score: 10 (Impact in GVN 10)

Justification: This ART is highly relevant because it converts advanced automated manufacturing from bespoke trust relationships into contractable, auditable, scalable capability. First-order it lowers qualification time for new machines and processes; second-order it changes who can enter supply chains, how insurers and buyers price risk, and how failures are attributed; third-order it speeds diffusion of reconfigurable and additive production models. That is transformative for the manufacturing side of the GVN.

Weak signals (9):

- (+) [Qualification bottlenecks] → [buyers accept machine-readable conformance certificates in procurement] (cuts adoption delay)
- (+) [SME access] → [smaller suppliers enter high-spec chains through certified benchmark jobs] (broadens participation)
- (+) [Process trust] → [new automated methods spread faster once common test suites exist] (reduces bespoke validation)
- (+) [Insurance] → [coverage terms reference certified process classes and test artifacts] (makes risk priceable)
- (+) [Remote auditing] → [inspectors rely on standardized digital evidence instead of site visits] (cuts verification labor)
- (+) [Reconfigurable factories] → [modular cells retain certification across redeployments] (supports fluid capacity)
- (–) [Gatekeeping] → [few labs or certifiers become mandatory approval points] (concentrates institutional power)
- (–) [Innovation friction] → [novel processes wait for standards before scaling] (shows lock-in risk)
- (–) [Data integrity] → [certificate fraud becomes a target in supply disputes] (raises assurance burden)

## GVN 11: Work and Income ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score: 20** (Impact in GVN 11)

**Justification (3–5 sentences):**

At maturity, this is a core layer of the challenger regime: it removes geography as a hard constraint on paid work, micro-entrepreneurship, platform participation, remote expertise, and digitally coordinated self-provisioning. The second-order effects are large: labor markets become more national/global, rural and low-density regions become more economically usable, and bargaining power shifts toward whichever platforms and service layers own identity, discovery, and payments. The downside is also large: wage arbitrage, surveillance, and stronger dependence on a few network operators can intensify insecurity. In a 5.5M society this plausibly changes weekly work/income conditions for hundreds of thousands of people and moves well above the >€1B anchor, so it is a linchpin rather than a mere enabler.

**Weak signals (9):**

- (+) [Equitable access to work] → remote vacancies in low-density regions rise after new coverage opens (geography barrier weakens)
- (+) [Self-employment] → households buy rugged terminals as business infrastructure (home enterprise becomes viable)
- (+) [Regional resilience] → coworking hubs market satellite/mesh redundancy (work continuity improves)
- (+) [Platform economy] → seller and freelancer counts jump in newly covered areas (market entry expands)
- (+) [Education/work pipeline] → training providers target previously underconnected populations (skills can convert)
- (+) [Public services for income] → welfare and employment portals support high-latency resilient access (formal participation widens)
- (–) [Bargaining power] → employers recruit nationally while offering location-flattened pay (wage arbitrage appears)
- (–) [Tax base] → tax authorities create new rules for cross-border remote work (income location blurs)
- (–) [Infrastructure dependence] → income-loss disputes follow prolonged service outages (network becomes livelihood-critical)

## ART 01.002 - Ultra-Low Latency Networks

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Mature ultra-low latency networks materially expand teleoperation, shared immersive workspaces, and remote control of machines, which changes who can perform certain jobs and from where. The main second-order effect is a new split between places with edge-grade infrastructure and those without, while labor shifts from site presence toward supervision, exception handling, and remote expert pools. The downside is tighter monitoring and centralization of control in firms that own the edge infrastructure. The plausible magnitude is in the €100M–1B / 50–500M person-hour band through logistics, manufacturing, care, and maintenance, but it is not a universal operating-model linchpin.

**Weak signals (9):**

- (+) [Remote skilled work] → teleoperation roles appear in industrial job postings (site presence weakens)
- (+) [Work infrastructure] → carriers sell deterministic-network SLAs to employers (timing becomes contractual)
- (+) [Training] → immersive work platforms require edge-certified setups (lag tolerance shrinks)
- (+) [SME access] → managed low-latency services target mid-sized firms (entry barrier falls)
- (+) [Insurance] → remote-control equipment policies differentiate by latency guarantees (trust becomes priced)
- (+) [Facility design] → edge nodes are sited next to industrial campuses (place value shifts)
- (–) [Worker autonomy] → labor agreements define override rights in remote control (control conflict visible)
- (–) [Regional equality] → premium jobs cluster near edge-rich regions (infrastructure inequality grows)

- (–) [Safety/accountability] → incident reports cite timing jitter in human-in-loop systems (new failure mode visible)

## ART 01.003 - Edge AI for Sensor Data

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

At maturity, edge AI gives small firms, households, and distributed workers local judgment at the point of work, lowering dependence on central experts and cloud connectivity. Institutionally, it shifts value toward whoever configures thresholds, models, and update channels, while also making privacy-compliant automation easier. The downside is deskilling and machine-led work pacing. The likely scale is significant—€100M–1B or 50–500M person-hours affected—especially in maintenance, retail, logistics, buildings, and small manufacturing.

**Weak signals (9):**

- (+) [SME productivity] → edge-AI inspection kits are sold as subscriptions (automation becomes affordable)
- (+) [Job redesign] → line workers are hired to supervise AI sensors (roles move upward)
- (+) [Local resilience] → firms choose on-device analytics over cloud dependence (connectivity risk falls)
- (+) [Privacy acceptance] → procurement requires raw data to stay on site (deployment becomes acceptable)
- (+) [Service markets] → local installers offer “AI monitoring” for small assets (new income niche)
- (+) [Insurance] → policies reward anomaly detection before failure (prevention becomes monetized)
- (–) [Labor intensity] → performance targets start using machine-generated classifications (pace pressure rises)
- (–) [Accountability] → disputes emerge over false alerts or missed detections (decision ownership blurs)
- (+) [Skills pipeline] → technician training shifts from repair only to model tuning (capability mix changes)

## ART 01.004 - Quantum & High-Precision Sensing

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The link to work and income is real but niche: better measurement can improve a few high-value sectors such as advanced manufacturing, navigation, and specialist diagnostics. Second- and third-order effects remain concentrated in technical clusters rather than changing the broad operating model of work and income. It is worth watching, but it stays below the major society-level anchors for this GVN. A higher score would require widespread embedding into everyday work infrastructure rather than premium specialist use.

**Weak signals (3):**

- (+) [High-value specialist work] → critical industries procure quantum-sensing services (niche demand forms)

- (+) [Skills pipeline] → precision-metrology certifications add quantum modules (specialist labor forms)
  - (+) [Industrial policy] → advanced instrumentation clusters get targeted support (niche jobs concentrate)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Mature micro/nano sensor networks make many more assets and environments continuously legible, which cuts inspection effort and allows smaller teams to manage larger physical footprints. Institutionally, this favors condition-based maintenance and data-rich asset owners, while creating surveillance and responsibility questions in workplaces. The effect is material but still bounded at society scale. A higher score would need a stronger pathway into broad labor-market surveillance or a major household self-service economy.

**Weak signals (5):**

- (+) [Asset management] → building and fleet owners deploy dense sensor patches (manual checking declines)
  - (+) [Maintenance models] → contracts move to condition-based service levels (work timing changes)
  - (+) [Skills pipeline] → technician training adds mesh/gateway diagnostics (new routine capability)
  - (+) [Insurance] → claims handling starts requiring sensor histories (trust shifts to logs)
  - (–) [Workplace monitoring] → employee representatives challenge ambient sensor density (surveillance concerns rise)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

This materially matters because it makes continuous sensing socially and legally deployable in work settings where raw monitoring would otherwise be blocked. The second-order effect is a governance shift: more workflows become machine-observed, but disputes move from “whether to sense” to “what may be inferred and retained.” That is meaningful for this GVN, but still not large enough to redefine the whole operating model. A higher score would require privacy-preserving sensing to unlock a much broader reorganization of labor markets.

**Weak signals (5):**

- (+) [Acceptable monitoring] → works councils approve on-device analytics where raw video is banned (deployment barrier falls)
- (+) [Procurement] → buyers require local processing and short retention defaults (trust gets operationalized)
- (+) [Compliance market] → privacy seals emerge for workplace sensing stacks (market trust forms)

- (–) [Bargaining power] → labor agreements define inference limits, not only data capture (conflict shifts upstream)
  - (+) [Cross-border work] → firms use privacy-preserving sensing to enable remote supervision abroad (jurisdiction friction eases)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

The main linkage is through trust in remote work, payments, identity, and automated operations whose records must remain secure for long periods. The institutional effect is mostly on compliance, insurance, and vendor selection rather than on the day-to-day structure of work itself. That makes the impact material but limited. A higher score would require widespread dependence of labor markets and income systems on long-horizon secure digital coordination.

**Weak signals (5):**

- (+) [Employment/payment integrity] → public tenders require post-quantum migration for payroll or benefit systems (trust standard rises)
  - (+) [Remote work infrastructure] → employers buy quantum-safe connectivity for critical operations (secure work expands)
  - (+) [Insurance] → cyber policies price upgrade paths into premiums (security becomes economic filter)
  - (–) [Market concentration] → only a few vendors can certify end-to-end compliance (supplier power rises)
  - (+) [Auditability] → labor and finance platforms advertise long-term record integrity (institutional confidence grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 - Integrated Sensing and Communication (ISAC)

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

ISAC reduces the need for separate monitoring infrastructure and supports more automated, responsive workplaces and logistics spaces. The second-order impact is mainly on safety practices, privacy rules, and who owns the new sensing layer embedded in communications networks. It is a real but bounded work-and-income effect. A higher score would require communications-based sensing to become a core labor-market control or access infrastructure.

**Weak signals (5):**

- (+) [Operational awareness] → warehouses and campuses buy ISAC-ready network upgrades (monitoring cost falls)
- (+) [Safety] → safety cases cite radio-sensing redundancy in crowded work areas (automation becomes acceptable)
- (+) [Facility services] → telecom contracts bundle sensing APIs with connectivity (new service layer forms)

- (–) [Worker privacy] → complaints rise about passive location or motion tracking (surveillance conflict appears)
  - (+) [Regulation] → building or workplace standards recognize communications-based occupancy sensing (institutional pathway opens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These chips matter for work and income because they cut the cost and power burden of embedded intelligence in tools, sensors, and robots, especially for low-margin or mobile use cases.

Institutionally, they broaden access to local AI but mostly as an enabling layer rather than a visible labor-market institution. The impact is concrete but limited at whole-society scale. A higher score would require a much clearer pathway from cheaper embedded AI to large-scale reorganization of work relations.

**Weak signals (5):**

- (+) [SME automation] → low-power AI devices replace cloud-only subscriptions (local capability expands)
  - (+) [Tool design] → always-on inference appears in battery-sensitive work tools (new use cases open)
  - (+) [Privacy] → buyers prefer on-device intelligence for sensitive sites (raw-data transfer declines)
  - (+) [Skills] → embedded-AI maintenance enters vocational curricula (new capability becomes routine)
  - (–) [Platform power] → chip-specific software stacks lock users into vendor ecosystems (dependency shifts)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

The work-and-income linkage is indirect but real: cheaper, denser, lower-power computing spreads AI and automation into more devices and more sectors. The second-order effects are mostly through supply-chain clustering, hardware competitiveness, and the falling cost of digital capability rather than through a direct labor-market institution. That keeps the score at a bounded material level. A higher score would require these hardware gains to translate more directly into broad workforce restructuring.

**Weak signals (5):**



- (+) [Distributed productivity] → work devices gain more local compute without higher power budgets (AI spreads downward)
  - (+) [Industrial policy] → regional fabs or packaging lines attract workforce programs (job base forms)
  - (+) [SME access] → advanced compute shows up in mid-market equipment tiers (capability democratizes)
  - (–) [Geopolitics] → export controls tighten around post-CMOS components (supply risk rises)
  - (+) [Skills] → device-service jobs shift toward advanced hardware diagnostics (labor mix evolves)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

Quantum platforms can matter in a few premium sectors, but broad work-and-income effects are indirect and concentrated. Most impacts arrive through specialist optimization, finance, or R&D services rather than through how most people earn, save, or access work. It stays a watch item rather than a major GVN driver. A higher score would require quantum services to become a routine layer in mainstream business operations.

**Weak signals (3):**

- (+) [Specialist digital work] → logistics or finance contracts start buying quantum-access services (niche demand emerges)
  - (+) [Skills pipeline] → hybrid quantum operations certificates appear (specialist labor forms)
  - (+) [Industrial cluster] → local policy funds quantum-cloud or cryogenic control capabilities (niche job base grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Photonic computing matters chiefly by lowering the cost and energy burden of AI-heavy and data-heavy services that increasingly shape work. The second-order effect is faster AI diffusion and more local or affordable inference, but the technology remains one layer down from the visible operating model of employment and income. That supports a material but not transformative score. A higher score would require more direct labor-market restructuring from much cheaper compute.

**Weak signals (5):**

- (+) [AI affordability] → cloud and edge services advertise lower inference costs via optical accelerators (capability gets cheaper)
- (+) [Energy burden] → data-heavy employers cite lower cooling loads in siting decisions (operating costs change)

- (+) [SME access] → advanced analytics become cheaper in standard software plans (entry barrier falls)
  - (+) [Skills] → electro-optic hardware integration jobs appear (new labor niche forms)
  - (–) [Vendor dependence] → workloads become tied to specialized photonic toolchains (lock-in risk grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Better memory and storage lower the cost of keeping models, records, and digital twins close to where work happens, which improves continuity and reduces loading, recovery, and data-movement frictions. Institutionally, that helps smaller firms use heavier data workflows without hyperscaler dependence, but it remains an enabling shift rather than a new work regime. Hence a bounded material score. A higher score would require a clearer path from storage abundance to widespread new earning models.

**Weak signals (5):**

- (+) [SME data capacity] → industrial and office systems ship with persistent non-volatile tiers (heavier workflows localize)
  - (+) [Continuity] → downtime costs drop where systems recover state instantly (earnings interruptions shrink)
  - (+) [Knowledge retention] → firms keep more live operational history on site (expertise becomes reusable)
  - (+) [Compliance] → long-lived audit storage becomes standard in small-business software (formal participation eases)
  - (–) [Platform power] → premium memory stacks are bundled into closed vendor ecosystems (dependency risk grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The linkage to this GVN is mostly through niche bio-process or chemical environments where electronics are a poor fit. Second-order effects remain concentrated in specialist sectors and are unlikely to materially alter how work and income are organized for the broader population. It is worth monitoring, but only as a niche pathway. A higher score would require surprising spillovers into mainstream industrial or service infrastructure.

**Weak signals (3):**

- (+) [Specialist production] → process-control kits begin embedding molecular logic modules (niche utility appears)
- (+) [Skills pipeline] → training appears for molecular-computing operations in bio labs (specialist labor forms)

- (+) [Industrial policy] → dedicated programs back molecular-computing pilot manufacturing (niche job base forms)  
Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Causal systems materially improve pricing, staffing, safety, and intervention choices, which directly affects earnings, productivity, and resource use across many sectors. Institutionally, they shift power toward actors that can run counterfactual simulations and justify rules with formal cause-effect models; the downside is overconfident managerial control disguised as “science.” The likely magnitude is in the €100M–1B / 50–500M person-hour range, but not a full regime linchpin. A 10 would require causal systems to become the dominant control layer for major labor markets and public programs.

**Weak signals (9):**

- (+) [Decision quality] → firms buy counterfactual tools for staffing or pricing (intervention quality rises)
- (+) [Policy design] → employment programs require causal evidence before scaling (public money targets better)
- (+) [Hiring] → job ads ask for causal-model audit skills (new expertise becomes valuable)
- (+) [Insurance] → insurers prefer interventions backed by causal testing (risk management sharpens)
- (–) [Worker power] → algorithmic productivity rules cite causal claims in disputes (managerial reach hardens)
- (+) [Platform transparency] → marketplaces explain ranking or pay changes via causal drivers (contestation improves)
- (+) [SME access] → low-code causal simulators reach non-specialists (analysis barrier falls)
- (–) [Accountability] → court cases question hidden assumptions in causal models (governance matures)
- (+) [Planning] → wage, pricing, and workflow scenarios become standard board tools (decision cycles shorten)

#### ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

This matters because it lets fragmented employers, workers, and institutions benefit from shared AI without surrendering raw sensitive data. The main second-order effect is a new institutional layer of sector consortia, data trusts, and managed collaboration, but the broad labor-market impact stays bounded. That places it in the material-but-limited band. A higher score would require federated learning to become a dominant backbone for labor-market intelligence and service delivery.

**Weak signals (5):**

- (+) [SME AI access] → sector consortia launch federated models for small firms (capability shares widen)
  - (+) [Worker privacy] → local-personalized tools run without centralized histories (trust barrier falls)
  - (+) [Procurement] → buyers require “data stays local” learning options (governance shifts)
  - (–) [Market structure] → a few orchestration providers dominate secure aggregation layers (new intermediary power)
  - (+) [Portable benefits] → shared models are used without raw cross-platform data pooling (institutional frictions ease)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 03.017 - Trustworthy AI Systems****Score: 10** (Impact in GVN 11)**Justification (3–5 sentences):**

Mature trustworthy AI is transformative because it makes automation, decision support, and AI-mediated services deployable in hiring, scheduling, finance, robotics, compliance, and public services without constant human distrust blocking adoption. The second-order effect is a major shift in liability, procurement, auditing, and labor relations: more decisions move to AI, but fairness, appeal rights, and traceability become central bargaining terrain. In a 5.5M society the weekly exposure is easily in the hundreds of thousands and above the >€1B anchor. It is still not as singularly foundational as the score-20 linchpins, because much of the value depends on broader AI diffusion already occurring.

**Weak signals (9):**

- (+) [Adoption barrier] → insurers price AI systems by auditability and fallback quality (trust becomes monetized)
- (+) [Public procurement] → contracts require provenance traces and safe fallback modes (deployment normalizes)
- (+) [Labor rights] → collective agreements specify review and appeal triggers for AI decisions (governance matures)
- (+) [SME access] → managed “trusted AI” services replace custom in-house compliance work (entry barrier falls)
- (–) [Work intensity] → firms expand AI-mediated scheduling and performance management (automation reaches labor control)
- (+) [Courts/compliance] → disputes turn on logged model behavior rather than black-box opacity (accountability operationalizes)
- (+) [Hiring/credit] → platforms publish confidence bands and contestation APIs (formal fairness improves)
- (+) [Standards] → workplace AI conformity assessments become routine (market trust scales)
- (–) [Power concentration] → certified high-trust stacks are dominated by a few vendors (compliance moats harden)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score: 20** (Impact in GVN 11)

**Justification (3–5 sentences):**

AutoML is a linchpin because it directly operationalizes the GVN’s challenger logic of easy access to productive tools and expertise: firms, communities, and individuals can build models and agents without scarce specialist labor. The second- and third-order effects are profound: automation diffuses into niches that large firms alone could not serve, new micro-enterprises appear, expert gatekeeping weakens, and labor-market turbulence rises as model creation becomes abundant and cheap. In a 5.5M society this plausibly changes weekly earning and work arrangements for hundreds of thousands and shifts well above the >€1B anchor. It is score 20 rather than 10 because it drastically increases the reach of many other ARTs rather than being just another AI capability.

**Weak signals (9):**

- (+) [Access to productive tools] → nontechnical staff deploy production models or agents (expert bottleneck breaks)
- (+) [SME competitiveness] → small firms buy AI “factories” instead of consulting projects (capability diffuses)
- (+) [Self-employment] → solo operators launch AI-native services with minimal technical hiring (microenterprise expands)
- (+) [Training] → reskilling shifts from coding models to specifying goals and guardrails (skill profile changes)
- (+) [Finance] → lenders finance AI upgrades for small businesses at scale (investment broadens)
- (–) [Job displacement] → routine analytics and support roles shrink quickly (middle-skill work erodes)
- (+) [Governance] → certification emerges for citizen-built models in high-stakes contexts (quality becomes institutionalized)
- (–) [Market saturation] → low-quality model spam floods digital service markets (trust costs rise)
- (+) [Tax base] → more value is created outside traditional firm structures (formal income models diversify)

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Collaborative multi-agent AI changes how work is organized by turning many tasks into orchestrated networks of software agents, machines, and a thinner layer of human supervisors. Institutionally, this shifts value toward orchestration platforms, data holders, and rule setters, while reducing demand for some coordination labor and increasing demand for exception handling, safety oversight, and customer trust. The scale is transformative for this GVN—hundreds of thousands can be affected weekly. It is not a score-20 linchpin because alternative pathways to automation and coordination could still emerge without full multi-agent maturity.

**Weak signals (9):**

- (+) [Work organization] → firms hire “agent fleet” supervisors for workflows once done by teams (coordination labor changes)
- (+) [Platform economy] → service platforms expose agent-to-agent APIs for task exchange (machine coordination scales)
- (+) [SME leverage] → very small firms run multi-agent service operations (small actors act large)
- (+) [Pricing models] → enterprise software moves from seat pricing to task pricing (labor economics shifts)
- (–) [Accountability] → incident logs cite failures between collaborating agents (responsibility blurs)
- (+) [Public services] → municipalities pilot agent coordination for local delivery (institutional acceptance grows)
- (–) [Worker power] → task allocation becomes more opaque and dynamic (bargaining terrain shifts)
- (+) [Safety] → regulation defines delegation and override thresholds (governance catches up)
- (+) [Cooperative work] → worker groups share agent pools instead of outsourcing admin (new organizational form appears)

## ART 03.020 - Quantum-Accelerated AI Systems

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The linkage is niche and premium: some optimization-heavy sectors may gain, but broad work-and-income structures do not depend on it. Second-order effects remain concentrated in high-end computing markets and specialist labor pools. That keeps it below the major anchors for this GVN. A higher score would require quantum acceleration to become routine inside mainstream AI services.

**Weak signals (3):**

- (+) [Premium digital work] → hybrid AI-quantum services appear in logistics or finance contracts (niche demand emerges)
  - (+) [Skills pipeline] → hiring appears for AI-quantum orchestration roles (specialist labor forms)
  - (+) [Market structure] → premium accelerator vendors bundle quantum subroutines into enterprise AI (niche stack forms)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

This materially affects R&D-intensive work by accelerating discovery cycles and changing the role of scientists, lab staff, and technical entrepreneurs. The second-order effects are meaningful in innovation systems, IP ownership, and research labor markets, but they do not directly reset the broad operating model of work and income. Hence a material but bounded score. A higher score would require much stronger spillovers from research automation into mass-market earning structures.

**Weak signals (5):**

- (+) [R&D employment] → labs hire fewer manual experiment planners and more automation operators (role mix shifts)
  - (+) [Innovation markets] → firms license AI-originated discoveries as standard assets (new value channel forms)
  - (+) [Public funding] → grant calls require autonomous discovery pipelines (institutional uptake grows)
  - (–) [IP ownership] → disputes emerge over inventor status and reward sharing (governance gap opens)
  - (+) [Regional clusters] → innovation hubs market autonomous-discovery infrastructure to firms (specialist jobs grow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

This is transformative because it directly supports one of the GVN's challenger pathways: remote work and telepresence through avatars, AR, and VR. The second-order effects are large—location constraints weaken, training becomes more embodied and scalable, and some service work becomes globally contestable. The downside includes biometric monitoring and new platform dependencies. The plausible magnitude easily exceeds the >€1B / hundreds-of-thousands-weekly threshold, though it is not the sole linchpin of the shift.

**Weak signals (9):**

- (+) [Remote work geography] → employers reimburse immersive work setups like core equipment (telepresence normalizes)
- (+) [Training] → training hours shift from classrooms to persistent simulations (knowledge transfer scales)
- (+) [Expert access] → remote expert services are sold as immersive shifts (scarce expertise travels)
- (+) [Disability inclusion] → employment programs fund spatial interfaces as accommodations (access broadens)
- (–) [Surveillance] → unions bargain over gaze, posture, and avatar analytics (biometric power grows)
- (+) [Commercial real estate] → office strategy assumes more spatial remote collaboration (space demand changes)
- (+) [Insurance] → insurers recognize immersive safety training in premiums (quality signal monetized)
- (–) [Wage competition] → firms source some spatial service labor globally (local bargaining weakens)
- (+) [Platform economy] → virtual coworking and marketplace rents become visible revenue streams (new intermediaries emerge)



## ART 04.023 - Brain-Computer Interfaces (BCI)

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

BCIs materially matter through accessibility and hands-free control in certain jobs, especially for people otherwise excluded from paid work. The main second-order effects are in disability inclusion, sensitive-data governance, and a few high-performance niche applications, but not in the broad structure of work for most people. That keeps the impact material yet limited. A higher score would require non-invasive BCIs to become mainstream interfaces across ordinary work.

**Weak signals (5):**

- (+) [Inclusive access to work] → vocational programs adopt non-invasive BCI accommodations (participation widens)
- (+) [Job redesign] → employers procure BCI control tools for specific hands-busy roles (interface barrier falls)
- (+) [Insurance] → return-to-work programs cover BCI-enabled assistive setups (income continuity improves)
- (–) [Neural privacy] → workplace policies restrict collection or reuse of neural data (power conflict visible)
- (+) [Standards] → safety and performance standards appear for workplace BCIs (market trust forms)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Mature prosthetics and exoskeletons materially expand who can participate in physical work, reduce injury losses, and support longer productive lives in manual occupations. Institutionally, they affect workers' compensation, retirement timing, accommodation duties, and workplace pace-setting, with the downside that employers may ratchet expectations once assisted work becomes normal. The likely magnitude is significant—well into the €100M–1B / 50–500M person-hour range. A 10 would require much broader normalization across mainstream work categories.

**Weak signals (9):**

- (+) [Physical work participation] → return-to-work programs fund powered wearables routinely (labor supply expands)
- (+) [Injury prevention] → warehouses and construction sites procure exosuits at scale (strain losses fall)
- (+) [Aging workforce] → employers redesign roles around wearable assistance (working lives lengthen)
- (+) [Insurance] → compensation premiums fall for assisted high-strain tasks (risk economics change)
- (–) [Work intensity] → productivity targets rise in assisted workplaces (pace pressure increases)
- (+) [Accessibility] → public procurement recognizes advanced prosthetic capability in employment inclusion (entry barriers shrink)

- (+) [Skills] → fit-testing, calibration, and wearable-maintenance roles emerge (new service jobs form)
- (–) [Labor rights] → unions negotiate voluntary-use and no-coercion clauses (control conflict appears)
- (+) [Asset models] → leasing markets emerge for assistive wearables (capital access widens)

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

The main work-and-income effect is through better teleoperation, training, and assistive control in selected sectors. Institutionally, that improves some remote skilled work and accessibility pathways, but it remains a bounded enabler rather than a broad labor-market transformer. So the impact is real but limited. A higher score would require haptic mediation to become central to mainstream remote work.

**Weak signals (5):**

- (+) [Remote skilled work] → teleoperation jobs specify haptic-certified setups (quality threshold rises)
  - (+) [Training] → apprenticeships use tactile simulation with scored performance (skills scale better)
  - (+) [Assistive work] → prosthetic or exoskeleton packages include closed-loop feedback by default (capability deepens)
  - (+) [Insurance] → policies distinguish haptic-assisted from visual-only remote work (risk becomes legible)
  - (–) [Vendor dependence] → high-end haptic ecosystems lock users into proprietary profiles (switching costs rise)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 - AI Understanding of Human Intent & Context

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

This is transformative because it changes the human-machine interface from explicit command-based operation to contextual cooperation, sharply lowering cognitive and skill barriers across many types of work. Institutionally, it redistributes power around behavioral data, attention inference, and adaptive management, which can widen inclusion while also enabling more intimate forms of surveillance and soft control. The scale plausibly crosses the transformative anchor because it changes everyday work tools for a very large share of workers. It is not a 20 because it is a major mode-shifter, but not the singular linchpin of the regime change.

**Weak signals (9):**

- (+) [Tool usability] → workplace software shifts from menus to intent-driven assistance (skill barrier falls)
- (+) [Accessibility] → employment support programs buy context-aware interfaces (participation widens)

- (+) [Customer work] → service staffing combines humans with intent-aware copilots (task mix changes)
- (+) [SME adoption] → off-the-shelf context-aware assistants reach ordinary office and service work (spread broadens)
- (–) [Behavioral surveillance] → HR policies restrict emotion or attention inference (soft control becomes salient)
- (+) [Productivity] → device bundles adapt timing and modality to user context (friction drops)
- (–) [Fairness] → disputes arise over misread intent affecting pay or evaluation (hidden inference harms appear)
- (+) [Device market] → enterprise devices ship with privacy-mode context models by default (institutionalization grows)
- (+) [Labor rights] → workers demand logs of inferred-state decisions (accountability becomes formal)

## ART 04.027 - Brain-to-Brain Interfaces

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

Even if technically mature, BBIs would affect work and income mainly in narrow specialist or accessibility contexts. The second-order effects are dominated by ethics, security, and liability rather than broad labor-market restructuring. That leaves it as a niche watch item for this GVN. A higher score would require widespread, non-specialist workplace adoption.

**Weak signals (3):**

- (+) [Specialist collaboration] → pilot industrial or medical teams use BBI channels (niche utility appears)
  - (+) [Ethics/governance] → workplace-use guidance is issued for transmitted neural states (boundary setting starts)
  - (–) [Insurance/liability] → policies add exclusions for neural-link harms (risk becomes explicit)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

Memory prostheses matter for a subset of workers with memory loss or highly interruption-sensitive tasks, but they do not clearly change how work and income are organized for the broader society. Second-order effects stay inside health, disability, and specialist professional settings. So the linkage is concrete but niche. A higher score would require mainstream cognitive augmentation in ordinary work.

**Weak signals (3):**

- (+) [Return to work] → rehabilitation programs trial implant-based memory aids (niche employment support appears)

- (+) [Credentials] → exam or certification rules adapt to memory-assist devices (institutional pathway opens)
  - (+) [Accommodation policy] → employers create formal policies for neural memory support (use becomes routine)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Self-driving vehicles transform a major work-and-income domain by automating driving labor, changing commuting and job-access patterns, and altering the time-cost structure of logistics and local services. The institutional effects are large: liability, insurance, fleet ownership, urban land use, and transport labor bargaining all shift, while the downside is direct displacement of a large occupational category. In a 5.5M society this easily reaches the transformative anchor in both € and weekly life exposure. It is not a 20 because the broader regime change in work and income does not strictly depend on autonomy in road transport.

**Weak signals (9):**

- (+) [Transport labor] → autonomous freight or passenger services scale commercially (driving labor substitutes)
- (–) [Occupation displacement] → driver vacancies fall while remote fleet-ops roles rise (job mix flips)
- (+) [Geographic access] → job-search radius expands where autonomous mobility is reliable (access widens)
- (+) [Insurance] → premiums split sharply between manual and autonomous fleets (risk model resets)
- (–) [Labor rights] → agreements focus on redeployment and notice periods for drivers (displacement becomes institutional)
- (+) [Urban economy] → depots, parking, and curb space are rezoned around autonomy (spatial model changes)
- (+) [Platform services] → human-driven delivery becomes premium-priced in some markets (labor revalues upward)
- (+) [Training] → colleges pivot from licensing drivers to training fleet supervisors (skills pipeline shifts)
- (–) [Accountability] → courts clarify no-driver liability repeatedly (governance matures under stress)

### ART 05.030 - Drone Swarms & Aerial Robots

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Drone swarms materially reduce the labor and time needed for inspection, mapping, security, and

some delivery work, while opening new remote service models. Institutionally, they favor data-rich operators and change airspace, safety, and privacy governance; the downside is aerial surveillance and reduced demand for some fieldwork. The likely magnitude is significant but sector-bounded. A 10 would require drones to become a mainstream labor and logistics layer beyond these domains.

#### **Weak signals (9):**

- (+) [Inspection work] → routine asset contracts specify swarm-based coverage (manual visits shrink)
- (+) [Service entrepreneurship] → small firms sell aerial mapping or response subscriptions (new income niches form)
- (+) [Zoning/airspace] → rooftop docking and corridor permissions appear in local rules (deployment normalizes)
- (+) [Insurance] → claims and maintenance insurers reward swarm evidence (faster decisions matter)
- (–) [Worker surveillance] → unions contest aerial monitoring of crews and sites (power conflict rises)
- (+) [Agriculture/construction] → bids include swarm monitoring line items routinely (adoption broadens)
- (+) [Jobs] → remote mission management roles replace some pilot-only roles (task mix shifts)
- (–) [Public trust] → local complaints cluster around noise and privacy hotspots (social license becomes visible)
- (+) [Software integration] → productivity/pay systems ingest drone-derived data (management practices change)

## **ART 05.031 - Humanoid and General-Purpose Robots**

**Score: 20** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

This is a linchpin because it extends automation into human-designed environments without waiting for total environmental redesign, directly targeting a huge share of physical work. The second- and third-order effects are profound: routine service, logistics, retail, care support, maintenance, and domestic labor can be reorganized around capital ownership of embodied machine labor, while human work shifts toward oversight, trust, relationship, creativity, and exception handling. Risks include deep displacement, new inequality, and stronger capital concentration. The plausible scale is well above the >€1B anchor and affects weekly life for hundreds of thousands, making it one of the most important regime-shifting ARTs for this GVN.

#### **Weak signals (9):**

- (+) [Physical labor substitution] → employers buy humanoid labor-as-a-service for multi-task shifts (embodied automation scales)
- (–) [Occupation displacement] → routine physical job postings fall while robot exception-handling roles rise (job structure flips)
- (+) [SME access] → banks finance robots against projected labor savings (capital access widens)
- (–) [Tax/governance] → policy debate shifts toward robot capital vs payroll taxes (tax base stress appears)

- (+) [Home/self-service economy] → households subscribe to robot-backed services (paid/free work boundary blurs)
- (+) [Standards] → “human-space safe” certifications become mainstream (deployment barrier falls)
- (–) [Inequality] → ownership of productive robots becomes a visible wealth divide (asset concentration grows)
- (+) [Labor rights] → bargaining includes robot deployment notice and gain-sharing (institutional conflict matures)
- (+) [Service models] → remote experts supervise fleets of embodied robots (skills leverage multiplies)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Soft robotics materially matters in specific settings where safe, adaptive handling beats rigid automation, which can reduce injuries and enable automation of awkward tasks. The second-order effects are concentrated in food, care, fragile-goods handling, and confined spaces rather than across the whole labor market. That supports a bounded material score. A higher score would require soft robotic formats to spread far beyond niche safe-handling contexts.

**Weak signals (5):**

- (+) [Safe handling work] → fragile-goods and care facilities adopt soft-contact automation (manual strain falls)
  - (+) [Procurement] → buyers prefer soft robots where injury claims are high (risk economics shift)
  - (+) [Skills] → technician training adds soft-actuator maintenance (niche labor forms)
  - (+) [SME access] → contract manufacturers market soft-robot cells to smaller firms (entry barrier falls)
  - (–) [Job redesign] → repetitive handling roles shrink in soft-robot-ready sites (task mix changes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

This family materially reduces the need for human presence in hazardous, remote, or hard-to-reach work, especially in utilities, inspection, environmental services, and infrastructure. Institutionally, it shifts work from field deployment toward remote supervision, data interpretation, and fleet maintenance, while concentrating value in operators that control maps, data, and mission software. The magnitude is significant but not broad enough for a 10. A higher score would require these systems to become mainstream across ordinary local service work as well.

**Weak signals (9):**

- (+) [Hazardous work] → utilities, ports, or mines cut routine field visits through autonomous fleets (exposure drops)

- (+) [Remote supervision] → mission-control hubs hire fewer field crews and more remote operators (job geography shifts)
- (+) [Procurement] → contracts require autonomy-ready logs and digital maps (institutionalization grows)
- (+) [Insurance] → continuous robotic inspection lowers interruption or failure premiums (prevention monetizes)
- (–) [Labor rights] → unions seek minimum human presence rules (displacement pressure visible)
- (+) [Local service jobs] → payload servicing and maintenance become local support trades (new niches form)
- (–) [Safety] → incident databases track unsupervised mission failures (governance matures)
- (+) [Regulation] → approved unattended-operation envelopes widen (deployment barrier falls)
- (+) [Productivity] → worker-per-asset ratios shift after autonomy rollout (labor leverage rises)

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score: 5** (Impact in GVN 11)

### **Justification (3–5 sentences):**

This infrastructure materially lowers the cost of deploying robots and autonomous systems in ordinary facilities, which can accelerate automation in logistics, hospitals, campuses, retail, and buildings. The second-order effect is a shift of value toward landlords, infrastructure owners, and standards setters, with downside risks that machine-native spaces are optimized against worker autonomy or comfort. The impact is significant, but still derivative of broader autonomy adoption. A 10 would require autonomy-support infrastructure to become as universal and economically decisive as roads or broadband for work access.

### **Weak signals (9):**

- (+) [Automation readiness] → new buildings market autonomy-ready certifications (deployment friction falls)
- (+) [Landlord power] → leases price access to robot lanes, docks, or localization layers (value shifts to infrastructure)
- (+) [Capex patterns] → retrofits for robot-readability appear in facility budgets (physical layer changes)
- (+) [Codes/governance] → building rules define machine-only circulation zones (institutional recognition grows)
- (+) [SME access] → simpler robots succeed once infrastructure does more of the work (capital threshold falls)
- (–) [Worker environment] → staff challenge layouts that prioritize machine flow over human comfort (distributional tension appears)
- (+) [Insurance] → certified autonomy infrastructure becomes a risk requirement (trust gets priced)
- (+) [Local jobs] → installers and auditors for autonomy infrastructure emerge (new service niche forms)
- (–) [Vendor lock-in] → facilities are tied to specific infrastructure standards (platform dependence grows)



## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The linkage is mainly through a narrow set of remote or hazardous operations where long-duration robotic uptime matters. Second-order effects remain concentrated in infrastructure, regulation, and specialist service contracts rather than broad employment patterns. It is a niche watchpoint for this GVN. A higher score would require beamed power to become a widespread enabling layer for normal local service robotics rather than exceptional environments.

**Weak signals (3):**

- (+) [Remote operations] → persistent-robot contracts include beam-powered uptime guarantees (niche value appears)
  - (+) [Safety governance] → regulators publish work-site exclusion-zone rules for beaming (institutional pathway opens)
  - (+) [Labor substitution] → remote asset owners replace battery-swap staffing with beaming tenders (niche job shift forms)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The work-and-income effect is narrow and component-level: it helps certain inspection and handling tasks, but does not by itself change the operating model of earning and work access. Spillovers remain inside specialized maintenance and robotics niches. That keeps the score low. A higher score would require dry-adhesion mobility to unlock a much broader class of routine service and construction work.

**Weak signals (3):**

- (+) [Height work] → facade or turbine inspection robots advertise dry-adhesion upgrades (niche substitution appears)
  - (+) [Safety] → standards approve residue-free climbing automation on sensitive surfaces (market pathway opens)
  - (+) [Maintenance labor] → contractors report fewer scaffold hours for specific jobs (task substitution becomes visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

## ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

This materially supports the GVN's "economy of smallness" by lowering minimum efficient scale for making complex goods, repairs, and customized items locally. Institutionally, it shifts value from assembly chains toward design files, feedstocks, and service networks, while also risking new IP concentration and fewer routine assembly roles. The likely magnitude is significant, especially for local manufacturing, repair, and microenterprise. A 10 would require these systems to become a dominant route for everyday household and SME production rather than an important niche.

**Weak signals (9):**

- (+) [Local production] → print farms replace outsourced assembly for complex low-volume parts (small-batch viability rises)
- (+) [Repair economy] → repair businesses sell printed replacements on demand (resource saving monetizes)
- (+) [Skills] → training shifts toward design-for-hybrid-print skills (capability mix changes)
- (+) [Public procurement] → buyers accept printed multi-material spares routinely (institutional trust rises)
- (–) [IP power] → disputes increase over printable component files (ownership tension grows)
- (+) [Household enterprise] → advanced printers are leased for microbusiness use (entry threshold falls)
- (+) [Insurance/certification] → printed embedded-electronics parts gain coverage or approval in some uses (market expands)
- (+) [Supply chains] → contracts move from finished parts to material-plus-design subscriptions (business model changes)
- (+) [Regional policy] → microfactory clusters are promoted as employment infrastructure (place-based adoption starts)

## ART 06.038 - Digital Twin & Simulation-Driven Production

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Digital twins materially lower downtime, scrap, and ramp-up time, which directly affects earnings, output, and business resilience. The second-order effect is a redistribution of power toward actors with better models and data continuity, while embedding scarce expertise into reusable digital assets that smaller firms can increasingly buy. The scale is significant, but mostly through production and asset-heavy sectors rather than the entire GVN. A 10 would require digital twins to become a generalized operating layer for most workplaces, not just production-intensive ones.

**Weak signals (9):**

- (+) [Operational productivity] → new lines require twin-linked commissioning before go-live (ramp-up risk falls)
- (+) [Expert leverage] → remote expert centers support multiple sites through shared twins (scarce skills scale)

- (+) [Insurance] → validated twins influence downtime or interruption premiums (trust becomes priced)
- (+) [Supplier access] → vendors must provide model-ready data with equipment (institutional standard rises)
- (+) [Training] → workers rehearse interventions in twins rather than only live systems (learning speed improves)
- (–) [Labor control] → model outputs are used in productivity targets and audits (work becomes more legible)
- (+) [SME access] → smaller manufacturers buy twin subscriptions instead of full engineering teams (entry barrier falls)
- (+) [Disputes] → downtime investigations rely on twin logs as evidence (accountability formalizes)
- (+) [Investment] → lenders favor better-modeled production upgrades (capital cost shifts)

## ART 06.039 - Reconfigurable & Agile Factories

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Reconfigurable factories materially support shorter runs, faster product changes, and more local manufacturing, which aligns with the GVN's move away from rigid large-scale specialization. Institutionally, they favor modular suppliers, multi-skilled workers, and firms that can orchestrate changeovers, while increasing volatility in work tasks and schedules. The likely magnitude is significant, but mainly within manufacturing and adjacent services. A 10 would require agile factories to become a dominant backbone of regional employment and small-firm production.

**Weak signals (9):**

- (+) [Batch-size barrier] → firms accept smaller production runs without severe price penalties (local variety becomes viable)
- (+) [Skills] → training moves toward recipe management and rapid changeover (multi-skilling rises)
- (+) [Regional production] → development agencies fund modular cell parks (local capacity diversifies)
- (+) [Finance] → lenders treat modular cells as flexible assets (investment risk falls)
- (–) [Work volatility] → labor contracts start covering frequent task reconfiguration (job stability changes)
- (+) [Supply resilience] → demand shocks cause shorter shutdowns in modular plants (income continuity improves)
- (+) [SME access] → firms rent modules by the month rather than own full lines (entry threshold falls)
- (+) [Procurement] → buyers prefer suppliers with fast variant-switch capability (market rewards flexibility)
- (–) [Cyber/governance] → reconfiguration errors and recipe-control disputes increase (new coordination risk appears)

## ART 06.040 - Circular & Sustainable Manufacturing

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

This materially changes work and income by creating local repair, remanufacture, sorting, and feedstock-processing work while lowering some household and business costs through reuse. Institutionally, it shifts value away from virgin-throughput models toward traceability, take-back, and material stewardship, with downside pressure on incumbent extractive or disposable business models. The likely magnitude is significant and spread across many sectors, though not fully transformative of the whole GVN. A 10 would require circular models to become the dominant operating logic for mainstream production and consumption.

#### **Weak signals (9):**

- (+) [Repair work] → manufacturers sign take-back and remanufacture contracts at scale (local loops grow)
- (+) [Jobs] → postings rise for disassembly, sorting, and material-passport roles (new labor niches form)
- (+) [Household savings] → refurbished goods gain mainstream share in durable categories (resource saving becomes normal)
- (+) [Procurement] → public buyers require recoverable or recycled content with tracking (market demand shifts)
- (+) [Finance] → recoverable material streams are valued as collateral (waste becomes asset)
- (–) [Incumbent disruption] → disposable or virgin-input producers lobby against new standards (distributional conflict appears)
- (+) [Waste sector change] → waste firms reposition as feedstock brokers (business model flips)
- (+) [Insurance] → warranties adapt to remanufactured quality assurance (trust formalizes)
- (+) [Regional policy] → local circular parks are used as employment strategy (place-based income effects start)

## **ART 06.041 - Bio-fabrication technologies**

**Score: 1** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

The link to work and income is real but concentrated in specialist biotech and healthcare production niches. Broader labor-market effects are indirect and too narrow to affect the main operating model of this GVN. So it remains a niche watch item. A higher score would require biofabrication to spill over far beyond specialized biomedical value chains.

#### **Weak signals (3):**

- (+) [Specialist production] → hospitals and firms buy standardized bioprinted products (niche demand forms)
  - (+) [Skills pipeline] → technician certifications for bioprinter operations appear (specialist labor forms)
  - (+) [Industrial policy] → clusters target biofabrication manufacturing capability (local niche job base grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The main linkage is via a few product and maintenance niches where self-changing components reduce labor or downtime. Second-order effects do not clearly propagate into the broad work-and-income regime. It is worth tracking, but only as a niche enabler. A higher score would require programmable materials to become a widespread substitute for labor-intensive maintenance or assembly.

**Weak signals (3):**

- (+) [Maintenance savings] → adaptive components enter premium product lines (labor-saving use case appears)
- (+) [Design practice] → lifecycle-state specifications appear in engineering workflows (institutional pathway opens)
- (+) [Service models] → maintenance contracts rely on self-deploying parts (niche task substitution forms)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Volumetric printing materially shortens prototyping and some custom production cycles, lowering inventory and speeding local experimentation. The main second-order effect is lower entry barriers for design-led small production firms, but the broader labor-market effects remain bounded. This fits the material-but-limited anchor. A higher score would require widespread use in ordinary consumer and SME production rather than specialized fast-cycle manufacturing.

**Weak signals (5):**

- (+) [Prototype speed] → product teams shift prototype cycles from weeks to days (iteration labor compresses)
- (+) [Service markets] → bureaus advertise minute-scale 3D production (small-batch timing changes)
- (+) [Inventory savings] → small firms use on-demand prints instead of stocking niche parts (capital is freed)
- (+) [Procurement] → volumetric-printed tooling or custom parts enter accepted vendor lists (market trust grows)
- (–) [IP/ownership] → print recipe licensing becomes more contentious (design power centralizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

## ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The work-and-income linkage is mostly indirect through better connectivity or sensing hardware rather than a direct change in labor structures. Second-order effects stay in specialized manufacturing and telecom equipment niches. That keeps the impact minor for this GVN. A higher score would require metamaterial surfaces to become a widespread enabling layer for everyday work access or industrial productivity.

**Weak signals (3):**

- (+) [Connectivity equipment] → telecom or building projects specify reconfigurable wave-control surfaces (niche demand forms)
- (+) [Manufacturing] → dedicated lines for metamaterial panels open locally (specialist jobs appear)
- (+) [Skills] → installation or testing certifications emerge for these surfaces (labor niche forms)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.045 - Room-Temperature Superconductors

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

If truly mature and economically deployable, room-temperature superconductors materially lower energy losses and enable compact high-power systems, which changes industrial competitiveness, cost of living, and the feasibility of local energy-intensive production. Institutionally, they shift value toward infrastructure owners and advanced manufacturing regions, while also reducing some operating costs that currently constrain small producers and households. The magnitude could be significant for this GVN, though it is still an enabling physical layer rather than a direct labor-platform shift. A 10 would require much broader, faster diffusion into everyday distributed energy and transport systems.

**Weak signals (9):**

- (+) [Industrial competitiveness] → energy-intensive employers relocate to superconducting infrastructure zones (place advantage shifts)
- (+) [Household/resource savings] → energy burdens fall in early-retrofit districts (saving capacity rises)
- (+) [Equipment design] → smaller high-current machines replace bulkier legacy systems (new capital mix appears)
- (+) [Grid economics] → tariffs or investment plans assume lower transmission losses (system economics reset)
- (+) [Skills] → installation and testing trades emerge around superconducting links (new labor niches form)
- (+) [Microgrids/self-sufficiency] → local energy systems adopt superconducting backbones (decentralized resilience grows)
- (–) [Market concentration] → a few material/process suppliers dominate early rollout (infrastructure rents centralize)

- (+) [Industrial policy] → reindustrialization plans cite abundant low-loss power (policy logic changes)
- (+) [Insurance/safety] → fire and heat risk assumptions are revised for retrofitted systems (trust improves)

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These materials materially reduce downtime and replacement labor across many assets, which helps firms and households preserve resources. The second-order effects are mainly via longer warranties, condition-based maintenance, and lower demand for some routine replacement work rather than through a broad labor-market reorganization. So the impact is meaningful but limited. A higher score would require smart polymers to substantially reshape major maintenance labor markets.

**Weak signals (5):**

- (+) [Maintenance savings] → warranties lengthen where self-healing materials are adopted (repair burden falls)
  - (+) [Insurance] → insurers accept longer replacement intervals for smart-polymer components (risk model shifts)
  - (+) [Job redesign] → maintenance work moves from routine replacement to diagnostics (task mix changes)
  - (+) [Procurement] → wear-heavy assets specify adaptive polymers by default (adoption normalizes)
  - (–) [Supply chain] → some spare-part demand declines in affected asset classes (routine work shrinks)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These technologies materially improve process efficiency and asset lifetime in many industrial settings, which affects costs, uptime, and some hazardous maintenance work. The institutional effects are mostly through procurement, warranties, and service contracts rather than a new work regime. That points to a bounded material impact. A higher score would require much broader spillovers into household savings or labor structure across many sectors.

**Weak signals (5):**

- (+) [Process productivity] → plants adopt upgrade-only retrofits centered on catalysts/coatings (output rises without expansion)
- (+) [Maintenance safety] → worker exposure to cleaning or corrosion tasks falls in adopters (hazard burden drops)
- (+) [Service models] → uptime guarantees are bundled with advanced coatings (trust is commercialized)
- (+) [Skills] → specialist QA roles grow for nanocoating application and monitoring (new niche labor forms)



- (–) [Input dependence] → scarce-element price shocks affect coating/catalyst supply (new vulnerability appears)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Advanced metals matter because they reduce failures and maintenance cycles in harsh equipment, which saves labor and supports more reliable local production. The second-order effects are primarily in premium manufacturing, certification, and maintenance planning rather than in society-wide work access. That keeps the score at 3. A higher score would require these materials to unlock a much larger wave of local reindustrialization or workforce change.

**Weak signals (5):**

- (+) [Asset uptime] → critical employers switch high-wear components to advanced-metal grades (replacement labor falls)
- (+) [Maintenance intervals] → service records show longer part lifetimes after alloy switch (cost burden eases)
- (+) [Certification] → approval pathways open for HEA stock and powders (market pathway forms)
- (+) [Skills] → machining and QA training includes advanced-metal workflows (specialist labor expands)
- (–) [Supply risk] → expensive alloying elements create new input volatility (costs stay selective)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The effect on this GVN is mostly indirect through industrial decarbonization and plant retention. It can matter for a few sectors and jobs, but it does not clearly change how people broadly earn, save, or access work. So the linkage remains niche. A higher score would require CO<sub>2</sub> capture deployment to become decisive for regional employment and household economics.

**Weak signals (3):**

- (+) [Industrial retention] → local sites keep operations by adding modular capture media (jobs are preserved)
- (+) [New roles] → staffing plans add carbon-handling and sorbent-service work (niche employment forms)
- (+) [Policy] → subsidies tie continued operation to capture retrofits (work link becomes explicit)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These composites materially affect work and income through lighter, longer-lived, sensorized equipment and structures, which lowers downtime and some maintenance effort. Institutionally, they support advanced manufacturing niches and better condition monitoring, but they do not directly restructure the broader labor system. That keeps the impact bounded. A higher score would require these materials to become standard across mainstream work equipment and infrastructure.

**Weak signals (5):**

- (+) [Asset productivity] → employers buy composite tools or vehicles with embedded health sensing (downtime drops)
- (+) [Condition monitoring] → maintenance services read strain or damage directly from components (inspection work changes)
- (+) [Manufacturing jobs] → regional suppliers advertise graphene/CNT composite expertise (niche cluster forms)
- (+) [Safety] → lighter structures are adopted in tasks limited by worker handling burden (manual strain falls)
- (–) [Health/regulation] → nanoparticle handling rules tighten in manufacturing plants (operational burden appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Smart thermal materials materially reduce energy costs and thermal stress in homes, offices, and processes, which supports savings, home-based work, and more reliable operations. The second-order effects are broad but diffuse, mainly through retrofits, tariffs, and building-value differentials rather than new labor institutions. That supports a material-but-limited score. A higher score would require much stronger adoption in household and SME economic infrastructure.

**Weak signals (5):**

- (+) [Household savings] → retrofits with thermal-storage or switchable materials scale in housing (resource burden falls)
- (+) [Home-based work] → home-business financing includes smart thermal upgrades (self-employment support grows)
- (+) [Utilities] → tariffs reward thermal-buffering materials in demand programs (asset value changes)
- (+) [Workplace resilience] → heat-related productivity losses fall in retrofitted sites (continuity improves)
- (–) [Distribution] → premium retrofits concentrate first in owner-occupied, higher-income properties (inequality risk appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

The main linkage is through motor and robotics supply resilience, which affects the cost and availability of many productive assets. Institutionally, this matters for industrial planning and expansion risk, but it stays one step removed from how work and income are directly organized. So the score remains bounded. A higher score would require rare-earth-free magnets to trigger a much larger, society-wide wave of affordable electrification and automation.

**Weak signals (5):**

- (+) [Automation supply] → motor suppliers market rare-earth-free lines to fleet and robotics buyers (input risk drops)
- (+) [Procurement] → tenders start preferring non-rare-earth magnet content (governance shifts)
- (+) [Factory expansion] → plants cite magnet availability when deciding capacity growth (employment link appears)
- (–) [Transition costs] → legacy designs need redesign before adoption (switching friction becomes visible)
- (+) [Skills] → workforce programs target alternative-magnet manufacturing (new niche jobs form)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

In this society, the linkage to work and income is mostly sectoral unless water scarcity becomes a much stronger constraint on housing or business growth. Most effects are indirect through utilities, selected industries, and resilience planning. That makes it a niche watchpoint. A higher score would require water availability to become a broad bottleneck on regional livelihoods.

**Weak signals (3):**

- (+) [Industrial continuity] → water-stressed employers sign low-energy desalination contracts (water becomes job enabler)
- (+) [Regional growth] → business or housing zones add decentralized desalination (water barrier starts to loosen)
- (+) [Utility costs] → utilities report labor and energy savings from longer membrane run-times (cost pressure eases)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These components materially improve the efficiency and compactness of power electronics in robots, tools, vehicles, chargers, and microgrids, which affects operating cost and uptime. The second-order effects are mostly through equipment design and maintenance economics rather than through a direct labor-market institution. That supports a bounded material score. A higher score would require these modules to sharply alter household and SME capital access across many sectors.

#### **Weak signals (5):**

- (+) [Equipment productivity] → industrial systems advertise smaller, cooler, higher-frequency power modules (OPEX drops)
- (+) [Robotics/fleets] → uptime-sensitive tenders require advanced power modules (reliability becomes differentiator)
- (+) [Maintenance] → field-service hours fall in heavily switched power systems (labor burden shrinks)
- (+) [Installation] → quieter/smaller converters enable new site deployments (space constraints ease)
- (–) [Supply chain] → a few module suppliers dominate high-performance tiers (dependency risk rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel**

**Score: 1** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

The linkage is through selected transport, backup-power, and industrial energy applications, not through the general organization of work and income. Second-order effects remain concentrated in safety practices and specialized energy logistics. So it stays a niche watch item. A higher score would require solid hydrogen storage to become a mainstream energy carrier for work and household systems.

#### **Weak signals (3):**

- (+) [Industrial energy logistics] → cartridge-like hydrogen storage pilots replace high-pressure handling at work sites (niche use becomes real)
- (+) [Safety governance] → regulators publish workplace handling rules for solid-storage systems (market pathway opens)
- (+) [Maintenance labor] → servicing plans shift from pressure systems to cartridge exchange (task structure changes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **8. Energy Generation, Storage & Conversion**

### **ART 08.056 - Fusion Energy Reactors**

**Score: 10** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

If mature and deployable, fusion materially changes work and income by lowering the cost and volatility of firm energy, enabling energy-intensive local industry, and reducing a major household expense burden. Institutionally, it reshapes industrial policy, utility power, and regional comparative advantage, while the downside is concentration of rents in owners of very large capital assets. The resulting shift plausibly clears the transformative anchor for this GVN, though fusion is not the only route to that shift. A 20 would require fusion to be a uniquely necessary linchpin of the whole regime transition rather than one strong route among several.

**Weak signals (9):**

- (+) [Industrial competitiveness] → employers site energy-intensive expansion near projected fusion supply (production geography shifts)
- (+) [Jobs] → utilities and suppliers publish workforce plans for fusion operations (new labor system forms)
- (+) [SME opportunity] → small manufacturers cluster around firm low-cost power expectations (entry conditions improve)
- (+) [Household savings] → electricity-burden metrics drop in early fusion-served areas (resource pressure eases)
- (+) [Policy] → industrial strategy explicitly links fusion to reindustrialization (institutional priority rises)
- (–) [Rent concentration] → debate focuses on who captures fusion cost savings (distributional conflict becomes visible)
- (+) [Labor negotiations] → wage claims reference lower energy overheads in exposed sectors (income bargaining shifts)
- (+) [Grid planning] → peaking assets are deprioritized after fusion commitments (system model resets)
- (+) [Finance] → long-term power contracts are used as employment attraction tools (energy becomes labor infrastructure)

## ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

SMRs materially affect this GVN by providing firm local power and heat for industry, critical employers, and resilient regional growth. The institutional effects are significant in siting, public risk governance, skilled labor formation, and local energy pricing, but the technology remains capital-intensive and not universally distributed. That places it in the significant-but-not-transformative band. A 10 would require much broader diffusion across local economies and household cost structures.

**Weak signals (9):**

- (+) [Industrial siting] → parks pursue co-located SMR heat/power proposals (firm energy attracts jobs)
- (+) [Jobs] → local training expands nuclear technician and maintenance credentials (new labor pipeline forms)
- (+) [Finance/insurance] → standardized products emerge for modular reactor projects (deployment trust grows)
- (+) [Regional development] → municipalities compete for SMR siting on employment grounds (place value shifts)

- (–) [Social license] → local opposition focuses on risk and rent distribution (governance tension persists)
- (+) [Critical continuity] → hospitals, data centers, or process plants buy continuity backed by SMRs (income disruptions shrink)
- (+) [Labor agreements] → staffing and remote-support rules become bargaining topics (institutionalization grows)
- (+) [Grid role] → planners treat SMRs as anchor resources for local industry (operating model changes)
- (+) [Supply chain] → regional suppliers retool for modular nuclear components (industrial capability broadens)

## ART 08.058 - Thin-film solar cells

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Thin-film solar directly supports the GVN's self-reliance and savings logic by putting generation on many more surfaces, homes, vehicles, and small businesses. Institutionally, it shifts value toward prosumers, landlords, and distributed energy service platforms, with the downside that benefits can concentrate in property owners if access is unequal. The likely impact is transformative because it changes everyday savings, resilience, and micro-enterprise economics across a large share of the population. It is not a 20 because distributed solar is a major driver, but not the singular linchpin of the whole shift in work and income.

**Weak signals (9):**

- (+) [Self-provisioning] → landlords and SMEs deploy solar laminates as standard retrofits (local saving capacity rises)
- (+) [Home enterprise] → loans for home businesses include integrated thin-film generation (microbusiness viability improves)
- (+) [Fleet economics] → delivery and service fleets use solar surfaces to cut operating cost (small margins improve)
- (+) [Prosumer income] → utilities roll out tariffs for many small flexible generators (households gain revenue option)
- (–) [Distribution] → renter-rights disputes focus on who receives building-integrated solar benefits (ownership inequality appears)
- (+) [Jobs] → installer work shifts toward integration and laminated retrofits (labor demand changes)
- (+) [Household resilience] → energy-burden variance falls where flexible solar spreads (income shocks soften)
- (+) [Insurance] → policies normalize building-integrated solar risk assessment (institutional trust forms)
- (+) [Peer markets] → neighborhood energy trading becomes visible supplementary income (new local market appears)

## ART 08.059 - Bionic Leaf Technology

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The main linkage is through a few remote or niche fuel/chemical production settings, not through

the general organization of work and income. Institutional spillovers remain limited unless the technology becomes a broad distributed energy source. So it stays a niche watchpoint. A higher score would require bionic-leaf systems to become a common local production layer for households or SMEs.

### **Weak signals (3):**

- (+) [Remote enterprise] → farms or remote worksites pilot panel-based molecule production (niche local value appears)
  - (+) [Service market] → maintenance firms begin supporting bionic-leaf systems (specialist jobs form)
  - (+) [Regulation] → certification appears for panel-produced fuels or intermediates (institutional pathway opens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 08.060 - Grid-Scale Energy Storage**

**Score: 5** (Impact in GVN 11)

### **Justification (3–5 sentences):**

Grid-scale storage materially affects work and income by lowering outage risks, reducing price spikes, and making more distributed energy mixes economically usable. The second-order effects are significant in tariff design, resilience, community energy, and the ownership of flexibility rents, though the operating model of work itself changes indirectly. That supports a score of 5. A 10 would require storage to move from a system stabilizer to a pervasive source of local income and autonomy.

### **Weak signals (9):**

- (+) [Business continuity] → employers cite storage-backed reliability in siting decisions (energy risk matters less)
- (+) [Price stability] → time-of-use volatility declines in storage-rich regions (income planning improves)
- (+) [Critical services] → diesel backup staffing shrinks where storage covers outages (labor exposure falls)
- (+) [Community energy] → co-ops finance shared storage as local resilience assets (collective self-reliance grows)
- (+) [Insurance] → interruption premiums fall in storage-protected zones (trust becomes priced)
- (–) [Rent capture] → disputes rise over who owns storage arbitrage gains (new energy rents appear)
- (+) [Tariffs/work timing] → utilities offer schedules that reward flexible work around dispatch (time patterns shift)
- (+) [Equity policy] → public programs target storage in low-income or remote areas (access becomes political)
- (+) [Operations] → workforce needs shift from fuel logistics to software and asset management (labor mix changes)



## ART 08.061 - Solid-State Batteries

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Solid-state batteries materially improve electric tools, vehicles, storage, and mobile work equipment through higher safety and better performance. Institutionally, they change fleet economics, insurance, downtime, and some infrastructure design, but do not themselves redefine the whole work regime. The likely impact is significant across transport, trades, logistics, and home energy. A 10 would require much wider changes in household savings and work geography driven specifically by this battery chemistry.

**Weak signals (9):**

- (+) [Fleet transition] → operators accelerate electrification once safety and range improve (operating costs shift)
- (+) [Tool uptime] → warehouses and field tools require fewer charging pauses (productive hours rise)
- (+) [Insurance] → premiums fall for lower thermal-runaway risk assets (risk burden eases)
- (+) [Public procurement] → service vehicles electrify faster under safer battery assumptions (adoption broadens)
- (+) [Charging routines] → work assets move to shorter, more flexible charging windows (workflow changes)
- (+) [Leasing] → asset-life assumptions extend in battery-backed equipment contracts (capital cost falls)
- (–) [Labor rights] → operators seek access to battery-health data that affects performance expectations (information conflict appears)
- (+) [Repair work] → service labor shifts from heavy thermal management to diagnostics/software (skill mix changes)
- (+) [Household mobility] → commuting cost and range constraints ease in battery-rich households (job access broadens)

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Power-to-X materially affects work and income by creating new industrial chains, reducing fossil input volatility, and enabling some sectors to stay local under decarbonization pressure. Institutionally, it changes port, pipeline, certification, and workforce systems, while the downside is potential concentration in large infrastructure owners and competition over electricity/water allocation. The impact is significant but not broad enough for a 10. A higher score would require green molecules to become a dominant foundation for regional energy self-reliance and household economics.

**Weak signals (9):**

- (+) [Industrial retention] → ports and industrial zones sign long-term green molecule offtake deals (jobs are anchored)
- (+) [New occupations] → electrolyzer, synthesis, and certification roles grow (new labor system forms)

- (+) [Transport work] → fleets and shipping begin sourcing locally produced green fuels (operating model shifts)
- (+) [Regional policy] → workforce programs target hydrogen and e-fuel skills (institutionalization grows)
- (+) [Input stability] → firms cite lower energy-price volatility where local P2X is available (planning improves)
- (–) [Distribution] → political conflict emerges over water and power allocation (resource trade-offs sharpen)
- (+) [Municipal services] → public fleets adopt locally produced fuels (local demand base forms)
- (+) [Certification] → origin/carbon certificates become routine trade assets (trust becomes marketable)
- (–) [Capital concentration] → a few infrastructure owners capture large value pools (rent concentration appears)

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Better wind systems materially lower energy costs and create maintenance, service, and community-revenue opportunities, which matters for household savings and regional employment. The second-order effects are in land/sea use, grid integration, local rent distribution, and industrial supply chains, with the downside that benefits can be unevenly captured. The overall work-and-income effect is significant but shared with other clean-energy infrastructures. A higher score would require wind-derived income and energy autonomy to become a more universal household and SME feature.

**Weak signals (9):**

- (+) [Local competitiveness] → employers tie expansion to wind-backed power contracts (energy cost matters for jobs)
- (+) [Service jobs] → blade repair, offshore access, or airborne-wind support trades expand (maintenance labor grows)
- (+) [Community income] → benefit schemes route turbine revenues into local skills or services (local gain becomes visible)
- (+) [Insurance] → uptime uncertainty falls as advanced monitoring improves (risk burden shrinks)
- (+) [Training] → programs expand for new turbine forms and long-blade logistics (labor pipeline shifts)
- (–) [Distribution] → public disputes focus on who receives local energy rents (ownership conflict sharpens)
- (+) [Household savings] → local tariffs reflect lower generation cost in wind-rich zones (energy burden eases)
- (+) [Circular jobs] → end-of-life blade reuse and recycling becomes a local niche (new work appears)
- (+) [System integration] → wind-rich regions pair turbines with storage/microgrids (resilience becomes economic strategy)

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The work-and-income pathway is narrow, mostly involving remote or temporary operations where wires or fuel deliveries are costly. Second-order effects stay in infrastructure and emergency-use niches rather than mainstream labor markets. That keeps the score low. A higher score would require wireless power to become a routine energy-access layer for broad civilian work and settlement patterns.

**Weak signals (3):**

- (+) [Remote operations] → temporary worksites replace fuel logistics with beam-powered receivers (niche continuity gains appear)
- (+) [Emergency economy] → pop-up recovery or service zones use wireless power routinely (situational work model forms)
- (+) [Governance] → regulators create workplace exposure and siting rules (market pathway opens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Advanced geothermal materially improves local access to steady heat and power, reducing energy volatility for firms and households and supporting industrial activity in more places. Institutionally, it shifts value toward regions with deep-heat capability, retrains drilling/service labor, and strengthens local resilience. The impact is significant but still mostly through energy and industrial structure rather than direct labor-market platforms. A 10 would require geothermal to become a widespread anchor of local self-sufficiency across many regions.

**Weak signals (9):**

- (+) [Industrial siting] → heat users sign geothermal supply deals tied to expansion or retention (jobs are anchored)
- (+) [Transition jobs] → drilling and service firms retrain from fossil to geothermal work (labor redeploys)
- (+) [Regional development] → municipalities market geothermal-backed business parks (place advantage shifts)
- (+) [Insurance] → interruption risk falls where local heat/power is firm (continuity value rises)
- (+) [Household savings] → financing packages include deep-geothermal or network heat access (cost burden eases)
- (–) [Governance] → permitting conflicts emerge around subsurface rights and seismic risk (institutional tension grows)
- (+) [Policy] → transition programs explicitly bridge oil/gas crews into geothermal (labor policy updates)
- (+) [SME growth] → heat-intensive small firms cluster near stable local heat (entry conditions improve)

- (+) [Land values] → reliable heat networks start affecting site values (economic geography shifts)

## ART 08.066 - Resilient microgrids

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Resilient microgrids directly support the GVN's self-reliance and savings logic by turning neighborhoods, campuses, and firms into more autonomous economic units that can keep working through wider disruptions. The second-order effects are large in local governance, shared asset ownership, utility relations, and equity of access, with upside for community resilience and downside if only wealthy sites can self-protect. The scale is transformative because it changes everyday continuity of work, home enterprise, and local production for a large number of people. It is not a 20 because microgrids are a powerful pathway, but not the uniquely necessary keystone of the entire shift.

**Weak signals (9):**

- (+) [Business continuity] → districts and campuses finance island-capable microgrids (outage exposure falls)
- (+) [Home/self-employment] → housing cooperatives add microgrids as economic infrastructure (household resilience rises)
- (+) [Community ownership] → local energy co-ops manage shared generation and storage (collective self-reliance grows)
- (+) [Insurance] → interruption premiums drop where black-start capability exists (resilience becomes priced)
- (+) [Regulation] → islanding and reconnection approvals are streamlined (institutional barrier falls)
- (+) [Jobs] → electricians, software integrators, and microgrid operators see rising demand (new labor niches form)
- (–) [Equity] → renters or poorer districts contest exclusion from resilience upgrades (distribution conflict surfaces)
- (+) [Peer income] → balancing or local energy payments become supplementary income (new micro-revenue appears)
- (–) [Utility power] → disputes increase over tariffs and control between utilities and local grids (governance rebalances)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Gene editing materially affects work and income through better health, biotech productivity, and selected agricultural or industrial gains. The institutional effects are mostly in ethics, access, and specialist production rather than in the broad operating model of earning and work access. That keeps the impact in the €10–100M / 5–50M person-hour band for this GVN. A higher score would require gene editing to become a much wider labor-capability or productivity platform rather than a

sectoral bioeconomy tool.

### Weak signals (5):

- (+) [Health-linked productivity] → edited-biologic therapies enter workforce health cost planning (labor supply improves)
  - (+) [Biotech jobs] → firms expand editing production and QA roles (specialist employment grows)
  - (–) [Enhancement governance] → public debate sharpens over therapy vs worker enhancement (boundary conflict appears)
  - (+) [Industrial policy] → biotech clusters are built around editing platforms (regional niche expands)
  - (+) [Disease burden] → hard-to-manage illnesses see editing-based pathways to work continuity (income stability improves)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

**Score: 5** (Impact in GVN 11)

### Justification (3–5 sentences):

Mature mRNA platforms materially reduce illness burden, absenteeism, and outbreak disruption, while creating flexible biomanufacturing work and shortening response times when health shocks threaten income continuity. Institutionally, they favor adaptable manufacturing and procurement systems, though access gaps and pricing power can still create inequality. The overall effect is significant for this GVN and plausibly in the €100M–1,000M / 50–500M person-hour range. A 10 would require mRNA platforms to reshape everyday health-maintenance and labor participation far more broadly than disease-response and targeted therapy.

### Weak signals (9):

- (+) [Labor continuity] → employers or insurers use rapid-updated mRNA programs to reduce absenteeism (workforce resilience rises)
- (+) [Biomanufacturing jobs] → regional plants produce multiple mRNA products from shared lines (platform manufacturing scales)
- (+) [Supply resilience] → procurement shifts from single products to redesign capability (response speed matters)
- (+) [Public health infrastructure] → sovereign or regional mRNA capacity is funded as economic resilience (state role grows)
- (+) [Access] → pharmacies or at-home delivery normalize administration (work disruption from care falls)
- (–) [Inequality] → personalized mRNA regimens remain expensive for some groups (benefit distribution diverges)
- (+) [Labor participation] → sectors with frequent exposure shocks recover faster after outbreaks (income stability improves)
- (+) [Skills] → technician roles expand in modular RNA manufacturing and analytics (new mid-skill work appears)
- (–) [Governance] → debates rise over pricing and update cadence for employer-linked programs (institutional conflict grows)

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Cellular agriculture materially changes food-sector work, input costs, and supply stability, which affects household savings and regional economic structure. Institutionally, it shifts value from land and animal management toward bioprocessing, IP, and controlled production, while also disrupting existing rural livelihoods if transition pathways are weak. That is significant for this GVN and can plausibly reach the €100M–1,000M band. A 10 would require cell-based food systems to become dominant enough to reconfigure everyday household consumption and rural labor structures at much larger scale.

**Weak signals (9):**

- (+) [Food-sector jobs] → cell-based protein plants hire bioprocess operators instead of conventional processing labor (task structure shifts)
- (+) [Price stability] → buyers use cultured protein to hedge food-input volatility (household cost pressure softens)
- (+) [Rural transition] → farming cooperatives invest in feedstock or cell-line participation (income adaptation begins)
- (+) [Public procurement] → institutions buy cultured products at scale (market demand legitimizes)
- (–) [Distribution] → rural communities contest loss of value to urban biomanufacturing hubs (regional conflict emerges)
- (+) [Regulation] → labeling and inspection rules stabilize (formal market pathway opens)
- (+) [Industrial policy] → development funds back fermentation and cell-culture hubs (new employment clusters form)
- (+) [Safety/worker profile] → labor shifts away from some hazardous animal-processing tasks (work conditions improve)
- (–) [Market power] → control of cell lines and media can concentrate rents (ownership conflict grows)

## ART 09.070 - Organoids & Tissue Engineering

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These technologies materially improve health R&D and some treatment pathways, which matters for biotech jobs and long-run workforce productivity. The second-order effects are concentrated in research, clinical development, and specialist care rather than the everyday work/income regime. That places the effect in the material-but-bounded band. A higher score would require organoid and tissue-engineering systems to become far more central to routine care and broad labor-force participation.

**Weak signals (5):**

- (+) [Biotech employment] → firms hire organoid manufacturing and assay staff (specialist labor grows)
- (+) [R&D speed] → trials narrow earlier using organoid evidence (development time falls)

- (+) [Hospital procurement] → standardized tissue patches enter care pathways (clinical market expands)
  - (+) [Regulation] → agencies accept organoid evidence in more approval steps (institutional uptake grows)
  - (–) [Access] → high-end tissue products remain concentrated in better-funded systems (benefit distribution diverges)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Synthetic biology materially supports distributed production of chemicals, materials, and enzymes, lowering the scale threshold for some forms of manufacturing and creating new local entrepreneurial opportunities. Institutionally, it shifts value toward strain IP, biosafety governance, and feedstock control, with the downside that containment rules and proprietary chassis can concentrate power. The overall impact is significant for local production and industrial restructuring, in the rough €100M–1,000M range. A 10 would require these biofactories to become a dominant new base layer of regional production and household-relevant goods.

**Weak signals (9):**

- (+) [Distributed production] → industrial parks offer fermentation-as-a-service for multiple products (small producers gain access)
- (+) [SME leverage] → firms license strains instead of building full chemistry stacks (entry barrier falls)
- (+) [Feedstock value] → waste streams become inputs for microbial production (resource saving becomes income source)
- (+) [Jobs] → biosafety, bioprocess automation, and downstream processing roles expand (new labor niches grow)
- (+) [Regional strategy] → biomanufacturing is used as reshoring policy (place-based production shifts)
- (–) [Ownership] → revenue splits increasingly favor strain IP holders over local producers (rent concentration appears)
- (+) [Regulation] → standardized containment and traceability rules open more sectors to use (institutional pathway broadens)
- (+) [Supply resilience] → firms switch outputs faster than with fixed chemical plants (adaptability becomes valuable)
- (–) [Public trust] → local opposition emerges around release and contamination fears (social license becomes active)

## ART 09.072 - Microbiome Engineering

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Microbiome engineering materially affects selected health, agriculture, and environmental maintenance activities, which can reduce sickness, contamination, or productivity losses. The second-order effects are dispersed and difficult to scale into the broader work-and-income regime, so the main changes remain sector-specific. That supports a bounded material score. A higher score



would require microbiome steering to become a widely used, everyday productivity or health-maintenance layer across the workforce.

#### **Weak signals (5):**

- (+) [Workforce health] → insurers or employers fund targeted microbiome interventions for high-absence groups (labor continuity improves)
  - (+) [Service markets] → utilities and farms buy microbiome management subscriptions (new niche work appears)
  - (+) [Diagnostics] → cheap at-home or field microbiome tests become routine inputs (decision cycles shorten)
  - (–) [Governance] → rules tighten around release and persistence of engineered strains (institutional friction appears)
  - (+) [Skills] → monitoring and adjustment roles emerge for microbiome-managed systems (specialist labor forms)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 09.073 - Precision Medicine & Genomic Diagnostics**

**Score: 5** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

Precision medicine materially improves healthy working life, reduces trial-and-error treatment, and lowers some catastrophic health and productivity losses. Institutionally, it changes insurance, consent, anti-discrimination law, and provider coordination, while the downside is new inequality if genomic advantages are priced and governed unevenly. The overall impact is significant for labor participation and household financial stability. A 10 would require precision diagnostics to become a universal, routine infrastructure for most workers rather than a strong but still unevenly distributed layer.

#### **Weak signals (9):**

- (+) [Healthy work life] → workforce health plans cover routine genomic or molecular panels (prevention becomes normal)
- (+) [Absenteeism] → sectors with chronic-condition burdens adopt precision pathways (labor continuity improves)
- (+) [Data portability] → workers carry actionable molecular profiles across providers (care coordination sharpens)
- (–) [Employment equality] → laws are tightened against use of genomic inference in hiring or pay (risk becomes visible)
- (+) [Regional jobs] → diagnostics and sequencing clusters create mid-skill lab and data roles (new employment grows)
- (+) [Public services] → health systems shift spending toward earlier detection (resource burden changes)
- (–) [Insurance conflict] → debates intensify over premium or coverage differences tied to genomic risk (distributional issue rises)
- (+) [Labor supply] → workers with previously unstable conditions stay employed longer (participation widens)
- (+) [Unions] → bargaining includes voluntary-only use of genomic data (rights become institutionalized)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These systems materially improve some R&D and testing workflows, which matters for biotech jobs, development cost, and specialist services. The broader spillovers to work and income remain concentrated in pharma, medtech, and related research ecosystems rather than across society. Hence a bounded material score. A higher score would require these platforms to become central enough to alter mass healthcare costs or broad industrial labor markets.

**Weak signals (5):**

- (+) [Testing productivity] → CROs replace portions of manual or animal testing with chip platforms (R&D labor shifts)
  - (+) [Regulation] → chip-based evidence is accepted in more approval steps (institutional pathway broadens)
  - (+) [Jobs] → labs hire chip-ops technicians and data analysts (specialist labor forms)
  - (+) [Industrial clustering] → semiconductor and biotech partnerships form around chip-bio workflows (new niche value chain grows)
  - (–) [Access] → high-end integrated systems remain concentrated in better-funded institutions (benefits remain uneven)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Interventions that slow or reverse aging barriers transform this GVN because they reshape labor supply, retirement, pensions, caregiving burdens, and the timing of skill accumulation and career change. The institutional effects are very large: age-based norms, insurance, savings behavior, and intergenerational distribution all move, with the downside that unequal access could harden class divides between longer-lived high-capability workers and others. The plausible magnitude clearly reaches the transformative anchor and affects the weekly lives of large populations. It is not a 20 because the challenger regime in work and income can still emerge without radical longevity extension.

**Weak signals (9):**

- (+) [Working-life length] → pension and retirement models are revised using slower aging assumptions (career horizons expand)
- (+) [Employer strategy] → firms redesign career ladders for longer healthy mid/late careers (age norms shift)
- (+) [Insurance] → anti-aging interventions are covered as periodic maintenance (health economics changes)
- (+) [Care burden] → later frailty reduces some family caregiving interruptions (work continuity improves)
- (–) [Inequality] → executive or affluent-only access becomes visible early (distributional conflict grows)

- (–) [Labor market] → age discrimination rules are contested as biological vs chronological age diverge (institutions destabilize)
- (+) [Reskilling] → education and career services target much older workers (learning markets widen)
- (+) [Savings behavior] → households change housing and savings horizons around longer healthy lives (income planning shifts)
- (–) [Politics] → debate intensifies over who funds and receives longevity gains (intergenerational conflict rises)

## ART 09.076 - Engineered Living Materials

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

These materials materially reduce inspection and repair burdens in some buildings and infrastructure while creating new maintenance and verification niches. The second-order effects are mostly in construction contracts, lifecycle costing, and property values rather than the broader labor regime. That keeps the effect in the €10–100M / 5–50M person-hour band. A higher score would require engineered living materials to become pervasive enough to materially restructure construction and maintenance labor across the economy.

**Weak signals (5):**

- (+) [Repair burden] → infrastructure tenders specify self-repairing or carbon-capturing living materials (maintenance work changes)
  - (+) [Lifecycle economics] → property valuations factor lower repair frequency (cost structure shifts)
  - (+) [New roles] → building-service firms add bio-material care and monitoring tasks (niche labor forms)
  - (+) [Auditability] → performance claims for living materials are independently verified (trust becomes marketable)
  - (–) [Operational constraints] → failures tied to survivability conditions create caution in deployment (adoption remains selective)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

**Score: 1** (Impact in GVN 11)

**Justification (3–5 sentences):**

The work-and-income pathway is mostly through agriculture and some public-health cost reduction, which is relevant but not broad in this GVN. Governance, reversibility, and ecological risk dominate the second-order picture. So it stays a niche watch item. A higher score would require pest pressure to become a much more central determinant of national employment and household costs.

**Weak signals (3):**

- (+) [Agricultural cost pressure] → agencies prepare gene-drive scenarios using labor-cost assumptions (niche economic link appears)
- (+) [Food production] → growers support drives after repeated pest losses (income protection motive becomes visible)

- (+) [Governance] → biosurveillance and liability frameworks are built for releases (institutional pathway opens)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Artificial wombs and synthetic embryos could materially change work and income by reducing some pregnancy-related labor interruptions, altering fertility timing, and redistributing gendered care burdens. Institutionally, they affect parental leave, insurance, reproductive rights, gender equality, and family planning markets, with major downside risks of commodification and unequal access. The likely magnitude is significant, though not clearly broad enough for a 10 under cautious scoring discipline. A 10 would require much wider normalization across reproduction, career design, and social policy.

**Weak signals (9):**

- (+) [Labor participation] → exo-gestation services move beyond emergency care into elective pathways (career timing becomes more flexible)
- (+) [Parental policy] → parental-leave law reviews consider non-pregnancy gestation scenarios (institutions adapt)
- (+) [Employer behavior] → career-break assumptions for women change in affected professions (gendered labor norms shift)
- (+) [Insurance] → formal coverage categories appear for artificial gestation (economic access becomes structured)
- (–) [Equality politics] → debate splits between liberation and commodification narratives (distributional conflict grows)
- (+) [Family planning markets] → later and more flexible parenthood becomes financially productized (life-course planning changes)
- (–) [Cross-border inequality] → reproductive tourism emerges around access differences (benefits stratify)
- (+) [Labor supply] → some women remain in fast-track careers without the same interruption profile (participation widens)
- (–) [Legal uncertainty] → courts confront parental status and workplace protections in new gestation models (governance lag surfaces)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

This is transformative for work and income because it expands reliable access to digital labor markets, education-to-work pipelines, remote services, and platform entrepreneurship in places where terrestrial infrastructure remains weak or fragile. Institutionally, it also shifts power toward constellation operators and creates new dependence in communications, timing, and Earth-

observation services, while the downside includes stronger global labor competition and geopolitical exposure. The impact plausibly crosses the transformative anchor for this GVN. It is not a 20 because satellite internet is a major route to the challenger regime, but not the uniquely necessary one.

#### **Weak signals (9):**

- (+) [Remote work access] → businesses in low-density areas adopt satellite terminals as primary work infrastructure (location barrier breaks)
- (+) [Job access] → remote vacancies grow in previously connectivity-constrained areas (labor market widens)
- (+) [SME support] → governments subsidize constellation access for households and small firms (formal participation broadens)
- (+) [Freelance/platform income] → cross-border gig participation rises after satellite rollout (market access expands)
- (–) [Income dependence] → service-outage disputes include lost earnings claims (livelihood dependence becomes explicit)
- (–) [Infrastructure power] → telecoms restructure around partnerships with constellation firms (control centralizes)
- (+) [Public services] → education, commerce, and finance services bundle through orbital connectivity (adjacent earning channels open)
- (–) [Geopolitics] → strategic debates intensify over foreign-owned constellation dependence (governance risk rises)
- (+) [Local economies] → rural coworking and digital service hubs cite satellite resilience as core asset (regional viability improves)

### **ART 10.080 - Space Resource Utilization (SRU)**

**Score: 1** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

The broad work-and-income linkage is weak unless the society develops a major domestic space-mining or re-entry industry. Most effects would be indirect through critical-materials supply and a small aerospace niche. So this remains a niche watch item. A higher score would require SRU to materially affect mainstream domestic industrial costs and employment.

#### **Weak signals (3):**

- (+) [Materials security] → domestic supply policy references off-Earth feedstocks (linkage starts to matter)
  - (+) [Aerospace jobs] → local firms win repeat assay, recovery, or re-entry contracts (niche employment forms)
  - (+) [Markets] → space-derived metals are priced separately in industrial contracts (economic pathway becomes concrete)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### **ART 10.081 - Closed-Loop Life Support System**

**Score: 0** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

Even at maturity, closed-loop life support has no clear standalone pathway into how most people in this society earn, save, or access work. Any spillovers would come through small terrestrial spin-offs in remote facilities or resilient buildings rather than through the core operating model of the GVN. That leaves it below the threshold for a meaningful score here. A higher score would require closed-loop habitat utilities to become a significant terrestrial infrastructure market.

**Weak signals (3):**

- (+) [Remote-site work] → mines, ships, or Arctic facilities adopt habitat-style air/water loops (spin-off starts to matter)
  - (+) [Industrial niche] → local firms export closed-loop utility modules at scale (niche jobs emerge)
  - (+) [Building resilience] → critical buildings are allowed to use closed-loop utility systems (new market opens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 10.082 - High-Altitude Platforms & Balloons**

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

HAPs materially help in regional connectivity and continuity where terrestrial infrastructure is weak, congested, or disrupted. The second-order effects are mostly in backup communications, temporary economic zones, and remote monitoring rather than in permanent everyday labor structures. That supports a bounded material score. A higher score would require HAPs to become a normal, lasting layer of work access rather than contingency or edge-case infrastructure.

**Weak signals (5):**

- (+) [Business continuity] → employers add HAP links to resilience plans (work continuity improves)
  - (+) [Remote work zones] → industrial or disaster-recovery areas use HAP coverage commercially (temporary labor access expands)
  - (+) [Telecom services] → enterprise bundles include aerial redundancy options (market pathway opens)
  - (+) [Operations jobs] → HAP maintenance and flight-ops roles appear regionally (niche labor forms)
  - (–) [Airspace governance] → disputes increase over corridors and permissions (institutional friction appears)
- Signal density: LOW (linkage weak; additional signals would be speculative).

# **11. Digital Platforms & Collective-Intelligence Systems**

## **ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)**

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Decentralized trust networks materially affect work and income by enabling programmable

payments, revenue sharing, portable identity, and alternative ownership models outside dominant platforms. Institutionally, they shift disputes from centralized rule-making toward protocol governance and custody, while downside risks include speculation, fraud, and hidden reconcentration in infrastructure and liquidity providers. The likely impact is significant, but not every work/income transformation depends on this path. A 10 would require these networks to become mainstream rails for a large share of labor, benefits, and everyday transactions.

#### **Weak signals (9):**

- (+) [Platform-independent income] → workers or creators receive programmable revenue shares on-chain (payout logic changes)
- (+) [Portable identity] → co-ops or freelance markets use wallet-based reputation records (switching costs fall)
- (+) [Settlement] → smart-contract escrow becomes routine in service marketplaces (trust cost declines)
- (+) [Community ownership] → municipalities or unions back tokenized pooled ownership experiments (institutional adoption grows)
- (–) [Fraud risk] → labor or creator losses from scams force new trust intermediaries (new gatekeepers appear)
- (+) [Tax/formality] → payroll, welfare, or invoicing tools integrate selective on-chain settlement (formalization widens)
- (–) [Platform power] → custody and exchange layers capture much of the value (reconcentration risk surfaces)
- (+) [Creator/gig mobility] → portable wallets reduce lock-in to single platforms (bargaining power improves)
- (–) [Regulation] → disputes rise over treatment of on-chain labor and asset claims (governance catches up)

## **ART 11.084 - Platform Cooperatives & Fair Work**

**Score: 10** (Impact in GVN 11)

#### **Justification (3–5 sentences):**

This is one of the most direct institutional challengers in the whole set because it targets the governance, payout, and ownership structure of platform-mediated work itself. The second-order effects are large in bargaining power, algorithmic transparency, pooled benefits, and equitable access, while the downside is slower capital formation and governance complexity if member control is weakly designed. The likely magnitude is transformative for the GVN because it changes how platform work's value is distributed, not just how efficiently it is executed. It is not a 20 because platform co-ops are a major alternative institutional form, but not the sole necessary keystone of the transition.

#### **Weak signals (9):**

- (+) [Fair distribution] → worker- or user-owned platforms reach viable regional scale (alternative model becomes real)
- (+) [Income transparency] → members routinely vote on fee and payout rules (rule opacity declines)
- (+) [Benefits access] → pooled insurance and benefit features become standard co-op platform layers (income security improves)



- (+) [Public procurement] → buyers favor fair-work platforms in service tenders (market access shifts)
- (+) [Worker retention] → churn falls where members share governance and surplus (model proves durable)
- (–) [Capital constraints] → growth slows when outside capital cannot dominate governance (trade-off becomes visible)
- (+) [Union strategy] → unions move from resistance to building/partnering with co-op platforms (institutional alignment changes)
- (+) [Municipal finance] → cities fund platform co-ops without control dilution (policy pathway opens)
- (–) [Incumbent response] → investor-owned platforms copy fairness features to retain labor (competitive pressure spreads norms)

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Data marketplaces materially lower barriers to using or monetizing useful data, which affects entrepreneurship, insurance access, demand forecasting, and smaller firms' competitiveness. Institutionally, they change who can control, license, and profit from operational data, with downside risks of enclosure and asymmetry if community-generated data is captured by stronger actors. The overall effect is significant but not a full regime shift on its own. A 10 would require open data markets to become a dominant, everyday income and coordination layer for much of the economy.

**Weak signals (9):**

- (+) [SME access to intelligence] → small firms buy useful datasets through self-service exchanges (capability gap narrows)
- (+) [New income streams] → workers or microfirms earn from sharing operational data under clear terms (data becomes livelihood asset)
- (+) [Public/private blending] → data trusts list civic and commercial datasets together (market scope broadens)
- (+) [Finance] → lenders use marketplace data to underwrite smaller firms (capital access improves)
- (–) [Ownership conflict] → disputes rise over provenance and rights to community-generated data (power struggle emerges)
- (+) [Price transparency] → markets reveal prices for previously opaque data classes (entry barriers fall)
- (+) [Collective bargaining] → unions or guilds negotiate shared data rights (institutional response appears)
- (+) [Privacy architecture] → compute-to-data options let smaller actors use sensitive data safely (access widens)
- (–) [Market concentration] → a few exchanges dominate discovery and terms (new gatekeepers form)

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Resilient social platforms materially support professional networking, organizing, commerce, and collective action when centralized platforms are unreliable, manipulative, or censorable.

Institutionally, they alter the infrastructure of reputation, moderation, and labor coordination, with downside risks of fragmentation and harder governance. The resulting effect is significant for this GVN, especially around social significance and collective influence. A 10 would require these systems to displace dominant social infrastructure much more broadly across everyday economic life.

**Weak signals (9):**

- (+) [Professional networks] → unions, guilds, and creator communities migrate key functions to resilient platforms (coordination infrastructure shifts)
- (+) [Business continuity] → firms include resilient social channels in continuity plans (social coordination becomes mission-critical)
- (+) [Portable reputation] → freelancers retain contacts and reputation when switching hosts (lock-in falls)
- (+) [Moderation trust] → auditable moderation becomes a selling point (governance legibility matters)
- (–) [Political risk] → censorship or outages push labor groups off centralized platforms (system fragility is revealed)
- (+) [Market access] → small merchants keep audiences across federated services (platform dependence weakens)
- (–) [Abuse/scams] → demand rises for verified private groups after fraud waves (trust cost becomes visible)
- (+) [Public-interest support] → resilient communication gets funded as economic infrastructure (institutional role grows)
- (+) [Enterprise spillover] → collaboration tools adopt interoperable social-federation features (work/community boundaries blur)

## ART 11.087 - Collective Open Innovation Networks

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

These networks materially change how high-skill work and innovation income are organized by letting expertise be matched, validated, and monetized outside conventional firm boundaries.

Institutionally, they shift value toward reputation systems, challenge design, and shared validation infrastructure, while downside risks include precarious projectized work and weaker capture of worker surplus. The effect is significant for knowledge work and innovation-heavy parts of the GVN. A 10 would require this mode to become a mainstream labor market structure well beyond high-skill innovation niches.

**Weak signals (9):**

- (+) [Distributed expert work] → firms source validated solutions through challenge networks (firm boundaries weaken)

- (+) [Portfolio careers] → independent experts earn recurring income from contribution trails (new career model grows)
- (+) [Reward structures] → IP and payout rules standardize on open innovation platforms (institutionalization rises)
- (+) [Public R&D] → challenge-based open innovation becomes a funding requirement (state demand shifts)
- (+) [Recruitment] → employers increasingly value solved challenges and network reputation (credential logic changes)
- (–) [Precarity] → contributors complain about unpaid exploratory labor before payout (risk shifts to workers)
- (+) [Knowledge retention] → failed pathways remain searchable assets (learning value accumulates)
- (+) [Union/professional response] → attribution and payout rules become bargaining issues (labor institutions adapt)
- (+) [Regional policy] → open innovation networks are treated as employment infrastructure (place-based value recognized)

## ART 11.088 - Scalable Decentralized Governance

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

This materially changes how distributed worker communities, co-ops, and pooled resources are governed, lowering some administrative overhead and making larger, flatter organizational forms more workable. The institutional effects on participation, rule legitimacy, and pooled asset management are significant, though risks of manipulation, low engagement, and governance capture remain substantial. That supports a score of 5 and a plausible €100M–1,000M equivalent effect across organizations. A 10 would require decentralized governance to become a mainstream management form across a much larger share of firms and public bodies.

**Weak signals (9):**

- (+) [Collective coordination] → member-run funds or work platforms use routine digital governance (administrative friction drops)
- (+) [Participation] → asynchronous governance replaces attendance-heavy meetings (more people can engage)
- (+) [Compliance] → machine-auditable governance records are accepted by counterparties (institutional trust grows)
- (+) [Scaling co-ops] → communities of work grow without thick admin layers (organizational ceiling rises)
- (+) [Procurement] → digitally governed collectives become eligible suppliers (market access broadens)
- (–) [Manipulation risk] → disputes shift toward delegation, identity, or reputation abuse (new power problems emerge)
- (+) [Worker voice] → participation rates rise in groups that adopt lower-friction governance (voice becomes measurable)
- (+) [Service layer] → governance vendors become core infrastructure for work communities (new market forms)
- (–) [Legal tension] → regulators question alignment with labor law and fiduciary duty (institutional mismatch appears)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

This is transformative because it directly addresses one of the GVN's named inhibitors: education systems optimized for stable hierarchical employment rather than continuous adaptation and self-directed capability building. The second-order effects are large in hiring, pay setting, mobility, reskilling, and equitable access, while the downside is credential micro-competition and new algorithmic gatekeeping if assessment quality is poor. The likely magnitude clearly reaches the transformative anchor for everyday work and income. It is not a 20 because skills networks are vital, but not the single indispensable linchpin of the whole challenger regime.

**Weak signals (9):**

- (+) [Access to work] → employers accept wallet-based skills credentials instead of degrees for more roles (entry barriers fall)
- (+) [Reskilling] → displaced workers return via short-cycle online skill stacks (transition speed improves)
- (+) [Pay ladders] → unions and employers tie portable credentials to wage progression (skills convert into income)
- (+) [Public support] → retraining vouchers plug directly into digital learning networks (institutional uptake broadens)
- (+) [Hiring markets] → platforms search verified skills evidence rather than titles alone (matching quality rises)
- (+) [Regional equality] → rural and low-income participation narrows vacancy-skill mismatch (access widens)
- (–) [Assessment power] → a few credential issuers dominate trusted skill verification (new gatekeepers form)
- (–) [Behavioral control] → anti-fraud and proctoring systems raise privacy concerns (surveillance risk grows)
- (+) [Education restructuring] → schools and universities unbundle teaching from credential issuance (system model changes)

## ART 11.090 - Prediction-Market Forecasting Platforms

**Score: 3** (Impact in GVN 11)

**Justification (3–5 sentences):**

Prediction markets materially improve some planning, resource allocation, and collective intelligence functions, which can affect entrepreneurship and institutional decision quality. But the second-order effects stay mostly in governance and management rather than in the direct operating model of work and income for the general population. So the score remains bounded. A higher score would require forecast markets to become a routine coordination and compensation layer across many workplaces and public systems.

**Weak signals (5):**

- (+) [Decision quality] → firms embed prediction markets in staffing or demand planning (coordination improves)

- (+) [Project selection] → funding choices cite market odds as formal evidence (resource allocation changes)
  - (+) [Reputation] → calibrated forecasting performance becomes a valued credential (new signal enters labor market)
  - (–) [Manipulation risk] → platforms add exposure caps and anomaly detection after attempted gaming (governance matures)
  - (+) [Integration] → forecast APIs trigger procurement or staffing actions automatically (decision loops shorten)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Universal interoperability materially lowers the cost of adopting automation, monitoring, and self-service systems across homes, small firms, and larger organizations. Institutionally, it reduces vendor lock-in, supports repair and local service markets, and broadens access to productive digital tools; the downside is that whoever controls certification and baseline security profiles can still shape the market. The impact is significant because it removes a widespread scaling bottleneck for distributed work and self-sufficiency. A 10 would require interoperability to trigger much larger, society-wide restructuring of household and SME production.

**Weak signals (9):**

- (+) [SME automation] → mixed-vendor device kits work without costly custom integration (entry barrier falls)
- (+) [Home/self-service economy] → households combine interoperable devices into income-earning systems (self-provisioning scales)
- (+) [Repair markets] → local service firms thrive because devices are no longer closed silos (maintenance stays local)
- (+) [Procurement] → buyers require standard telemetry and update profiles (market norms harden)
- (+) [Secondary markets] → used interoperable devices keep value longer (capital access improves)
- (+) [Landlord/tenant flexibility] → shared smart infrastructure can support tenant businesses easily (access broadens)
- (–) [Certification power] → gatekeeping shifts to certifiers and compliance test owners (new control layer appears)
- (+) [Cybersecurity] → baseline security becomes easier to audit across fleets (trust barrier falls)
- (+) [SME innovation] → smaller vendors can enter without bespoke gateway deals (competition widens)

## ART 12.092 - Interoperable Digital Twin Ecosystems

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Interoperable twin ecosystems materially broaden access to high-productivity planning, maintenance, and remote expertise by making digital representations portable across vendors and owners. Institutionally, they reduce data lock-in and improve coordination between many actors around the same asset, while shifting value toward those who maintain trusted models and uncertainty bounds. The impact is significant, particularly in asset-heavy sectors. A 10 would require interoperable twins to become a common operating layer across most work environments, not mainly production and infrastructure.

**Weak signals (9):**

- (+) [Asset portability] → handovers include portable twins as routine deliverables (knowledge stays transferable)
- (+) [SME access] → smaller firms subscribe to shared twin services instead of custom stacks (entry barrier falls)
- (+) [Insurance/finance] → lenders and insurers use standardized twin data in risk assessment (model trust monetizes)
- (+) [Jobs] → twin-literate technician roles spread across sectors (capability generalizes)
- (+) [Public infrastructure] → projects require cross-vendor twin exchange (institutional standard forms)
- (+) [Remote expertise] → experts can support many sites because context is portable (scarce skills scale)
- (–) [Data power] → disputes shift from raw access to control of authoritative models (new governance conflict appears)
- (+) [Disputes] → downtime and maintenance conflicts rely on twin audit trails (accountability improves)
- (+) [Software markets] → closed suites lose some power to interoperable twin components (competition broadens)

## ART 12.093 - Global Supply Chain Traceability Networks

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Traceability networks materially affect work and income by changing market access, authenticity, compliance cost, and the ability of smaller producers to prove origin, handling, and labor standards. Institutionally, they redistribute power toward actors with auditable provenance and away from opaque intermediaries, though they can also burden weaker suppliers with new data costs. The likely magnitude is significant across manufacturing, food, trade, and circular systems. A 10 would require traceability to become a dominant gatekeeper of everyday consumer markets and labor conditions across the whole economy.

**Weak signals (9):**

- (+) [Market access] → major buyers require machine-readable provenance for supplier entry (entry rules change)

- (+) [Small-producer leverage] → verified origin opens premium channels without large intermediaries (bargaining power improves)
- (+) [Labor standards] → wage or working-condition claims appear in digital product histories (social value becomes visible)
- (+) [Finance] → customs, insurers, and lenders use traceability events directly (friction drops)
- (+) [Anti-counterfeit] → fraud losses fall where full-chain records are used (trust improves)
- (–) [Compliance burden] → smaller suppliers struggle with tagging and scanning requirements (cost pressure rises)
- (+) [Circular economy] → recycled or repaired goods monetize better with provenance (resource savings gain value)
- (+) [Union/NGO oversight] → labor claims are audited through shared traceability rails (accountability broadens)
- (–) [Data control] → conflicts shift to who owns or can query chain histories (new power layer appears)

## ART 12.094 - Personal Data Portability & Trust Frameworks

**Score: 10** (Impact in GVN 11)

### **Justification (3–5 sentences):**

Personal data portability is transformative for this GVN because it directly affects switching costs, worker autonomy, portable benefits, access to services, and control over reputation and records. Institutionally, it can redistribute power away from incumbent platforms and employers if permissions are real and usable, while downside risks include phishing, account takeover, and a new market for monetizing personal data under pressure. The scale is large enough to change everyday work and income options for a broad share of the population. It is not a 20 because portability is a major enabler of the challenger regime, but not its sole indispensable keystone.

### **Weak signals (9):**

- (+) [Worker mobility] → ratings, work history, and credentials move between platforms easily (lock-in weakens)
- (+) [Portable benefits] → benefit providers accept user-controlled data wallets (income security travels)
- (+) [Job search friction] → verified selective sharing cuts application and onboarding time (access improves)
- (+) [Market competition] → third-party services compete on top of user-held data (incumbent advantage falls)
- (+) [Finance] → user-authorized data sharing unlocks more tailored credit or insurance offers (service access broadens)
- (–) [Security risk] → phishing and recovery failures rise around data wallets (new vulnerability appears)
- (–) [Power asymmetry] → employers or platforms pressure users into broad sharing (consent can be coerced)
- (+) [Rights enforcement] → regulators punish fake portability that only exports unusable dumps (portability becomes substantive)
- (+) [Collective bargaining] → unions and consumer groups negotiate default sharing profiles (data rights become labor issue)



## ART 12.095 - Interoperable Digital Currency Payment Networks

**Score: 10** (Impact in GVN 11)

**Justification (3–5 sentences):**

Payment interoperability directly changes how income is earned, transferred, settled, and saved across platforms, employers, borders, and public systems. Institutionally, it shifts power in payroll, remittances, platform lock-in, tax collection, and welfare delivery, while the downside is a possible expansion of fine-grained surveillance and programmable control over money if governance is weak. The likely magnitude is transformative because it touches daily earning and transaction friction for a large share of the population. It is not a 20 because multiple payment architectures could coexist; this is a powerful mode-shifter rather than the single necessary linchpin.

**Weak signals (9):**

- (+) [Earning friction] → freelancers and migrant workers get same-day low-fee cross-system settlement (income friction falls)
- (+) [Platform lock-in] → marketplaces let workers choose payout rails freely (switching power improves)
- (+) [Public transfers] → benefits, refunds, or tax flows move onto interoperable digital rails (state/payment link strengthens)
- (+) [Micro-payments] → milestone, escrow, or conditional payments become routine in work contracts (new business models open)
- (+) [Working capital] → small firms face less receivables delay after faster settlement (cash stress eases)
- (–) [Surveillance risk] → rules expand around traceability and programmable limits (control over spending grows)
- (+) [Cooperative finance] → co-ops or unions build pooled saving and mutual-aid tools on common rails (community finance strengthens)
- (–) [Gray economy] → easier digital settlement changes what informal work becomes visible (tax base dynamics shift)
- (+) [Cross-border labor] → cross-system discovery and payment make international service work easier (labor market widens)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Rules as code materially lowers compliance cost and uncertainty, which helps smaller actors enter regulated markets and adapt faster to rule changes. Institutionally, it shifts value from bespoke legal interpretation toward software-mediated compliance, while creating new power in whoever encodes and updates executable rules. The impact is significant because regulation is a major bottleneck in many earning and market-entry pathways. A 10 would require rules-as-code to become a dominant coordinating layer across most business formation, work contracts, and social transfers.

**Weak signals (9):**

- (+) [SME market entry] → business software checks eligibility, tax, and labor rules directly from official packages (compliance cost falls)

- (+) [Faster adaptation] → rule changes are implemented in downstream systems within days (transition friction drops)
- (+) [Regulated work access] → microbusinesses enter more regulated sectors once automation handles compliance (entry barriers fall)
- (+) [Auditability] → disputes rely on executable rule traces (decision legitimacy improves)
- (+) [Public procurement] → tenders require certified rules-as-code integration (institutional uptake rises)
- (–) [Encoding power] → a few vendors dominate interpretation layers around official rules (new gatekeepers appear)
- (+) [Worker rights clarity] → pay and entitlement explanations become more explicit and testable (access improves)
- (+) [Legal work shift] → legal labor moves toward exceptions and model upkeep (professional mix changes)
- (–) [Policy volatility] → authorities change rules more often because rollout is easier (planning uncertainty can rise)

## ART 12.097 - Open Metaverse Interoperability Protocols

**Score: 5** (Impact in GVN 11)

### **Justification (3–5 sentences):**

Open metaverse protocols materially matter because they can keep immersive work, training, and creator economies from collapsing into closed silos. Institutionally, they lower switching costs and make identities, assets, and reputation more portable across virtual labor markets, though the downside is new governance complexity and cross-platform abuse management. The impact is significant, especially when combined with immersive work adoption. A 10 would require interoperable virtual environments to become a mainstream setting for everyday work and income for a much larger population.

### **Weak signals (9):**

- (+) [Virtual work portability] → employers use cross-platform 3D workspaces instead of single-vendor environments (lock-in falls)
- (+) [Creator income] → freelancers carry assets and reputation between worlds (market mobility improves)
- (+) [Training] → interoperable immersive training content replaces vendor-specific modules (costs fall)
- (+) [Remote services] → firms sell work performed in shared 3D environments (new labor channel grows)
- (–) [Identity risk] → disputes over avatar identity and conduct span multiple worlds (governance strain appears)
- (+) [Accessibility] → user settings travel across virtual work platforms (access widens)
- (+) [Device ecosystem] → common identity and asset standards are supported broadly (institutional pathway strengthens)
- (–) [Value capture] → legacy platform owners lose some lock-in rents (competitive conflict intensifies)
- (+) [Education-to-work] → immersive portfolios and credentials become portable across services (transition improves)

## ART 12.098 - Content Authenticity Infrastructure

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

Content authenticity infrastructure materially affects digital labor markets, hiring, contracting, and trust in work products by making provenance easier to verify. Institutionally, it shifts value toward attributable creators and reliable publishers, while also creating downside risks for anonymous or informal contributors if authenticity requirements become exclusionary. The overall impact is significant as synthetic media scales. A 10 would require provenance infrastructure to become a near-universal gateway for digital work participation and reputation.

**Weak signals (9):**

- (+) [Hiring trust] → employers prefer provenance-attested portfolios and work samples (verification burden falls)
- (+) [Fraud reduction] → identity or portfolio fraud drops where provenance is checked by default (market trust improves)
- (+) [Creator rights] → contracts require preservation of authenticity metadata (authorship becomes protected)
- (+) [Insurance/compliance] → misinformation or fraud risk is priced using provenance coverage (trust becomes monetized)
- (+) [Consumer tools] → browsers and operating systems show simple provenance summaries (mass adoption begins)
- (–) [Exclusion risk] → anonymous or informal creators lose market access in provenance-heavy channels (entry can narrow)
- (+) [Legal disputes] → courts rely on provenance chains in authorship conflicts (institutional weight grows)
- (+) [Labor institutions] → creator groups negotiate mandatory attribution retention (rights become collective issue)
- (–) [Adversarial shift] → attacks move from fake media to metadata compromise (new security layer matters)

## ART 12.099 - Privacy-Preserving Collaboration Protocols

**Score: 5** (Impact in GVN 11)

**Justification (3–5 sentences):**

These protocols materially expand the ability of organizations to collaborate on analysis and model-building without pooling raw sensitive data, which lowers a major coordination barrier in labor, health, finance, and local planning. Institutionally, they support new consortia and public-private collaborations, while also giving advantage to actors who can afford secure-compute infrastructure and governance overhead. The impact is significant but not fully transformative by itself. A 10 would require privacy-preserving collaboration to become a default coordination layer across most economic sectors and public services.

**Weak signals (9):**

- (+) [Joint insight without pooling] → sector groups run shared analytics without centralizing raw data (coordination barrier falls)

- (+) [SME inclusion] → smaller actors join collaborative forecasting or modeling for the first time (capability access widens)
- (+) [Procurement] → buyers ask for MPC or privacy-preserving options by default (institutional pathway broadens)
- (+) [Audits] → regulators accept privacy-preserving proofs of calculations (trust becomes operational)
- (+) [Labor observatories] → worker-benefit or labor-market systems use secure cross-agency analysis (policy quality improves)
- (–) [Infrastructure power] → specialized service firms dominate secure-collaboration nodes (new intermediaries appear)
- (+) [Approval speed] → cross-organization projects face fewer legal delays under secure protocols (decision cycles shorten)
- (+) [Experimentation] → sensitive populations can be studied without raw-data exposure (use cases expand)
- (–) [Governance tension] → disputes move from data sharing to output control and inclusion (power conflict persists)

## **ART 12.100 - Manufacturing-specific standards, conformance testing & certification infrastructure**

**Score: 5** (Impact in GVN 11)

### **Justification (3–5 sentences):**

This infrastructure materially lowers the uncertainty and cost of adopting advanced production methods, which is critical if smaller firms are to compete and local manufacturing is to scale. Institutionally, it changes procurement, insurance, finance, and trust by making quality claims machine-readable and portable; the downside is that overly costly certification can entrench incumbents. The impact is significant because standards are often the hidden bottleneck behind wider economic diffusion. A 10 would require this certification layer to become a decisive, economy-wide gateway for most production work and market entry.

### **Weak signals (9):**

- (+) [Supplier access] → buyers accept reusable machine-readable conformity certificates (qualification burden falls)
- (+) [SME entry] → smaller firms win high-assurance contracts after standard test compliance (market access widens)
- (+) [Finance/insurance] → lenders and insurers price assets using certified performance data (capital costs improve)
- (+) [Jobs] → conformance testing, calibration, and digital QA roles expand (new labor niches form)
- (+) [Procurement speed] → contract cycles shorten because benchmark evidence is portable (transaction cost falls)
- (–) [Incumbent power] → established firms lobby for thresholds that disadvantage newcomers (gatekeeping risk appears)
- (+) [Shared infrastructure] → regions build common certification labs for advanced manufacturing (local capability broadens)
- (+) [Regulatory uptake] → approval paths reference digital conformance suites (institutional trust increases)

- (-) [Work restructuring] → tacit shop-floor know-how is partly replaced by formalized test evidence (skill profile shifts)

## GVN 12: Health Care ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 — Global Broadband Connectivity

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this expands access to telehealth, remote mental-health support, specialist consults, and continuous home monitoring across the whole society, especially outside major cities. Institutionally, it weakens the old assumption that diagnosis and follow-up must happen inside licensed facilities, while increasing dependence on connectivity providers and exposing new cyber and outage risks. Third-order effects include less travel, earlier escalation from home data, wider participation in self-care markets, and sharper inequality if affordability or coverage remains uneven. Because it can change the weekly care experience of hundreds of thousands of people, I treat it as transformative rather than merely enabling.

Weak signals (9):

- (+) [rural primary care] → telepsychiatry and chronic-care visits become default first contact (distance barrier collapsing)
- (+) [home-monitoring vendors] → ship kits with embedded multi-network connectivity as standard (care leaves clinic walls)
- (+) [payers] → reimburse continuous remote follow-up on parity with in-person care (business model normalizes)
- (+) [specialist hospitals] → run remote consult queues for peripheral clinics daily (expertise centralizes outward)
- (-) [consumer advocates] → publish maps of medical-connectivity affordability gaps (inequality becomes measurable)
- (-) [liability insurers] → add outage clauses to remote-monitoring coverage (network dependence priced in)
- (+) [mental health providers] → open always-available video/text care outside urban centers (access broadens fast)
- (+) [emergency services] → integrate live patient telemetry from remote homes into dispatch (response loop tightens)
- (-) [cybersecurity agencies] → classify telecare networks as critical health infrastructure (attack surface recognized)

## ART 01.002 — Ultra-Low Latency Networks

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Ultra-Low Latency Networks matters where health care needs real-time feedback—remote robotics, high-fidelity rehab, critical monitoring, or tightly synchronized assistive systems. The bigger effect is institutional: scarce expertise can be centralized and projected outward, but liability, safety certification, and network-dependence rise with it. Because most care does not require millisecond performance, the total impact is meaningful but bounded. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [rehab clinics] → pilot Ultra-Low Latency Networks for interactive therapy (direct use being tested)
- (+) [regulators] → define latency thresholds for remote procedures (adoption rulebook forming)
- (-) [insurers] → treat network lag as patient-safety factor (risk priced in)
- (+) [hospital groups] → centralize niche expertise using guaranteed links (institutional shift begins)

## ART 01.003 — Edge AI for Sensor Data

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this turns wearables, bedside devices, inhalers, implants, and home kits into front-line interpreters rather than just data collectors, so warning signs can be acted on immediately. Institutionally, it moves triage and some diagnostic judgment away from centralized experts and into products used by patients, pharmacists, nurses, and community providers; that lowers privacy and bandwidth burdens but raises model-validation and liability demands. Third-order effects include more preventive outreach, more self-adjustment of behavior or treatment, and more over-alerting or automation bias if thresholds are poorly tuned. At plausible scale this is transformative because it changes how the GVN's personalized, proactive care model is actually delivered day to day.

Weak signals (9):

- (+) [primary care] → prescribes edge-AI wearables for chronic disease plans (monitoring becomes routine)
- (+) [hospital procurement] → favors devices that send summaries not raw streams (workflow shifts local)

- (+) [pharmacies] → sell clinician-linked diagnostic kits with on-device interpretation (self-care commercializes)
- (+) [payers] → reimburse anomaly-triggered outreach from local device alerts (payment follows prevention)
- (-) [patients] → report false escalation or alert fatigue from consumer-clinical devices (threshold harm visible)
- (+) [regulators] → publish update rules for adaptive edge models in medical devices (formal pathway opens)
- (-) [professional associations] → warn against unsupervised treatment changes from device inference (authority contested)
- (+) [eldercare providers] → cut manual checks after deploying edge-interpreting room sensors (labor substitution visible)
- (-) [cyber teams] → disclose exploits in model-update pipelines for home medical devices (new attack surface)

## ART 01.004 — Quantum & High-Precision Sensing

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Quantum & High-Precision Sensing expands richer, more continuous measurement and earlier intervention in homes, clinics, and care facilities. Institutionally, it shifts work from episodic appointments toward algorithmic triage, exception handling, and patient self-management, while raising false-positive, privacy, and overmedicalization risks. Third-order effects include new insurance, employer, and consumer incentives built around always-on health signals. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [primary care] → annual care plans include Quantum & High-Precision Sensing kits (monitoring becomes routine)
- (+) [hospital procurement] → buy ambient/embedded sensing instead of periodic checks (labor model shifting)
- (+) [payers] → reimburse anomaly-triggered outreach from continuous data (payment follows prevention)
- (-) [patients] → report alert fatigue or hidden surveillance complaints (trust friction visible)
- (+) [pharmacies] → sell clinician-linked self-measurement bundles based on Quantum & High-Precision Sensing (self-care commercializing)
- (+) [medical regulators] → publish accuracy benchmarks for Quantum & High-Precision Sensing in triage (formal validation path)



- (-) [professional bodies] → warn against unsupervised treatment changes from sensor outputs (authority contest)
- (+) [eldercare providers] → reduce routine night rounds after sensor deployment (staff substitution visible)
- (-) [privacy watchdogs] → fine providers for secondary use of continuous data (governance stress)

## ART 01.005 — Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Micro/Nano Sensor Networks expands richer, more continuous measurement and earlier intervention in homes, clinics, and care facilities. Institutionally, it shifts work from episodic appointments toward algorithmic triage, exception handling, and patient self-management, while raising false-positive, privacy, and overmedicalization risks. Third-order effects include new insurance, employer, and consumer incentives built around always-on health signals. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [primary care] → annual care plans include Micro/Nano Sensor Networks kits (monitoring becomes routine)
- (+) [hospital procurement] → buy ambient/embedded sensing instead of periodic checks (labor model shifting)
- (+) [payers] → reimburse anomaly-triggered outreach from continuous data (payment follows prevention)
- (-) [patients] → report alert fatigue or hidden surveillance complaints (trust friction visible)
- (+) [pharmacies] → sell clinician-linked self-measurement bundles based on Micro/Nano Sensor Networks (self-care commercializing)
- (+) [medical regulators] → publish accuracy benchmarks for Micro/Nano Sensor Networks in triage (formal validation path)
- (-) [professional bodies] → warn against unsupervised treatment changes from sensor outputs (authority contest)
- (+) [eldercare providers] → reduce routine night rounds after sensor deployment (staff substitution visible)
- (-) [privacy watchdogs] → fine providers for secondary use of continuous data (governance stress)

## ART 01.006 — Privacy-Preserving Pervasive Sensing

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Privacy-Preserving Pervasive Sensing makes dense health sensing and device interoperability usable beyond tightly controlled clinical settings by lowering privacy, integration, or maintenance frictions. Institutionally, it weakens the old monopoly of institution-owned monitoring systems and supports more patient-controlled, home-based, or cross-vendor care pathways, while also making surveillance conflicts more visible. Third-order effects include faster market scaling for self-care and ambient monitoring, but also sharper disputes over secondary data use and gatekeeping. At plausible scale this affects the weekly lives of very large patient groups and can exceed the >€1B / hundreds-of-thousands anchor, so I treat it as transformative.

Weak signals (9):

- (+) [primary care] → annual care plans include Privacy-Preserving Pervasive Sensing kits (monitoring becomes routine)
- (+) [hospital procurement] → buy ambient/embedded sensing instead of periodic checks (labor model shifting)
- (+) [payers] → reimburse anomaly-triggered outreach from continuous data (payment follows prevention)
- (-) [patients] → report alert fatigue or hidden surveillance complaints (trust friction visible)
- (+) [pharmacies] → sell clinician-linked self-measurement bundles based on Privacy-Preserving Pervasive Sensing (self-care commercializing)
- (+) [medical regulators] → publish accuracy benchmarks for Privacy-Preserving Pervasive Sensing in triage (formal validation path)
- (-) [professional bodies] → warn against unsupervised treatment changes from sensor outputs (authority contest)
- (+) [eldercare providers] → reduce routine night rounds after sensor deployment (staff substitution visible)
- (-) [privacy watchdogs] → fine providers for secondary use of continuous data (governance stress)

## **ART 01.007 — Quantum-Resilient and Secure Communication Networks**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Quantum-Resilient and Secure Communication Networks makes sensitive health data, models, records, and transactions easier to share, verify, or govern without fully centralizing them. Institutionally, it reshapes who can learn from data, who can move patient information across boundaries, and who is liable when automated or distributed systems fail. Third-order effects include faster scaling of personalized medicine and health AI, but also new forms of lock-in, data commodification, and re-identification pressure. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → trial Quantum-Resilient and Secure Communication Networks for cross-organization data use (governance pathway forming)
- (+) [regulators] → issue guidance naming this architecture (formal recognition appears)
- (-) [patients] → raise consent or opacity complaints (social license being tested)
- (+) [auditors] → demand traceable logs for these systems (accountability maturing)

## **ART 01.008 — Integrated Sensing and Communication (ISAC)**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Integrated Sensing and Communication (ISAC) expands richer, more continuous measurement and earlier intervention in homes, clinics, and care facilities. Institutionally, it shifts work from episodic appointments toward algorithmic triage, exception handling, and patient self-management, while raising false-positive, privacy, and overmedicalization risks. Third-order effects include new insurance, employer, and consumer incentives built around always-on health signals. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Integrated Sensing and Communication (ISAC) in home or ward monitoring (care linkage forming)
- (+) [payers] → test reimbursement tied to continuous measurements (economic pathway opening)
- (-) [patients] → complain about false alerts or surveillance (social limits emerging)
- (+) [regulators] → draft validation standards for these measurements (adoption path formalizing)

## **2. Computing Hardware & Non-Von-Neumann Paradigms**

### **ART 02.009 — Compute-in-Memory & Neuromorphic Chips**

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Compute-in-Memory & Neuromorphic Chips lowers the power, latency, and size barriers for running useful health analytics in wearables, implants, handheld diagnostics, and bedside devices. Institutionally, that moves some judgment out of central clouds and into products used by patients, nurses, and community providers, though it also makes supply-chain concentration and hardware validation more important. Third-order effects include more privacy-preserving and always-on care services because local computation becomes practical. That comfortably fits the

€100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (6):

- (+) [device makers] → embed Compute-in-Memory & Neuromorphic Chips in portable diagnostics or implants (local compute moves closer)
- (+) [labs] → rerun imaging/genomics workflows with lower cost per case (analysis expands)
- (+) [procurement teams] → cite power/heat savings in medtech tenders (economics improve)
- (-) [supply-chain managers] → flag dependence on a few chip/material vendors (concentration risk rises)
- (+) [regulators] → approve smaller always-on devices using this hardware (new form factors open)
- (-) [security teams] → discover patching or hardware-root vulnerabilities (embedded risk surfaces)

## **ART 02.010 — Novel transistor technologies and materials beyond silicon CMOS**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Novel transistor technologies and materials beyond silicon CMOS improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Novel transistor technologies and materials beyond silicon CMOS for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## **ART 02.011 — Quantum Computing Platforms**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Quantum Computing Platforms improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Quantum Computing Platforms for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## ART 02.012 — Photonic and Optical Computing

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Photonic and Optical Computing improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Photonic and Optical Computing for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## ART 02.013 — Next-Gen Memory & Storage

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Next-Gen Memory & Storage improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Next-Gen Memory & Storage for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## ART 02.014 — Molecular Computing

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Molecular Computing improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Molecular Computing for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 — Causal Learning & Reasoning

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, causal AI matters because healthcare decisions are about interventions: what happens if a dose changes, a behavior changes, or a therapy is switched for a specific person. Institutionally, it shifts value away from one-size-fits-all guidelines toward systems that can justify individualized recommendations and make trade-offs explicit, while also creating new disputes about confounding, evidence quality, and model authority. Third-order effects include faster learning from real-world care, tighter personalization, and stronger payer pressure to justify why one intervention rather than another was chosen. That reaches the transformative anchor because it changes how the GVN's core promise of individualized health optimization is operationalized.

Weak signals (9):

- (+) [clinical pathways] → embed counterfactual tools in treatment selection (intervention logic becomes explicit)
- (+) [payers] → require causal-effect evidence for reimbursement optimization tools (economic pull strengthens)
- (+) [care teams] → compare “what if” options in routine dashboards (population averages lose dominance)
- (-) [auditors] → flag hidden-confounder failures after poor outcomes (limits become visible)
- (+) [registries] → collect intervention-response data specifically for causal models (feedback loop improves)
- (-) [clinicians] → publish override patterns where model recommendations conflict with judgment (authority boundary visible)
- (+) [digital therapeutics] → personalize nudges based on estimated intervention effect (behavioral care matures)
- (-) [patient groups] → contest opaque trade-offs embedded in algorithmic treatment choice (legitimacy stress)
- (+) [quality agencies] → benchmark providers on individualized outcome gains (system incentives shift)

### ART 03.016 — Federated & Privacy-Preserving Learning

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):



Directly, this unlocks one of healthcare's biggest bottlenecks: the best data are fragmented across hospitals, devices, and homes but cannot easily be pooled. Institutionally, it lets smaller providers and public systems benefit from shared models without surrendering raw records, while also changing who controls model updates, who bears security risk, and how consent is interpreted. Third-order effects include faster personalization, less data-hoarding by incumbents, and more pressure to standardize local data capture so distributed learning actually works. That is transformative because it makes large-scale learning compatible with the GVN's strong privacy constraints instead of forcing a choice between the two.

Weak signals (9):

- (+) [hospital groups] → train shared models without central data lakes (privacy bottleneck easing)
- (+) [smaller clinics] → join national model consortia from local infrastructure (power disperses outward)
- (+) [regulators] → publish guidance specific to federated health AI (scale path becomes legible)
- (-) [patient advocates] → challenge hidden secondary use of local records for model updates (consent boundary tested)
- (+) [device ecosystems] → personalize models on phone or wearable while retaining local histories (self-care improves)
- (-) [auditors] → require evidence that local updates cannot be reverse-engineered (trust bar rises)
- (+) [payers] → accept performance evidence from distributed model networks (economic adoption starts)
- (-) [vendors] → push proprietary federation stacks that lock in participants (market power conflict)
- (+) [research ethics boards] → approve multi-site studies faster when raw data never leaves sites (coordination friction falls)

## ART 03.017 — Trustworthy AI Systems

Score: 20 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this is what determines whether AI remains an advisory novelty or becomes core health infrastructure for triage, diagnosis, recommendation, monitoring, and mental-health support. Institutionally, trustworthy AI is the bridge between the challenger regime and the dominant one: it gives regulators, clinicians, payers, and liability insurers a basis to accept AI at scale, while the negative mirror image is automated gatekeeping, unfair scoring, and opaque denials if governance is weak. Third-order effects include rapid diffusion of AI into home care and primary care, heavier documentation of model behavior, and new competitive advantage for organizations that can prove safety and fairness continuously. I score it 20 because it is a keystone layer for the personalized, AI-mediated healthcare shift described in the GVN rather than just another useful component.

Weak signals (9):

- (+) [medical regulators] → create continuous-certification pathways for adaptive clinical AI (institutional gate opens)

- (+) [payers] → reimburse AI-mediated triage only when audit/fallback features are present (trust becomes monetized)
- (+) [hospital boards] → approve AI for front-door triage and chronic-care escalation (authority boundary moves)
- (-) [patient groups] → litigate opaque denial or prioritization decisions made by AI (harm becomes actionable)
- (+) [liability insurers] → price lower premiums for AI systems with traceable safe-fallback logs (insurability improves)
- (+) [procurement teams] → require provenance, robustness, and bias dashboards in tenders (market standards harden)
- (-) [auditors] → publish incident classes where AI failed safely vs unsafely (governance quality visible)
- (+) [primary care networks] → shift routine documentation and first-line risk screening to AI (labor structure changes)
- (-) [civil-rights and equality bodies] → monitor automated inequity in access or follow-up (distribution conflict exposed)

## ART 03.018 — Automated Machine Learning (AutoML)

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Automated Machine Learning (AutoML) improves intervention choice, coordination, modeling, or scientific search in areas where clinicians and health systems currently rely on slow trial-and-error or fragmented judgment. Institutionally, it shifts authority toward machine-mediated planning and away from purely professional intuition, while creating new audit, reward-design, and accountability issues. Third-order effects include faster learning loops, more standardized pathways, and greater concentration of advantage in organizations with the best data and governance. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [care pathways] → use Automated Machine Learning (AutoML) to choose treatments or escalation routes (decision layer shifting)
- (+) [hospital ops teams] → delegate scheduling/coordination choices to AI agents (managerial workload falls)
- (+) [research funders] → back AI-designed studies or trials (learning loop accelerates)
- (-) [clinicians] → document override rates for model recommendations (trust boundary visible)
- (+) [payers] → reimburse AI-supported decision workflows (economic adoption begins)
- (-) [auditors] → require causal or provenance traces after bad outcomes (accountability hardens)
- (+) [vendor market] → consolidate around few validated model stacks (power concentrates)

- (-) [patient groups] → contest opaque optimization against human preferences (social pushback emerges)
- (+) [quality agencies] → compare sites by AI-assisted outcome gains (scaling becomes measurable)

## ART 03.019 — Collaborative Multi-Agent AI

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Collaborative Multi-Agent AI improves intervention choice, coordination, modeling, or scientific search in areas where clinicians and health systems currently rely on slow trial-and-error or fragmented judgment. Institutionally, it shifts authority toward machine-mediated planning and away from purely professional intuition, while creating new audit, reward-design, and accountability issues. Third-order effects include faster learning loops, more standardized pathways, and greater concentration of advantage in organizations with the best data and governance. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [care pathways] → use Collaborative Multi-Agent AI to choose treatments or escalation routes (decision layer shifting)
- (+) [hospital ops teams] → delegate scheduling/coordination choices to AI agents (managerial workload falls)
- (+) [research funders] → back AI-designed studies or trials (learning loop accelerates)
- (-) [clinicians] → document override rates for model recommendations (trust boundary visible)
- (+) [payers] → reimburse AI-supported decision workflows (economic adoption begins)
- (-) [auditors] → require causal or provenance traces after bad outcomes (accountability hardens)
- (+) [vendor market] → consolidate around few validated model stacks (power concentrates)
- (-) [patient groups] → contest opaque optimization against human preferences (social pushback emerges)
- (+) [quality agencies] → compare sites by AI-assisted outcome gains (scaling becomes measurable)

## ART 03.020 — Quantum-Accelerated AI Systems

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Quantum-Accelerated AI Systems improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical

authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Quantum-Accelerated AI Systems for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## ART 03.021 — AI-Driven Autonomous Scientific Discovery

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, AI-Driven Autonomous Scientific Discovery improves intervention choice, coordination, modeling, or scientific search in areas where clinicians and health systems currently rely on slow trial-and-error or fragmented judgment. Institutionally, it shifts authority toward machine-mediated planning and away from purely professional intuition, while creating new audit, reward-design, and accountability issues. Third-order effects include faster learning loops, more standardized pathways, and greater concentration of advantage in organizations with the best data and governance. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [care pathways] → use AI-Driven Autonomous Scientific Discovery to choose treatments or escalation routes (decision layer shifting)
- (+) [hospital ops teams] → delegate scheduling/coordination choices to AI agents (managerial workload falls)
- (+) [research funders] → back AI-designed studies or trials (learning loop accelerates)
- (-) [clinicians] → document override rates for model recommendations (trust boundary visible)
- (+) [payers] → reimburse AI-supported decision workflows (economic adoption begins)
- (-) [auditors] → require causal or provenance traces after bad outcomes (accountability hardens)
- (+) [vendor market] → consolidate around few validated model stacks (power concentrates)
- (-) [patient groups] → contest opaque optimization against human preferences (social pushback emerges)

- (+) [quality agencies] → compare sites by AI-assisted outcome gains (scaling becomes measurable)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 — Immersive Augmented & Virtual Reality

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Immersive Augmented & Virtual Reality changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [rehab and therapy providers] → standardize programs built around Immersive Augmented & Virtual Reality (use moves mainstream)
- (+) [payers] → reimburse home-based digital therapy or assistive sessions (care leaves institutions)
- (+) [patients with disability/cognitive decline] → show higher independent-living rates (functional value visible)
- (-) [ethics bodies] → issue guidance on manipulation, dependency, or neuro-rights (governance tightens)
- (+) [caregivers] → adopt these tools to cover staff shortages (substitution channel opens)
- (-) [equity monitors] → report uptake skewed to affluent users (distribution gap visible)
- (+) [medical schools] → add these interfaces to standard training (professional norms shift)
- (-) [insurers] → litigate responsibility when adaptive systems misread intent or state (liability exposed)
- (+) [consumer medtech markets] → bundle therapy/support with everyday devices (normalization deepens)

### ART 04.023 — Brain-Computer Interfaces (BCI)

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Brain-Computer Interfaces (BCI) changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [rehab and therapy providers] → standardize programs built around Brain-Computer Interfaces (BCI) (use moves mainstream)
- (+) [payers] → reimburse home-based digital therapy or assistive sessions (care leaves institutions)
- (+) [patients with disability/cognitive decline] → show higher independent-living rates (functional value visible)
- (-) [ethics bodies] → issue guidance on manipulation, dependency, or neuro-rights (governance tightens)
- (+) [caregivers] → adopt these tools to cover staff shortages (substitution channel opens)
- (-) [equity monitors] → report uptake skewed to affluent users (distribution gap visible)
- (+) [medical schools] → add these interfaces to standard training (professional norms shift)
- (-) [insurers] → litigate responsibility when adaptive systems misread intent or state (liability exposed)
- (+) [consumer medtech markets] → bundle therapy/support with everyday devices (normalization deepens)

## ART 04.024 — Advanced Prosthetics & Exoskeletons

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Advanced Prosthetics & Exoskeletons changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [rehab and therapy providers] → standardize programs built around Advanced Prosthetics & Exoskeletons (use moves mainstream)

- (+) [payers] → reimburse home-based digital therapy or assistive sessions (care leaves institutions)
- (+) [patients with disability/cognitive decline] → show higher independent-living rates (functional value visible)
- (-) [ethics bodies] → issue guidance on manipulation, dependency, or neuro-rights (governance tightens)
- (+) [caregivers] → adopt these tools to cover staff shortages (substitution channel opens)
- (-) [equity monitors] → report uptake skewed to affluent users (distribution gap visible)
- (+) [medical schools] → add these interfaces to standard training (professional norms shift)
- (-) [insurers] → litigate responsibility when adaptive systems misread intent or state (liability exposed)
- (+) [consumer medtech markets] → bundle therapy/support with everyday devices (normalization deepens)

## ART 04.025 — Haptic and Multi-Sensory Feedback Systems

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Haptic and Multi-Sensory Feedback Systems changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Haptic and Multi-Sensory Feedback Systems in rehab, therapy, or assistive care (clinical pathway forming)
- (+) [payers] → test reimbursement outside specialist centers (access model shifting)
- (-) [ethics bodies] → open review on dependency or manipulation risks (norm conflict visible)
- (+) [training programs] → add these interfaces to curricula (professional adaptation begins)

## ART 04.026 — AI Understanding of Human Intent & Context

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):



Directly, this can change healthcare interactions by letting systems detect distress, confusion, adherence problems, pain, fatigue, or escalating mental-health risk from multimodal behavior rather than waiting for explicit self-report. Institutionally, it shifts some relational and observational labor from humans to adaptive systems in mental health, eldercare, disability support, and triage, while also creating powerful manipulation and surveillance risks. Third-order effects include more personalized and earlier intervention, but also normalization of continuous behavioral scoring in care and insurance contexts. That reaches the transformative threshold because it changes how care is recognized and triggered, not just how it is documented.

Weak signals (9):

- (+) [mental health services] → deploy context-aware agents for first-line support (relational care scales)
- (+) [eldercare providers] → use multimodal intent detection to spot distress before crises (early escalation improves)
- (+) [accessibility services] → replace rigid interfaces with context-adaptive ones (participation barrier shrinks)
- (-) [ethics bodies] → issue rules on emotion inference in care settings (surveillance risk acknowledged)
- (+) [payers] → reimburse context-aware digital support for defined conditions (market adoption starts)
- (-) [patients] → complain of manipulative nudging or hidden behavioral profiling (trust friction visible)
- (+) [triage systems] → prioritize follow-up based on interaction signals, not only forms (care routing changes)
- (-) [equity monitors] → find higher error rates across cultures or communication styles (bias becomes measurable)
- (+) [professional training] → teach clinicians to supervise AI-read context signals (role definition matures)

## ART 04.027 — Brain-to-Brain Interfaces

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Brain-to-Brain Interfaces changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Brain-to-Brain Interfaces in rehab, therapy, or assistive care (clinical pathway forming)
- (+) [payers] → test reimbursement outside specialist centers (access model shifting)
- (-) [ethics bodies] → open review on dependency or manipulation risks (norm conflict visible)
- (+) [training programs] → add these interfaces to curricula (professional adaptation begins)

## ART 04.028 — Memory Prostheses

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Memory Prostheses changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [rehab and therapy providers] → standardize programs built around Memory Prostheses (use moves mainstream)
- (+) [payers] → reimburse home-based digital therapy or assistive sessions (care leaves institutions)
- (+) [patients with disability/cognitive decline] → show higher independent-living rates (functional value visible)
- (-) [ethics bodies] → issue guidance on manipulation, dependency, or neuro-rights (governance tightens)
- (+) [caregivers] → adopt these tools to cover staff shortages (substitution channel opens)
- (-) [equity monitors] → report uptake skewed to affluent users (distribution gap visible)
- (+) [medical schools] → add these interfaces to standard training (professional norms shift)
- (-) [insurers] → litigate responsibility when adaptive systems misread intent or state (liability exposed)
- (+) [consumer medtech markets] → bundle therapy/support with everyday devices (normalization deepens)

## 5. Robotics & Physical Autonomy

## ART 05.029 — Self-Driving Vehicles

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Self-Driving Vehicles reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [hospitals and eldercare homes] → redeploy staff after Self-Driving Vehicles automation (labor substitution visible)
- (+) [home-care providers] → expand service territory with robotic support (care reaches farther)
- (+) [facility planners] → redesign wards and homes for machine circulation (built environment adapts)
- (-) [unions and worker councils] → contest deskilling or pace-setting by robots (labor conflict appears)
- (+) [payers] → reimburse robotic assistance where it avoids institutionalization (cost logic changes)
- (-) [safety agencies] → publish incident classes for near-patient robotics (risk becomes measurable)
- (+) [families] → choose machine-supported home care over facility entry (care model shifts homeward)
- (-) [vendors] → lock customers into proprietary service networks (dependency grows)
- (+) [malpractice insurers] → create products for autonomous-care workflows (institutionalization deepens)

## ART 05.030 — Drone Swarms & Aerial Robots

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Drone Swarms & Aerial Robots reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Drone Swarms & Aerial Robots in logistics, rehab, or home support (health linkage forming)
- (+) [payers] → test reimbursement where machines replace travel or routine labor (economic path opens)
- (-) [safety agencies] → track near-patient incidents separately (risk channel visible)
- (+) [facility planners] → include robot-ready design in new builds (infrastructure starts adapting)

## ART 05.031 — Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, these robots matter because healthcare and eldercare are full of human-shaped spaces, tools, and daily-support tasks that current narrow automation handles badly. Institutionally, they can relieve chronic labor shortages in logistics, cleaning, transport, lifting, and some routine support, but they also reshape staffing, facility design, family expectations, and the meaning of human contact in care. Third-order effects include more home-based aging, more vendor dependence, and sharper labor conflict if robots become the default answer to shortages rather than a complement to workers. That is transformative because it changes how the GVN's care capacity is physically delivered, not just how efficiently current routines run.

Weak signals (9):

- (+) [eldercare homes] → redeploy staff after robots take transport and routine support tasks (labor substitution visible)
- (+) [families] → choose robot-supported home care over early facility entry (care model shifts homeward)
- (+) [facility planners] → specify robot-readable layouts in new care buildings (infrastructure adapts)
- (-) [unions] → contest staffing cuts or pace-setting linked to robots (labor conflict materializes)
- (+) [payers] → reimburse robotic support when it delays institutionalization (economic logic changes)
- (-) [safety agencies] → publish incident categories for near-patient general robots (risk becomes measurable)
- (+) [hospitals] → use shared robot fleets for night logistics and sanitation (coverage expands off-hours)
- (-) [vendors] → lock providers into proprietary service ecosystems (dependency grows)
- (+) [training programs] → make robot supervision a standard care skill (professional norms shift)

## ART 05.032 — Soft Robotics & Bio-Inspired Machines

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Soft Robotics & Bio-Inspired Machines reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [hospitals and eldercare homes] → redeploy staff after Soft Robotics & Bio-Inspired Machines automation (labor substitution visible)
- (+) [home-care providers] → expand service territory with robotic support (care reaches farther)
- (+) [facility planners] → redesign wards and homes for machine circulation (built environment adapts)
- (-) [unions and worker councils] → contest deskilling or pace-setting by robots (labor conflict appears)
- (+) [payers] → reimburse robotic assistance where it avoids institutionalization (cost logic changes)
- (-) [safety agencies] → publish incident classes for near-patient robotics (risk becomes measurable)
- (+) [families] → choose machine-supported home care over facility entry (care model shifts homeward)
- (-) [vendors] → lock customers into proprietary service networks (dependency grows)
- (+) [malpractice insurers] → create products for autonomous-care workflows (institutionalization deepens)

## ART 05.033 — Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Fully Autonomous Drones, Robots & Underwater Vehicles reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on

vendors, telemetry, and remote supervision. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Fully Autonomous Drones, Robots & Underwater Vehicles in logistics, rehab, or home support (health linkage forming)
- (+) [payers] → test reimbursement where machines replace travel or routine labor (economic path opens)
- (-) [safety agencies] → track near-patient incidents separately (risk channel visible)
- (+) [facility planners] → include robot-ready design in new builds (infrastructure starts adapting)

## ART 05.034 — Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Supportive Infrastructure for Autonomy reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [hospitals and eldercare homes] → redeploy staff after Supportive Infrastructure for Autonomy automation (labor substitution visible)
- (+) [home-care providers] → expand service territory with robotic support (care reaches farther)
- (+) [facility planners] → redesign wards and homes for machine circulation (built environment adapts)
- (-) [unions and worker councils] → contest deskilling or pace-setting by robots (labor conflict appears)
- (+) [payers] → reimburse robotic assistance where it avoids institutionalization (cost logic changes)
- (-) [safety agencies] → publish incident classes for near-patient robotics (risk becomes measurable)
- (+) [families] → choose machine-supported home care over facility entry (care model shifts homeward)
- (-) [vendors] → lock customers into proprietary service networks (dependency grows)

- (+) [malpractice insurers] → create products for autonomous-care workflows (institutionalization deepens)

## **ART 05.035 — Optical/Microwave Power Beaming for Persistent Robotics**

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Optical/Microwave Power Beaming for Persistent Robotics reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Optical/Microwave Power Beaming for Persistent Robotics in logistics, rehab, or home support (health linkage forming)
- (+) [payers] → test reimbursement where machines replace travel or routine labor (economic path opens)
- (-) [safety agencies] → track near-patient incidents separately (risk channel visible)
- (+) [facility planners] → include robot-ready design in new builds (infrastructure starts adapting)

## **ART 05.036 — Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Gecko-Inspired Dry-Adhesion Mobility & Manipulation reduces the need for human physical presence in transport, logistics, sanitation, inspection, rehabilitation, or daily support tasks around care. Institutionally, it can ease labor shortages and extend home-based care, but it also reallocates jobs, changes facility design, and introduces safety and depersonalization risks. Third-order effects include wider acceptance of machine-mediated care routines and new dependence on vendors, telemetry, and remote supervision. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Gecko-Inspired Dry-Adhesion Mobility & Manipulation in logistics, rehab, or home support (health linkage forming)



- (+) [payers] → test reimbursement where machines replace travel or routine labor (economic path opens)
- (-) [safety agencies] → track near-patient incidents separately (risk channel visible)
- (+) [facility planners] → include robot-ready design in new builds (infrastructure starts adapting)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 — Multi-Material & Hybrid 3D Printing

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Multi-Material & Hybrid 3D Printing improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [medtech procurement] → source custom parts or tissues through digital files (production localizes)
- (+) [regulators] → create certification pathways for lot-size-one or living products (compliance adapts)
- (+) [hospitals] → run point-of-care or near-care fabrication units (supply chain shortens)
- (-) [quality auditors] → flag batch drift across decentralized sites (fragmentation risk visible)
- (+) [surgeons and rehab teams] → prescribe patient-specific devices as routine (personalization deepens)
- (-) [insurers] → dispute liability across file designer, producer, and provider (responsibility blurs)
- (+) [shortage response systems] → switch faster between products during disruptions (resilience value proven)
- (+) [buyers] → prefer digital inventories over physical stock for some devices (working capital falls)
- (-) [standards bodies] → tighten traceability rules after fabrication errors (governance hardens)

### ART 06.038 — Digital Twin & Simulation-Driven Production

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Digital Twin & Simulation-Driven Production improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech firms] → test Digital Twin & Simulation-Driven Production for custom or shortage-prone products (use case appearing)
- (+) [regulators] → open pathway for decentralized or patient-specific output (formal route forming)
- (-) [auditors] → find quality variation across sites (scale friction visible)
- (+) [hospitals] → explore near-care fabrication capacity (supply model shifting)

## **ART 06.039 — Reconfigurable & Agile Factories**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Reconfigurable & Agile Factories improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech firms] → test Reconfigurable & Agile Factories for custom or shortage-prone products (use case appearing)
- (+) [regulators] → open pathway for decentralized or patient-specific output (formal route forming)
- (-) [auditors] → find quality variation across sites (scale friction visible)
- (+) [hospitals] → explore near-care fabrication capacity (supply model shifting)

## **ART 06.040 — Circular & Sustainable Manufacturing**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Circular & Sustainable Manufacturing improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech firms] → test Circular & Sustainable Manufacturing for custom or shortage-prone products (use case appearing)
- (+) [regulators] → open pathway for decentralized or patient-specific output (formal route forming)
- (-) [auditors] → find quality variation across sites (scale friction visible)
- (+) [hospitals] → explore near-care fabrication capacity (supply model shifting)

## **ART 06.041 — Bio-fabrication technologies**

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, bio-fabrication expands what healthcare can produce locally or semi-locally: tissue patches, organoids, customized grafts, and other living products become more programmable and repeatable. Institutionally, it reduces dependence on donor scarcity and long centralized supply chains, but also concentrates value in heavily regulated manufacturing nodes and raises difficult quality, safety, and pricing questions. Third-order effects include shorter repair/regeneration loops, more personalized surgical planning, and growth of elective or enhancement-oriented tissue services once basic therapeutic use is established. That is transformative because it changes the feasible supply of biological repair, not just the efficiency of current transplantation and lab workflows.

Weak signals (9):

- (+) [transplant and reconstructive services] → order printed tissue constructs as standard options (repair supply expands)
- (+) [regulators] → create product classes for living printed tissues (compliance pathway opens)
- (+) [hospitals] → build near-care biomanufacturing suites for time-sensitive products (supply chain shortens)
- (-) [quality auditors] → flag viability drift across production sites (scaling friction visible)
- (+) [surgeons] → prescribe patient-specific tissue patches instead of generic substitutes (personalization deepens)

- (-) [insurers] → dispute liability across design file, cell source, and production site (responsibility blurs)
- (+) [procurement] → replace some donor-dependent inventory with digital/biological recipes (inventory model changes)
- (+) [clinical trials] → test regenerative products in smaller, more personalized cohorts (evidence model shifts)
- (-) [ethics bodies] → review enhancement uses once restorative use normalizes (boundary conflict emerges)

## ART 06.042 — 4D Printed & Programmable Materials

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, 4D Printed & Programmable Materials improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [medtech procurement] → source custom parts or tissues through digital files (production localizes)
- (+) [regulators] → create certification pathways for lot-size-one or living products (compliance adapts)
- (+) [hospitals] → run point-of-care or near-care fabrication units (supply chain shortens)
- (-) [quality auditors] → flag batch drift across decentralized sites (fragmentation risk visible)
- (+) [surgeons and rehab teams] → prescribe patient-specific devices as routine (personalization deepens)
- (-) [insurers] → dispute liability across file designer, producer, and provider (responsibility blurs)
- (+) [shortage response systems] → switch faster between products during disruptions (resilience value proven)
- (+) [buyers] → prefer digital inventories over physical stock for some devices (working capital falls)
- (-) [standards bodies] → tighten traceability rules after fabrication errors (governance hardens)

## ART 06.043 — Volumetric Additive Manufacturing

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Volumetric Additive Manufacturing improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech firms] → test Volumetric Additive Manufacturing for custom or shortage-prone products (use case appearing)
- (+) [regulators] → open pathway for decentralized or patient-specific output (formal route forming)
- (-) [auditors] → find quality variation across sites (scale friction visible)
- (+) [hospitals] → explore near-care fabrication capacity (supply model shifting)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 — Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Metamaterials for Novel Optics & Connectivity mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Metamaterials for Novel Optics & Connectivity in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.045 — Room-Temperature Superconductors

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Room-Temperature Superconductors mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Room-Temperature Superconductors in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.046 — Self-Healing & Smart Polymers

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Self-Healing & Smart Polymers mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Self-Healing & Smart Polymers in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.047 — Nano-Catalysts & Advanced Coatings

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Nano-Catalysts & Advanced Coatings mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Nano-Catalysts & Advanced Coatings in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.048 — High-Entropy Alloys & Advanced Metals

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, High-Entropy Alloys & Advanced Metals mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference High-Entropy Alloys & Advanced Metals in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)



## ART 07.049 — Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.050 — Graphene and Nanotube Composites for Lightweight Strength

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Graphene and Nanotube Composites for Lightweight Strength mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Graphene and Nanotube Composites for Lightweight Strength in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.051 — Smart Thermal Materials for Energy-Efficient Heating & Cooling

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Smart Thermal Materials for Energy-Efficient Heating & Cooling mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Smart Thermal Materials for Energy-Efficient Heating & Cooling in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.052 — Rare-Earth-Free Magnets for Sustainable Motors

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Rare-Earth-Free Magnets for Sustainable Motors mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Rare-Earth-Free Magnets for Sustainable Motors in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Nano-Engineered Membranes for Low-Energy Desalination mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Nano-Engineered Membranes for Low-Energy Desalination in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 07.054 — Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Ultra-Wide-Bandgap (UWBG) Power Semiconductors improves the cost/performance envelope for imaging, genomics, simulation, records, and AI workloads used across healthcare. The main pathway is second-order: lower compute bottlenecks make more analysis affordable and faster, but clinical authority and care pathways change only indirectly. Third-order effects show up through wider deployment of data-heavy tools rather than through immediate front-line disruption. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech vendors] → market Ultra-Wide-Bandgap (UWBG) Power Semiconductors for portable diagnostics (health use case appears)
- (+) [labs] → cite lower compute cost in workflow redesign (economic relevance grows)
- (-) [buyers] → delay adoption over supplier concentration (dependency visible)
- (+) [regulators] → review smaller always-on devices enabled by new hardware (clinical pathway forming)

## ART 07.055 — Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Solid Hydrogen Storage Materials mainly improves healthcare through better devices, buildings, water, storage, imaging, or protective surfaces rather than through a new care model by itself. The bigger effect is second-order: procurement costs, reliability, sterility, portability, or operating conditions improve, while adoption depends on capital turnover and standards. Third-order effects are real but usually indirect, arriving through better infrastructure and equipment rather than new clinical authority. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Solid Hydrogen Storage Materials in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 — Fusion Energy Reactors

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Fusion Energy Reactors affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Fusion Energy Reactors in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)

- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## **ART 08.057 — Small Modular Fission Reactors (SMRs)**

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Small Modular Fission Reactors (SMRs) affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Small Modular Fission Reactors (SMRs) in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## **ART 08.058 — Thin-film solar cells**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Thin-film solar cells affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Thin-film solar cells in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.059 — Bionic Leaf Technology

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Bionic Leaf Technology affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Bionic Leaf Technology in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.060 — Grid-Scale Energy Storage

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Grid-Scale Energy Storage affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Grid-Scale Energy Storage in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.061 — Solid-State Batteries

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Solid-State Batteries matters to healthcare by making medical devices, mobility aids, portable diagnostics, and backup systems safer, denser, and easier to use. Institutionally, that changes procurement, insurance, and service models for home care and emergency response more than it changes medical decision-making itself. Third-order effects include more portable care and less downtime, but also new quality-control and recycling obligations. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (6):

- (+) [health-sector buyers] → mention Solid-State Batteries in procurement criteria (health relevance becomes explicit)
- (+) [facility or product designers] → redesign around these performance gains (use-case hardens)
- (-) [insurers or regulators] → open review after unexpected failure mode (risk becomes legible)
- (+) [public health or provider pilots] → test operational savings tied to this ART (linkage quantified)
- (+) [standards bodies] → add healthcare-specific validation requirements (adoption path appears)
- (-) [equity monitors] → show benefits concentrated in better-resourced sites (distribution gap visible)

## ART 08.062 — Green Hydrogen & Power-to-X

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Green Hydrogen & Power-to-X affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Green Hydrogen & Power-to-X in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)



## ART 08.063 — High-Efficiency Wind Turbines

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, High-Efficiency Wind Turbines affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference High-Efficiency Wind Turbines in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.064 — Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Wireless & Space-Based Power Transfer affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Wireless & Space-Based Power Transfer in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.065 — Advanced geothermal technology

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Advanced geothermal technology affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Advanced geothermal technology in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## ART 08.066 — Resilient microgrids

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Resilient microgrids affects healthcare mostly through energy reliability, operating costs, cold-chain continuity, and the resilience of hospitals, labs, and health-data infrastructure. Its main pathway is institutional rather than clinical: stronger power resilience protects care during shocks and frees budgets, but it does not by itself change diagnosis or personalization. Third-order effects appear when resilient energy makes digital, home-based, or remote care dependable in more places. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health-sector buyers] → reference Resilient microgrids in tenders or pilots (health relevance emerging)
- (+) [standards bodies] → add healthcare-specific test requirements (adoption path forming)
- (-) [insurers or regulators] → flag new failure/liability class (risk channel visible)
- (+) [providers] → quantify savings or resilience gains in pilot use (linkage becoming concrete)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this moves healthcare toward fixing causes rather than managing symptoms by allowing precise, repeatable changes at the molecular level. Institutionally, it forces new rules for delivery, long-term monitoring, consent, pricing, and what counts as acceptable intervention or enhancement, while also challenging the old boundary between treatment and optimization. Third-order effects include more screening to find editable conditions, more pressure for earlier intervention, and sharper inequality if the most powerful edits remain premium services. At plausible scale this is transformative because it changes both the therapeutic frontier and the logic of prevention.

Weak signals (9):

- (+) [clinical guidelines] → add targeted editing to routine care for defined conditions (root-cause treatment normalizes)
- (+) [newborn and carrier screening] → expands for editable variants (detection pulls treatment upstream)
- (+) [payers] → experiment with long-term outcome contracts for editing therapies (pricing model changes)
- (-) [ethics bodies] → open consultations on enhancement, germline spillover, or access rationing (boundary conflict visible)
- (+) [registries] → track edited patients for decade-scale outcomes (long-horizon governance matures)
- (-) [patient groups] → report uneven access by income or geography (distribution conflict sharpens)
- (+) [specialist centers] → replace repeated chronic management with one-time editing programs (care pathway flips)
- (-) [insurers/employers] → attempt to use editability in risk segmentation (power misuse emerges)
- (+) [labs] → build faster confirmatory pipelines for off-target and mosaic outcomes (evidence stack deepens)

### ART 09.068 — mRNA Therapies & Vaccines

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, mRNA turns many therapies into rapidly reprogrammable information products, which is powerful for infectious disease, cancer, and increasingly individualized treatment. Institutionally, it shortens design-to-manufacture cycles and supports smaller-batch or personalized products, but it also shifts value toward delivery platforms, adaptive regulation, and data-rich post-market

monitoring. Third-order effects include more iterative care, faster response to biological change, and more expectation that therapies should be frequently updated or individualized. That is transformative because it changes the speed and flexibility with which health systems can generate and deploy treatment.

Weak signals (9):

- (+) [public health agencies] → keep warm manufacturing capacity between outbreaks (rapid-response norm forms)
- (+) [oncology services] → order patient-specific mRNA products on short cycles (personalized therapy scales)
- (+) [regulators] → approve platform updates with lighter repetitive review (software-like iteration emerges)
- (-) [pharmacovigilance systems] → expand active monitoring for adaptive or personalized dosing (safety burden rises)
- (+) [manufacturers] → offer smaller-batch regional production contracts (supply chain decentralizes)
- (-) [patient groups] → question access if personalized products remain premium-priced (equity issue visible)
- (+) [payers] → reimburse biomarker-guided repeat dosing strategies (data-linked care strengthens)
- (+) [cold-chain/logistics] → shift to more stable formats and direct-to-clinic delivery (operational friction falls)
- (-) [delivery-platform vendors] → gain disproportionate leverage over therapeutic ecosystems (market concentration deepens)

## ART 09.069 — Cellular Agriculture & Cultured Meat

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Cellular Agriculture & Cultured Meat has a healthcare linkage, but mainly through prevention, food quality, research tools, or environmental health rather than through mainstream diagnosis and treatment. Institutionally, any larger effect depends on policy choices, public acceptance, and whether adjacent sectors translate the capability into health gains. That makes it worth watching, but not a central healthcare transformation on its own. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [public health planners] → examine Cellular Agriculture & Cultured Meat as a prevention or exposure lever (health linkage emerging)
- (+) [research funders] → back pilots measuring downstream health effects (evidence route opening)
- (-) [ethics bodies] → scrutinize ecological or social spillovers (governance boundary visible)

- (+) [adjacent sectors] → market explicit health claims from the technology (linkage becomes concrete)

## ART 09.070 — Organoids & Tissue Engineering

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, these technologies make human-like biological models and repair tissues far more available, improving disease modeling, drug selection, and regenerative options. Institutionally, they reduce dependence on crude surrogate models and donor scarcity, while pulling more healthcare value into cell handling, biobanking, and model-validation infrastructures. Third-order effects include faster iteration of treatments, more patient-specific testing before therapy, and more standardized biological evidence across distributed sites. That is transformative because it changes both how therapies are chosen and what kinds of tissue repair become practical.

Weak signals (9):

- (+) [precision oncology] → uses patient-derived organoids before treatment choice (trial-and-error shrinks)
- (+) [drug development] → replaces some animal or low-fidelity assays with organoid platforms (evidence model shifts)
- (+) [biobanks] → store organoid-ready cell lines as routine assets (infrastructure deepens)
- (-) [quality auditors] → flag reproducibility gaps across sites or cell sources (standardization challenge visible)
- (+) [regulators] → cite organoid evidence in approval or labeling decisions (formal acceptance grows)
- (+) [surgical teams] → adopt engineered tissue patches in defined repairs (repair options widen)
- (-) [ethics bodies] → review consent and ownership for patient-derived living models (governance tightens)
- (+) [payers] → cover pre-treatment testing on patient organoids where it avoids failed therapy (economic pull strengthens)
- (-) [lab labor markets] → show shortages in tissue-engineering skills (capability bottleneck surfaces)

## ART 09.071 — Synthetic Biology & Designer Microbes

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Synthetic Biology & Designer Microbes shifts health care toward earlier molecular intervention, root-cause treatment, and more individualized prevention or repair. Institutionally, it challenges the old model of standardized treatment by requiring new regulation, reimbursement, evidence generation, and patient consent practices, while also creating strong inequality and safety risks if access is uneven. Third-order effects include more self-testing, more elective intervention,

and a larger market for preventive and enhancement-oriented care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [clinical guidelines] → add Synthetic Biology & Designer Microbes to routine pathways (molecular care becomes normal)
- (+) [payers] → reimburse prevention or treatment based on individual biomarkers (personalization monetized)
- (+) [labs] → shift from episodic tests to longitudinal molecular monitoring (data depth increases)
- (-) [ethics and privacy bodies] → challenge unequal access or coercive use (distribution conflict visible)
- (+) [patients] → use clinician-linked self-testing before symptoms escalate (care moves upstream)
- (-) [professional associations] → dispute scope between algorithmic recommendations and clinician judgment (authority contested)
- (+) [drug/device firms] → run smaller, more stratified trials around biomarker-defined groups (evidence model shifts)
- (+) [healthy adults] → buy elective optimization/longevity services based on the tech (medicalization expands)
- (-) [insurers/employers] → attempt risk segmentation using these signals (power misuse emerges)

## ART 09.072 — Microbiome Engineering

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Microbiome Engineering shifts health care toward earlier molecular intervention, root-cause treatment, and more individualized prevention or repair. Institutionally, it challenges the old model of standardized treatment by requiring new regulation, reimbursement, evidence generation, and patient consent practices, while also creating strong inequality and safety risks if access is uneven. Third-order effects include more self-testing, more elective intervention, and a larger market for preventive and enhancement-oriented care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [clinical guidelines] → add Microbiome Engineering to routine pathways (molecular care becomes normal)
- (+) [payers] → reimburse prevention or treatment based on individual biomarkers (personalization monetized)
- (+) [labs] → shift from episodic tests to longitudinal molecular monitoring (data depth increases)
- (-) [ethics and privacy bodies] → challenge unequal access or coercive use (distribution conflict visible)

- (+) [patients] → use clinician-linked self-testing before symptoms escalate (care moves upstream)
- (-) [professional associations] → dispute scope between algorithmic recommendations and clinician judgment (authority contested)
- (+) [drug/device firms] → run smaller, more stratified trials around biomarker-defined groups (evidence model shifts)
- (+) [healthy adults] → buy elective optimization/longevity services based on the tech (medicalization expands)
- (-) [insurers/employers] → attempt risk segmentation using these signals (power misuse emerges)

## ART 09.073 — Precision Medicine & Genomic Diagnostics

Score: 20 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this is the core information layer for the challenger regime in the GVN: prevention, diagnosis, treatment choice, nutrition, and self-care all become keyed to individual molecular profiles rather than statistical averages. Institutionally, it redistributes authority across labs, AI systems, clinicians, payers, and patients, because who can interpret and act on personal molecular data becomes a central source of power; the negative mirror is privacy invasion, discrimination, and overmedicalization. Third-order effects include much earlier detection, more elective monitoring, more targeted therapies, and strong pressure to redesign reimbursement, regulation, and public-health guidance around stratified populations. I score it 20 because it is the clearest linchpin of the GVN's most important shift—from centralized generalized care toward personalized, proactive, data-rich healthcare.

Weak signals (9):

- (+) [primary care] → adds genomic/multi-omic profiles to routine longitudinal records (personalization becomes normal)
- (+) [payers] → reimburse biomarker-stratified prevention and dosing pathways (economic model shifts)
- (+) [labs] → move from one-off tests to continuous molecular monitoring subscriptions (data depth increases)
- (-) [privacy and equality bodies] → challenge genetic risk use in insurance or employment (power misuse visible)
- (+) [clinical guidelines] → split common conditions into biomarker-defined subgroups (population averages lose primacy)
- (+) [patient apps] → show plain-language genomic risk and action summaries linked to care teams (self-care intensifies)
- (-) [professional associations] → contest which actors may interpret and act on genomic findings (authority boundary shifts)
- (+) [drug trials] → shrink and stratify around specific molecular responders (evidence regime changes)



- (-) [consumer markets] → sell unvalidated interpretation layers on top of test results (misinformation channel opens)

## ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Organs-on-Chips & Bio-Computational Hybrids shifts health care toward earlier molecular intervention, root-cause treatment, and more individualized prevention or repair. Institutionally, it challenges the old model of standardized treatment by requiring new regulation, reimbursement, evidence generation, and patient consent practices, while also creating strong inequality and safety risks if access is uneven. Third-order effects include more self-testing, more elective intervention, and a larger market for preventive and enhancement-oriented care. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [clinical guidelines] → add Organs-on-Chips & Bio-Computational Hybrids to routine pathways (molecular care becomes normal)
- (+) [payers] → reimburse prevention or treatment based on individual biomarkers (personalization monetized)
- (+) [labs] → shift from episodic tests to longitudinal molecular monitoring (data depth increases)
- (-) [ethics and privacy bodies] → challenge unequal access or coercive use (distribution conflict visible)
- (+) [patients] → use clinician-linked self-testing before symptoms escalate (care moves upstream)
- (-) [professional associations] → dispute scope between algorithmic recommendations and clinician judgment (authority contested)
- (+) [drug/device firms] → run smaller, more stratified trials around biomarker-defined groups (evidence model shifts)
- (+) [healthy adults] → buy elective optimization/longevity services based on the tech (medicalization expands)
- (-) [insurers/employers] → attempt risk segmentation using these signals (power misuse emerges)

## ART 09.075 — Biological Aging & Longevity Barriers

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this targets one of the GVN's explicit end-values—healthy longevity—by intervening in the biology of aging rather than waiting to manage downstream disease. Institutionally, it could move substantial spending from late-life disease management toward recurring preventive maintenance, while also creating new access, enhancement, and evidence-threshold disputes. Third-order effects include changed retirement and care-demand patterns, more elective optimization

behavior among healthy adults, and potential widening of inequality if life-extending care is premium-priced. That is transformative because it changes the demand structure of healthcare itself, not just a single disease area.

Weak signals (9):

- (+) [clinical guidelines] → add senescence or biological-age markers to routine prevention (aging becomes measurable target)
- (+) [payers] → test coverage for periodic longevity interventions tied to biomarkers (maintenance model emerges)
- (+) [healthy adults] → buy clinician-linked longevity monitoring before disease onset (medicalization expands upstream)
- (-) [ethics bodies] → review fairness and enhancement concerns around healthy-life extension (distribution conflict sharpens)
- (+) [geriatric care] → shifts from crisis management toward scheduled biological maintenance (care logic changes)
- (-) [public finance planners] → model retirement and care-load impacts from healthier older cohorts (system feedback recognized)
- (+) [employers] → offer longevity-linked benefits or monitoring (non-clinical demand grows)
- (-) [patient groups] → challenge premium-only access to age-slowing therapies (inequality becomes political)
- (+) [regulators] → accept composite aging endpoints in trials (evidence regime adapts)

## ART 09.076 — Engineered Living Materials

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Engineered Living Materials has a healthcare linkage, but mainly through prevention, food quality, research tools, or environmental health rather than through mainstream diagnosis and treatment. Institutionally, any larger effect depends on policy choices, public acceptance, and whether adjacent sectors translate the capability into health gains. That makes it worth watching, but not a central healthcare transformation on its own. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [public health planners] → examine Engineered Living Materials as a prevention or exposure lever (health linkage emerging)
- (+) [research funders] → back pilots measuring downstream health effects (evidence route opening)
- (-) [ethics bodies] → scrutinize ecological or social spillovers (governance boundary visible)

- (+) [adjacent sectors] → market explicit health claims from the technology (linkage becomes concrete)

## ART 09.077 — Gene Drive Pest Control

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Gene Drive Pest Control has a healthcare linkage, but mainly through prevention, food quality, research tools, or environmental health rather than through mainstream diagnosis and treatment. Institutionally, any larger effect depends on policy choices, public acceptance, and whether adjacent sectors translate the capability into health gains. That makes it worth watching, but not a central healthcare transformation on its own. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [public health planners] → examine Gene Drive Pest Control as a prevention or exposure lever (health linkage emerging)
- (+) [research funders] → back pilots measuring downstream health effects (evidence route opening)
- (-) [ethics bodies] → scrutinize ecological or social spillovers (governance boundary visible)
- (+) [adjacent sectors] → market explicit health claims from the technology (linkage becomes concrete)

## ART 09.078 — Artificial Wombs & Synthetic Embryos

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Artificial Wombs & Synthetic Embryos shifts health care toward earlier molecular intervention, root-cause treatment, and more individualized prevention or repair. Institutionally, it challenges the old model of standardized treatment by requiring new regulation, reimbursement, evidence generation, and patient consent practices, while also creating strong inequality and safety risks if access is uneven. Third-order effects include more self-testing, more elective intervention, and a larger market for preventive and enhancement-oriented care. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [specialist clinics] → pilot Artificial Wombs & Synthetic Embryos for defined patient groups (direct pathway forming)
- (+) [payers] → test biomarker-linked reimbursement or coverage (economic route opening)

- (-) [ethics bodies] → open consultations on access, consent, or enhancement (governance stress visible)
- (+) [labs] → build longitudinal testing around the technology (monitoring layer forming)

## 10. Space & Aeronautical Engineering

### ART 10.079 — Satellite Mega-Constellations & Space Internet

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Satellite Mega-Constellations & Space Internet expands access to telehealth, remote monitoring, specialist support, and continuity of care outside major institutions. Institutionally, it shifts bargaining power toward distributed platforms and away from place-bound providers, while also creating outage, cybersecurity, and affordability risks. Third-order effects include more self-care, earlier intervention, and less travel/time loss, but also sharper inequality if coverage or pricing is uneven. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [rural primary care] → contracts bundle telehealth with Satellite Mega-Constellations & Space Internet (access bottleneck easing)
- (+) [payers] → reimburse remote specialist visits at parity (virtual care monetized)
- (+) [device makers] → ship home diagnostic kits with always-on links (monitoring leaves clinics)
- (-) [medical liability insurers] → add outage clauses for remote monitoring (network dependence exposed)
- (+) [mental health providers] → open always-connected therapy services in sparse regions (coverage broadens)
- (-) [consumer advocates] → document medical-monitoring households priced off service (inequality channel visible)
- (+) [ambulance and home-care services] → use live remote telemetry in dispatch (care coordination tightens)
- (-) [cybersecurity agencies] → classify telecare links as critical infrastructure (attack surface recognized)
- (+) [communications regulators] → reserve traffic priority for medical services (health use prioritized)

### ART 10.080 — Space Resource Utilization (SRU)

Score: 0 (Impact in GVN 12)

Justification (3–5 sentences):

There is no clear healthcare-GVN bottleneck that Space Resource Utilization (SRU) directly relaxes in a 5.5M-person society. Any effect would come mainly through very general macroeconomic spillovers rather than prevention, diagnosis, treatment, or health-data governance. That linkage is too weak for scoring, so this remains a watchpoint rather than a meaningful healthcare impact.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [adjacent sectors] → begin framing Space Resource Utilization (SRU) as a health-system input (possible linkage emerging)
- (+) [public planners] → include the technology in health-resilience scenarios (watchpoint activated)
- (-) [providers] → report no meaningful use case after review (linkage remains weak)
- (+) [research funders] → back targeted healthcare pilots anyway (first real bridge appears)

## **ART 10.081 — Closed-Loop Life Support System**

Score: 0 (Impact in GVN 12)

Justification (3–5 sentences):

There is no clear healthcare-GVN bottleneck that Closed-Loop Life Support System directly relaxes in a 5.5M-person society. Any effect would come mainly through very general macroeconomic spillovers rather than prevention, diagnosis, treatment, or health-data governance. That linkage is too weak for scoring, so this remains a watchpoint rather than a meaningful healthcare impact.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [adjacent sectors] → begin framing Closed-Loop Life Support System as a health-system input (possible linkage emerging)
- (+) [public planners] → include the technology in health-resilience scenarios (watchpoint activated)
- (-) [providers] → report no meaningful use case after review (linkage remains weak)
- (+) [research funders] → back targeted healthcare pilots anyway (first real bridge appears)

## **ART 10.082 — High-Altitude Platforms & Balloons**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, High-Altitude Platforms & Balloons expands access to telehealth, remote monitoring, specialist support, and continuity of care outside major institutions. Institutionally, it shifts bargaining power toward distributed platforms and away from place-bound providers, while also creating outage, cybersecurity, and affordability risks. Third-order effects include more self-care, earlier intervention, and less travel/time loss, but also sharper inequality if coverage or pricing is

uneven. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [remote clinics] → pilot High-Altitude Platforms & Balloons for specialist backup (access pathway forming)
- (+) [payers] → test reimbursement for connectivity-dependent care (business model emerging)
- (-) [providers] → report outages disrupting medical workflows (dependency becomes visible)
- (+) [public planners] → include healthcare traffic in coverage obligations (health linkage formalized)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Decentralized Trust Networks (Web3 & Blockchain) makes sensitive health data, models, records, and transactions easier to share, verify, or govern without fully centralizing them. Institutionally, it reshapes who can learn from data, who can move patient information across boundaries, and who is liable when automated or distributed systems fail. Third-order effects include faster scaling of personalized medicine and health AI, but also new forms of lock-in, data commodification, and re-identification pressure. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → trial Decentralized Trust Networks (Web3 & Blockchain) for cross-organization data use (governance pathway forming)
- (+) [regulators] → issue guidance naming this architecture (formal recognition appears)
- (-) [patients] → raise consent or opacity complaints (social license being tested)
- (+) [auditors] → demand traceable logs for these systems (accountability maturing)

### ART 11.084 — Platform Cooperatives & Fair Work

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Platform Cooperatives & Fair Work changes how care work, patient support, payments, or governance are coordinated rather than how disease is biologically treated. Institutionally, the main

effect is on bargaining power, transparency, access, and trust between patients, workers, platforms, and providers. Third-order effects can be meaningful, but they depend heavily on adoption by care organizations and public rules. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers/workers/patients] → test Platform Cooperatives & Fair Work for coordination or payment workflows (health use case emerging)
- (+) [regulators] → ask for auditable records or portable rights in these platforms (governance path forming)
- (-) [advocates] → surface exclusion, coercion, or opacity problems (social limits becoming visible)
- (+) [public systems] → compare this model with incumbent intermediaries (power redistribution assessed)

## ART 11.085 — Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Open Data Sharing Marketplaces makes sensitive health data, models, records, and transactions easier to share, verify, or govern without fully centralizing them. Institutionally, it reshapes who can learn from data, who can move patient information across boundaries, and who is liable when automated or distributed systems fail. Third-order effects include faster scaling of personalized medicine and health AI, but also new forms of lock-in, data commodification, and re-identification pressure. That comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [hospital groups] → sign cross-site agreements enabled by Open Data Sharing Marketplaces (fragmented data becomes usable)
- (+) [regulators] → publish health-specific certification for Open Data Sharing Marketplaces (scale path becomes legible)
- (+) [patient apps] → expose granular consent/revocation or audit trails (control becomes visible)
- (-) [patient groups] → challenge opaque secondary use despite privacy claims (trust stress test)
- (+) [payers] → accept outputs from external trusted pipelines (interoperability monetized)
- (-) [incumbent vendors] → lobby to preserve proprietary silos (power struggle visible)
- (+) [cyber agencies] → treat exchange nodes/model pipelines as critical infrastructure (dependency acknowledged)
- (+) [smaller clinics] → join shared analytics without sending raw data away (power disperses)



- (-) [courts and auditors] → test liability after automated or distributed failure (accountability clarified)

## **ART 11.086 — Secure & Resilient Social Platforms**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Secure & Resilient Social Platforms changes how care work, patient support, payments, or governance are coordinated rather than how disease is biologically treated. Institutionally, the main effect is on bargaining power, transparency, access, and trust between patients, workers, platforms, and providers. Third-order effects can be meaningful, but they depend heavily on adoption by care organizations and public rules. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers/workers/patients] → test Secure & Resilient Social Platforms for coordination or payment workflows (health use case emerging)

- (+) [regulators] → ask for auditable records or portable rights in these platforms (governance path forming)

- (-) [advocates] → surface exclusion, coercion, or opacity problems (social limits becoming visible)

- (+) [public systems] → compare this model with incumbent intermediaries (power redistribution assessed)

## **ART 11.087 — Collective Open Innovation Networks**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Collective Open Innovation Networks affects healthcare by speeding collaboration, challenge-solving, and distributed innovation rather than by acting in care delivery itself. Institutionally, it can reduce dependence on a few incumbent R&D organizations, but also creates IP, validation, and governance tensions. The largest effects show up over time through faster research and problem-solving, not immediate bedside disruption. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [health researchers] → pilot Collective Open Innovation Networks for medical challenge-solving (R&D linkage forming)

- (+) [funders] → reward shared provenance and validation trails (coordination model emerging)

- (-) [IP disputes] → increase around collaborative outputs (governance boundary visible)
- (+) [clinical networks] → retain failed pathways as searchable knowledge (learning loop strengthens)

## **ART 11.088 — Scalable Decentralized Governance**

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Scalable Decentralized Governance changes how care work, patient support, payments, or governance are coordinated rather than how disease is biologically treated. Institutionally, the main effect is on bargaining power, transparency, access, and trust between patients, workers, platforms, and providers. Third-order effects can be meaningful, but they depend heavily on adoption by care organizations and public rules. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers/workers/patients] → test Scalable Decentralized Governance for coordination or payment workflows (health use case emerging)
- (+) [regulators] → ask for auditable records or portable rights in these platforms (governance path forming)
- (-) [advocates] → surface exclusion, coercion, or opacity problems (social limits becoming visible)
- (+) [public systems] → compare this model with incumbent intermediaries (power redistribution assessed)

## **ART 11.089 — Digital Learning Networks and Skill Credentialing**

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this matters because healthcare has chronic training bottlenecks: staff shortages, fast-changing AI tools, and large amounts of tacit practice that are hard to scale through traditional education alone. Institutionally, portable digital credentialing can open pathways for faster upskilling, role redesign, and cross-organizational verification of competence, while also creating risks of low-quality automated assessment and credential inflation. Third-order effects include more fluid labor markets, quicker diffusion of new care tools, and potential redistribution of training power away from legacy institutions. That is significant because workforce capability is a major system constraint, but it is still an enabling layer rather than the core therapeutic transformation.

Weak signals (9):

- (+) [health employers] → accept portable micro-credentials for defined care tasks (verification cost falls)

- (+) [nursing and allied-health programs] → use AI simulation for routine skill refresh (training capacity expands)
- (+) [public systems] → retrain staff for AI-supervision and remote-care roles at scale (role redesign accelerates)
- (-) [professional bodies] → dispute validity of automated assessments in high-stakes skills (legitimacy tested)
- (+) [rural providers] → fill capability gaps using verified online training pathways (geographic inequality shrinks)
- (-) [workers] → report pressure to self-fund constant recredentialing (cost shift becomes visible)
- (+) [payers/regulators] → reference digital credentials in service authorization (institutional acceptance grows)
- (-) [auditors] → uncover mismatch between credentials and real performance (quality control challenge)
- (+) [credential wallets] → integrate verified clinical skills into hiring workflows (matching friction falls)

## ART 11.090 — Prediction-Market Forecasting Platforms

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Prediction-Market Forecasting Platforms improves intervention choice, coordination, modeling, or scientific search in areas where clinicians and health systems currently rely on slow trial-and-error or fragmented judgment. Institutionally, it shifts authority toward machine-mediated planning and away from purely professional intuition, while creating new audit, reward-design, and accountability issues. Third-order effects include faster learning loops, more standardized pathways, and greater concentration of advantage in organizations with the best data and governance. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → test Prediction-Market Forecasting Platforms in pathway or ops decisions (direct use emerging)
- (+) [payers] → reimburse AI-supported decisions on limited pathways (commercial proof starts)
- (-) [clinicians] → publish high override rates or bias findings (trust boundary visible)
- (+) [auditors] → request explicit reasoning/provenance traces (governance catching up)

## 12. Protocols, Standards & Socio-Technical Infrastructure

## ART 12.091 — Universal IoT Interoperability Standards

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this removes a structural bottleneck in connected healthcare: devices, wearables, home sensors, and hospital equipment can finally talk to each other without bespoke integration. Institutionally, it weakens vendor lock-in, lowers the cost of distributed monitoring and home care, and makes it easier for patients and smaller providers to assemble multi-vendor care stacks; the downside is a larger shared attack surface if the standards are weakly governed. Third-order effects include faster scaling of preventive sensing, more portable care plans, and stronger competition around analytics and service quality rather than closed hardware ecosystems. That is transformative because the GVN's self-care and personalized-monitoring vision is much harder to scale while every device remains a silo.

Weak signals (9):

- (+) [hospital procurement] → requires standards-compliant device APIs in all new tenders (lock-in starts breaking)
- (+) [home-care providers] → mix multi-vendor sensors and actuators in one care plan (distributed care stack forms)
- (+) [payers] → reimburse interoperable remote-monitoring bundles rather than brand-specific kits (market broadens)
- (-) [incumbent vendors] → resist opening proprietary device data models (power struggle visible)
- (+) [patient apps] → let users connect clinical and consumer devices with common permissions (self-care control rises)
- (-) [cybersecurity agencies] → issue critical advisories for flaws in common device stacks (shared risk acknowledged)
- (+) [certifiers] → launch conformance labels specifically for health IoT (adoption path hardens)
- (+) [smaller clinics] → deploy connected monitoring without major integration projects (access to capability widens)
- (-) [auditors] → test whether interoperability really preserves provenance and access controls (governance quality checked)

## ART 12.092 — Interoperable Digital Twin Ecosystems

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Interoperable Digital Twin Ecosystems improves intervention choice, coordination, modeling, or scientific search in areas where clinicians and health systems currently rely on slow trial-and-error or fragmented judgment. Institutionally, it shifts authority toward machine-mediated planning and away from purely professional intuition, while creating new audit, reward-design, and accountability issues. Third-order effects include faster learning loops, more standardized pathways, and greater concentration of advantage in organizations with the best data and governance. That

comfortably fits the €100M–€1B / tens-to-hundreds-of-millions-of-hours band, but it is not a single linchpin of the healthcare regime shift.

Weak signals (9):

- (+) [care pathways] → use Interoperable Digital Twin Ecosystems to choose treatments or escalation routes (decision layer shifting)
- (+) [hospital ops teams] → delegate scheduling/coordination choices to AI agents (managerial workload falls)
- (+) [research funders] → back AI-designed studies or trials (learning loop accelerates)
- (-) [clinicians] → document override rates for model recommendations (trust boundary visible)
- (+) [payers] → reimburse AI-supported decision workflows (economic adoption begins)
- (-) [auditors] → require causal or provenance traces after bad outcomes (accountability hardens)
- (+) [vendor market] → consolidate around few validated model stacks (power concentrates)
- (-) [patient groups] → contest opaque optimization against human preferences (social pushback emerges)
- (+) [quality agencies] → compare sites by AI-assisted outcome gains (scaling becomes measurable)

## ART 12.093 — Global Supply Chain Traceability Networks

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, traceability networks matter to healthcare because medicines, devices, diagnostics, and biologics are only as safe as the chain that produced, transported, and authenticated them. Institutionally, they reduce counterfeit risk, speed recalls, and make procurement more evidence-based, while also shifting bargaining power toward actors who control standards, tags, and verification infrastructure. Third-order effects include shorter shortage response loops, tighter cold-chain discipline, and more pressure for transparency about origin, composition, and handling. That is significant rather than transformative: it strongly improves reliability and safety, but it does not by itself redefine how care is personalized or delivered.

Weak signals (9):

- (+) [hospital procurement] → requires end-to-end provenance for high-risk products (trust becomes operational)
- (+) [regulators] → run digital recall drills using shared traceability records (response speed improves)
- (+) [cold-chain logistics] → attach custody events to biologics and vaccines as default (handling discipline deepens)
- (-) [suppliers] → resist revealing origin or transformation data (power conflict becomes visible)
- (+) [pharmacies] → scan authenticity and handling status before dispensing (counterfeit barrier rises)

- (-) [auditors] → find gaps between physical and digital chain-of-custody records (data quality limit exposed)
- (+) [payers/public buyers] → prefer traceable suppliers in tenders (market incentive strengthens)
- (-) [smaller vendors] → struggle with tagging/compliance costs (distribution effects surface)
- (+) [quality teams] → identify root causes faster after device or medicine incidents (recall loop shortens)

## ART 12.094 — Personal Data Portability & Trust Frameworks

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, this gives patients practical control over who can access which health data and for what purpose, instead of forcing them to remain inside one provider or platform. Institutionally, it changes bargaining power in healthcare by making patient-directed data flows easier than provider-controlled siloing, while also creating new fraud, coercion, and consent-design risks. Third-order effects include more consumer-facing health services, easier second opinions, faster AI personalization, and stronger competition among providers because data lock-in weakens. That is transformative because patient-controlled portability is a core precondition for the individualized, self-directed care model described in the GVN.

Weak signals (9):

- (+) [patient portals] → issue reusable consent receipts and revocation logs (control becomes tangible)
- (+) [second-opinion services] → import longitudinal records without bespoke provider agreements (switching cost collapses)
- (+) [payers] → accept patient-directed data feeds from external apps/devices (boundary opens outward)
- (-) [consumer groups] → document dark-pattern consent flows in health apps (coercion risk visible)
- (+) [smaller providers] → compete using imported patient histories rather than incumbent lock-in (market power redistributes)
- (-) [fraud teams] → track account-takeover attempts against data wallets (security burden surfaces)
- (+) [regulators] → standardize purpose-bound and time-bound health data permissions (framework matures)
- (-) [employers/insurers] → pressure users to share more than needed (power misuse emerges)
- (+) [patient communities] → coordinate selective disclosure for research and peer support (collective agency grows)

## ART 12.095 — Interoperable Digital Currency Payment Networks

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Interoperable Digital Currency Payment Networks changes how care work, patient support, payments, or governance are coordinated rather than how disease is biologically treated. Institutionally, the main effect is on bargaining power, transparency, access, and trust between patients, workers, platforms, and providers. Third-order effects can be meaningful, but they depend heavily on adoption by care organizations and public rules. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers/workers/patients] → test Interoperable Digital Currency Payment Networks for coordination or payment workflows (health use case emerging)
- (+) [regulators] → ask for auditable records or portable rights in these platforms (governance path forming)
- (-) [advocates] → surface exclusion, coercion, or opacity problems (social limits becoming visible)
- (+) [public systems] → compare this model with incumbent intermediaries (power redistribution assessed)

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

Score: 5 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, machine-readable regulation matters in healthcare because the sector is rule-dense: AI tools, data sharing, reimbursement, medical devices, and personalized therapies all hit slow interpretation bottlenecks. Institutionally, it shifts compliance from ad hoc legal interpretation toward programmable checks and faster updating, which can lower barriers for smaller providers and innovators while also hardening automated gatekeeping if rules are badly encoded. Third-order effects include faster rollout of compliant care models, less manual administrative work, and more contest over whether encoded rules capture legal intent and ethical nuance. That is significant because it can remove a major inhibitor in the GVN, but it is still a governance layer rather than the primary source of health gain.

Weak signals (9):

- (+) [health regulators] → publish computable versions of reimbursement or device rules (administrative friction drops)
- (+) [hospital compliance teams] → test AI tools against live rule packages before deployment (adoption speed increases)
- (+) [smaller clinics] → use off-the-shelf rule engines instead of bespoke legal interpretation (capability spreads outward)



- (-) [courts] → hear disputes where coded logic diverges from legal intent (boundary becomes visible)
- (+) [vendors] → ship compliance-by-design modules for health data and AI workflows (market matures)
- (-) [patient advocates] → challenge opaque automated denials based on encoded rules (automated gatekeeping exposed)
- (+) [public agencies] → update policy parameters faster after evidence changes (feedback loop shortens)
- (-) [auditors] → flag inconsistent implementations across jurisdictions (standardization challenge visible)
- (+) [reimbursement systems] → reduce manual claim handling for rule-heavy pathways (person-hours affected)

## **ART 12.097 — Open Metaverse Interoperability Protocols**

Score: 1 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Open Metaverse Interoperability Protocols changes how patients and professionals interact with treatment, rehabilitation, therapy, or assistive support. Institutionally, it can move care out of specialist settings and improve independence, but it also changes reimbursement, skill requirements, and expectations about what bodies and minds should be able to do. Third-order effects include new norms around disability, cognitive augmentation, and remote participation in care. That keeps the total impact concrete but limited, so it sits at the 1 level rather than becoming a material system shift.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → pilot Open Metaverse Interoperability Protocols in rehab, therapy, or assistive care (clinical pathway forming)
- (+) [payers] → test reimbursement outside specialist centers (access model shifting)
- (-) [ethics bodies] → open review on dependency or manipulation risks (norm conflict visible)
- (+) [training programs] → add these interfaces to curricula (professional adaptation begins)

## **ART 12.098 — Content Authenticity Infrastructure**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Content Authenticity Infrastructure makes sensitive health data, models, records, and transactions easier to share, verify, or govern without fully centralizing them. Institutionally, it reshapes who can learn from data, who can move patient information across boundaries, and who is liable when automated or distributed systems fail. Third-order effects include faster scaling of

personalized medicine and health AI, but also new forms of lock-in, data commodification, and re-identification pressure. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [providers] → trial Content Authenticity Infrastructure for cross-organization data use (governance pathway forming)
- (+) [regulators] → issue guidance naming this architecture (formal recognition appears)
- (-) [patients] → raise consent or opacity complaints (social license being tested)
- (+) [auditors] → demand traceable logs for these systems (accountability maturing)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

Score: 10 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, these protocols let health systems, researchers, labs, and payers compute shared answers from sensitive data without handing over raw records. Institutionally, that reduces one of the biggest blockers to personalized care and system learning—fragmented, high-trust data silos—while also shifting value toward parties that control the protocols, governance, and safe-output rules. Third-order effects include higher-frequency cross-organizational learning, less manual redaction and contracting, and more contest over what outputs are legitimate when nobody sees the full raw picture. That is transformative because it makes large-scale coordination possible without demanding the politically fragile centralization of all health data.

Weak signals (9):

- (+) [hospital networks] → run joint analytics without moving raw patient records (coordination friction falls)
- (+) [research consortia] → approve multi-party studies faster using secure computation (study setup accelerates)
- (+) [payers and providers] → compare outcomes on shared sensitive cohorts without direct pooling (governance barrier eases)
- (-) [auditors] → challenge unsafe-output assumptions after reconstruction scares (trust bar rises)
- (+) [smaller providers] → join advanced analytics networks without surrendering local data control (power disperses)
- (-) [vendors] → compete to own the neutral compute layer for health collaboration (platform power struggle)
- (+) [regulators] → reference secure multi-party methods in compliance guidance (formal pathway appears)
- (-) [patients] → question whether “privacy-preserving” still counts as consented use (social license tested)

- (+) [public health agencies] → use secure collaboration for real-time surveillance and planning (population learning improves)

## **ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure**

Score: 3 (Impact in GVN 12)

Justification (3–5 sentences):

Directly, Manufacturing-specific standards/conformance/certification infrastructure improves the ability to make customized or rapidly reconfigurable medical products, components, or supply chains. Institutionally, it shifts some value from centralized batch manufacturing toward local, digital, or low-volume production, while making certification and quality assurance more complex. Third-order effects include faster shortage response and more personalized devices, but also more fragmentation in standards and procurement. That plausibly reaches the material €10–100M / 5–50M person-hour band, but the pathway is still too indirect or narrow for a higher score.

Weak signals (4):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [medtech firms] → test Manufacturing-specific standards/conformance/certification infrastructure for custom or shortage-prone products (use case appearing)
- (+) [regulators] → open pathway for decentralized or patient-specific output (formal route forming)
- (-) [auditors] → find quality variation across sites (scale friction visible)
- (+) [hospitals] → explore near-care fabrication capacity (supply model shifting)

## **GVN 13: Redressing Disabilities ART Impact**

### **1. Sensing, Measurement & Connectivity**

#### **ART 01.001 - Global Broadband Connectivity**

Score: 10 (Impact in GVN 13)

Justification (3–5 sentences):

Reliable near-ubiquitous connectivity makes remote rehab, remote device tuning, telepresence support, AI assistants, and safety monitoring viable in ordinary homes and rural areas, directly supporting the shift from institutional care toward independent living. It also changes the surrounding system: public payers can substitute some travel and in-person care hours with connected services, while telecom firms and platform vendors gain leverage over essential disability infrastructure. That can change weekly life for very large user groups, so it fits 10. It is not a 20 because some high-value assistive pathways still work offline or locally.

**Weak signals (9):**

- (+) [Independent living / rural users] → municipal disability packages bundle fixed-wireless or satellite links (home support going remote-first)
- (+) [Rehabilitation funding] → tele-rehab reimbursement codes specify bandwidth and uptime (payment following connectivity)
- (+) [Assistive-device vendors] → service contracts add remote diagnostics and tuning (devices becoming ongoing services)
- (+) [Home care agencies] → visit schedules are redesigned around connected check-ins (care model shifting outward)
- (+) [Accessible housing] → public housing specs include managed connectivity as accessibility (infrastructure redefined as accessibility)
- (+) [Disability advocacy] → campaigns frame connectivity as a functional-right entitlement (norms shifting toward inclusion)
- (+) [Supported employment] → return-to-work programs fund secure home links (work reintegration expanding)
- (-) [Low-income users] → missed connectivity payments interrupt assistive services (affordability becoming failure mode)
- (-) [Cybersecurity / essential aids] → outage or spoofing incidents disrupt monitoring or prompts (dependency risk becoming visible)

**ART 01.002 - Ultra-Low Latency Networks****Score: 5 (Impact in GVN 13)****Justification (3–5 sentences):**

Millisecond links matter where assistive systems need tight feedback loops: remote haptic rehab, teleoperation, collaborative robotics, high-performance prosthetics, and low-jitter AR guidance. Their main second-order effect is to favor providers with edge infrastructure and to intensify liability around network performance when digital assistance becomes safety-critical. That makes them an important part of specialized service transformation, large enough for a 5, but not broad enough for a 10 without mass everyday deployment across consumer-grade aids.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rehab providers] → neuro-rehab centers install edge-connected teletherapy rooms (feedback quality becoming billable)
- (+) [Mobility aids] → exoskeleton and wheelchair vendors publish latency limits (network now affects device safety)
- (+) [Remote assistance] → service-level agreements add millisecond guarantees (timing becoming operationally critical)
- (+) [Standards bodies] → assistive robotics profiles define critical-traffic classes (infrastructure specializing for disability use)
- (-) [Liability / insurers] → near-miss reviews cite jitter or edge failures (network delay gaining legal salience)
- (-) [Geographic equity] → advanced services cluster around edge-rich cities (benefits concentrating spatially)

## ART 01.003 - Edge AI for Sensor Data

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Mature on-device AI is a core enabler for machine vision aids, local speech support, fall detection, intent recognition, smart hearing, adaptive prosthetics, and cognitive prompting without constant cloud dependence. Because inference happens locally, it softens two major GVN inhibitors at once, privacy concern and unreliable connectivity, while making smaller providers less dependent on centralized expert monitoring. That combination can materially change how disability support is delivered at home and in everyday environments for large populations, so it reaches 10.

### **Weak signals (9):**

- (+) [Vision impairment support] → public tenders buy on-device object and navigation aids (assistive perception becoming mainstream)
- (+) [Hearing / speech support] → hearing devices market local contextual filtering (latency and privacy improving)
- (+) [Home independence] → fall-detection systems advertise offline operation (cloud no longer prerequisite)
- (+) [Rehab clinics] → prosthetic fitting tools use local gait and intent models (personalization moving to point-of-care)
- (+) [Data governance] → providers rewrite consent around local processing by default (privacy barrier weakening)
- (+) [Smaller municipalities] → low-staff care units buy edge monitoring instead of centers (expert scarcity easing)
- (+) [Workplace accommodation] → employers pilot wearable edge-AI safety aids (function entering employment settings)
- (-) [Safety / bias] → adverse-event reviews mention missed detections in unusual homes or bodies (edge blind spots surfacing)
- (-) [Market power] → a few chip and software stacks dominate certified assistive AI (new lock-in forming)

## ART 01.004 - Quantum & High-Precision Sensing

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The plausible linkage is narrow: better biosignal capture, balance sensing, or implant calibration could improve some high-end diagnostic or neuro-assistive applications. However, most of the GVN's main shift depends on affordable, scalable everyday aids rather than ultra-precise measurement. This is worth watching, but on present linkage it is only a concrete niche contributor.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Neuro-assistive R&D] → elite rehab centers add ultra-precise sensing labs (niche performance frontier emerging)

- (+) [Implant manufacturers] → calibration claims cite high-precision sensing modules (device precision starting to matter)
- (-) [Public procurement] → disability budgets reject premium sensing features (translation barrier persisting)
- (-) [Clinical workflows] → specialist-only operation keeps usage in tertiary centers (scale still institutionally bounded)

## ART 01.005 - Micro/Nano Sensor Networks

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Dense low-cost sensor networks can turn homes, wheelchairs, prosthetic sockets, footwear, and care spaces into continuously observable environments, improving fit, safety, and adaptation. Their second-order effect is important: support can shift from episodic assessment toward continuously tuned assistance, but only if users trust the monitoring and standards avoid vendor silos. That is significant enough to change a substantial part of the GVN, especially home support and preventive maintenance, even though it is still an enabling layer rather than the final service.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Accessible housing] → retrofits include distributed motion, pressure, and humidity meshes (homes becoming adaptive environments)
- (+) [Prosthetics / orthotics] → sockets and braces ship with embedded fit sensors (fit becoming continuously managed)
- (+) [Care quality] → wound and moisture dashboards enter home-care reviews (complications detected earlier)
- (+) [Public buyers] → procurement asks for open APIs across many low-cost sensors (platform effects becoming visible)
- (-) [Privacy / dignity] → residents contest room-level behavioral sensing (continuous observation meeting resistance)
- (-) [Data overload] → care teams report alarm fatigue from dense deployments (information burden becoming limiting)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Continuous sensing is one of the strongest routes to safer independent living, but in this GVN the privacy and data-security barrier is explicit, so mature privacy-preserving architectures unlock adoption rather than merely optimize it. They also redistribute power by allowing disability users and families to accept monitoring without surrendering raw personal data to central platforms, while still leaving room for new forms of hidden exclusion or overconfident automation. Because this directly removes a major inhibitor to smart homes, AI assistants, and passive support at scale, it plausibly reaches transformative magnitude.

### **Weak signals (9):**

- (+) [Supported housing] → residents approve monitoring pilots only with local-only raw data (privacy architecture driving uptake)
- (+) [Municipal procurement] → tenders require on-device analytics and minimal export (public buyers operationalizing privacy)
- (+) [Regulators] → guidance treats local processing as lower-risk assistive monitoring (compliance barrier softening)
- (+) [Families / caregivers] → consent rates rise when dashboards show summaries not recordings (social acceptance improving)
- (+) [Cross-provider care] → shared reports shift from recordings to encrypted event summaries (data minimization becoming norm)
- (+) [Advocacy groups] → disability organizations endorse privacy-by-design toolkits (trust becoming organized)
- (+) [Insurers] → premiums fall for local-processing assistive systems (risk getting priced favorably)
- (-) [Algorithmic opacity] → users complain private systems are harder to audit (local black boxes emerging)
- (-) [Vendor strategy] → firms disable features unless users share more data (power asymmetry reappearing)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Security is not a side issue here because compromised implants, home sensors, or care platforms can directly threaten safety and autonomy. Mature post-quantum security would mostly act as a confidence layer: reducing adoption friction for long-lived implants and high-stakes remote support, while raising costs and favoring well-capitalized providers. That gives it a material but not central role, important for risk management rather than as the main driver of functional restoration.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Implantable devices] → long-life implants advertise post-quantum update paths (future-proof security becoming selling point)
- (+) [Hospital procurement] → assistive telemetry tenders add post-quantum requirements (security entering purchasing criteria)
- (+) [Regulators] → guidance links neural and mobility implants to upgraded cryptography (safety governance tightening)
- (-) [Smaller providers] → community-care vendors drop out due to secure-network costs (security raising concentration)
- (-) [Incident reporting] → breach reviews cite harvest-now risks to disability data (threat model becoming concrete)

## ART 01.008 - Integrated Sensing and Communication (ISAC)

**Score: 3 (Impact in GVN 13)**



**Justification (3–5 sentences):**

ISAC could reduce the dedicated sensor burden in smart homes and public environments by letting communication infrastructure also detect movement, presence, and hazards. That helps passive support and indoor accessibility, but it also blurs the line between connectivity and surveillance in exactly the environments where dignity and consent matter most. The likely impact is material in selected built environments, yet still too dependent on infrastructure retrofits and governance choices to score higher.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care facilities] → Wi-Fi or 5G upgrades bundle occupancy and fall sensing (communications gear becoming sensory infrastructure)
- (+) [Transport hubs] → indoor guidance pilots use network-based localization (navigation layer consolidating)
- (+) [Building standards] → smart-building specs mention radio-based safety sensing (built environment reframing)
- (-) [Residents / advocates] → objections focus on invisible sensing through ordinary networks (consent challenge becoming salient)
- (-) [Procurement] → buyers separate comms and care-sensing contracts after disputes (convergence meeting institutional resistance)

## 2. Computing Hardware & Non Von Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 5 (Impact in GVN 13)

**Justification (3–5 sentences):**

These chips make always-on perception and intent decoding feasible inside hearing aids, vision aids, prosthetics, wheelchairs, implants, and smart-home nodes under tight power budgets. Their second-order effect is to reduce dependence on cloud platforms and make smaller or public providers more able to deploy privacy-sensitive assistive intelligence locally, while potentially concentrating power in a few certified chip ecosystems. The impact is significant because it lowers core technical barriers across many device classes, but it remains an enabling substrate rather than the visible operating-model shift itself.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Hearing and vision aids] → all-day local AI becomes a standard spec (power budget barrier dropping)
- (+) [Public procurement] → tenders reward battery life with local inference (energy efficiency becoming functional)
- (+) [Exoskeletons] → backpack compute is replaced by embedded modules (wearability improving)
- (+) [Implants] → approvals cite event-driven low-heat processors (implant practicality increasing)

- (-) [Supply chain] → assistive makers queue behind a few certified chip vendors (hardware concentration growing)
- (-) [Security] → advisories cluster around shared chip stacks (systemic failure modes emerging)

## ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Smaller, cooler, lower-leakage electronics steadily improve implants, wearables, hearing devices, and edge assistants by shrinking size, heat, and charging burden. The main institutional effect is cost/performance rebalancing in favor of more continuous assistive computation, but the GVN does not hinge on this specific hardware path versus other efficiency gains. That makes it a material but indirect contributor.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Implants] → next-generation neural and hearing devices advertise lower heat profiles (miniaturization becoming user-visible)
- (+) [Wearables] → charging intervals lengthen without larger batteries (always-on support becoming practical)
- (+) [Mobility aids] → control boards shrink and free physical space (device form factors improving)
- (-) [Public buyers] → procurement treats gains as premium extras (cost barrier limiting reach)
- (-) [Standards] → qualification cycles lag new materials in medical devices (translation bottleneck persisting)

## ART 02.011 - Quantum Computing Platforms

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The main path is through research optimization and perhaps some difficult scheduling or drug-design tasks, not everyday disability compensation. It could matter in specialist planning or discovery, but the GVN's operational shift is not contingent on quantum compute. So it is watch-worthy but minor here.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rare-disease R&D] → disability-focused research consortia buy quantum optimization access (research-only pathway opening)
- (+) [Scheduling] → tertiary rehab systems test quantum-assisted resource planning (niche operational use emerging)

- (-) [Assistive vendors] → no front-line products cite quantum dependencies (direct pathway still absent)
- (-) [Public payers] → quantum costs remain outside disability procurement logic (institutional distance persisting)

## ART 02.012 - Photonic and Optical Computing

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Faster, cooler computing helps data-intensive models, but most disability value comes from applications and interfaces, not the specific compute substrate. Benefits would mainly appear through upstream platforms rather than direct changes in support practices. This stays in the concrete-but-limited range.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [AI infrastructure] → assistive-model providers adopt optical accelerators for edge training (upstream cost barrier easing)
- (+) [AR/vision aids] → vendors cite photonic compute in lightweight headsets (form-factor gains becoming relevant)
- (-) [Clinical procurement] → no disability-service tenders mention optical compute (translation to care still weak)
- (-) [Standards] → certification pathways stay generic, not assistive-specific (diffuse linkage persisting)

## ART 02.013 - Next-Gen Memory & Storage

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Better non-volatile memory supports always-on assistive logs, personal digital histories, offline functioning, and low-power edge devices. It also strengthens longitudinal personalization: care plans, mobility patterns, and device tuning can persist more reliably across interruptions, while raising new questions about who controls those memories. The impact is material but not primary.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Assistive logs] → devices keep longer local histories without battery penalties (personalization persistence improving)
- (+) [Care continuity] → home-care systems export persistent user-state profiles (handoffs becoming less lossy)
- (+) [Offline support] → cognitive-assistance tools retain rich local models (cloud dependency decreasing)
- (-) [Data rights] → disputes rise over ownership of long-lived device histories (memory control becoming contested)

- (-) [Procurement] → memory gains are hidden inside closed ecosystems (user agency not improving automatically)

## ART 02.014 - Molecular Computing

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The plausible route is in-body biochemical sensing or ultra-embedded medical logic, which could someday support niche implants or smart therapeutics. But the GVN's dominant shift toward assistive independence does not depend on molecular computation in particular. This therefore remains a narrow watchpoint.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Implant R&D] → disability-related therapeutic devices begin using molecular logic modules (niche medical pathway opening)
- (+) [Biochemical sensing] → prototypes target in-body event detection for neuro or metabolic disability (new assistive modality appearing)
- (-) [Clinical translation] → no reimbursement pathways mention molecular computation (institutional uptake absent)
- (-) [Safety review] → regulators keep such systems inside experimental categories (scale still distant)

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 - Causal Learning & Reasoning

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Causal models help clinicians, families, and users choose interventions that actually improve function rather than blindly following averages, directly answering the GVN tension between equal treatment and need-based treatment. Systemically, that can shift reimbursement and regulation toward explainable individualized pathways, though hidden confounders or biased assumptions can still encode unfairness. This is significant because it can change decision quality across many services, but it is not itself the physical assistive layer.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rehab planning] → care teams use counterfactual dashboards to compare interventions (decision quality becoming model-driven)
- (+) [Funding] → pilots reimburse explainable causal decision support (payment rewarding individualized reasoning)

- (+) [Assistive-device tuning] → vendors market “what-if” adjustment tools (users seeing intervention logic)
- (+) [Auditability] → review boards ask why-models for denied supports (causal trace becoming governance issue)
- (-) [Representation] → advocates flag underrepresented disability groups in causal graphs (fairness risks surfacing)
- (-) [Payers] → causal tools are used to tighten eligibility thresholds (optimization turning exclusionary)

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Disability data are fragmented across hospitals, home-care providers, schools, devices, and users, and are too sensitive to pool casually; mature federated learning directly unlocks better models without requiring central data hoarding. That changes the surrounding economics by letting smaller municipalities, clinics, and device fleets benefit from collective learning while preserving local control, though dominant platforms may still capture orchestration power. Because it attacks one of the core bottlenecks behind personalized assistive AI at scale, it plausibly reaches transformative magnitude.

### **Weak signals (9):**

- (+) [Hospitals / devices] → rehab networks launch federated model consortia (shared learning without central pooling)
- (+) [Hearing and vision aid firms] → marketing stresses training without raw uploads (privacy-preserving improvement becoming visible)
- (+) [Regulators] → approvals allow cross-site learning with local data retention (governance barrier weakening)
- (+) [Small municipalities] → join national model pools without new data centers (smaller actors gaining capability)
- (+) [User devices] → procurement asks for local fine-tuning of shared models (personalization staying near user)
- (+) [Patient organizations] → negotiate model-governance rights in consortia (users entering data governance)
- (+) [Benchmarking] → rural or small-site performance starts catching up (fragmentation costs falling)
- (-) [Platform power] → orchestrators take revenue shares over learning networks (new intermediary dominance forming)
- (-) [Model integrity] → incident reviews mention poisoned or skewed local updates (distributed trust becoming operational risk)

## ART 03.017 - Trustworthy AI Systems

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The GVN explicitly faces AI surprise, conservative institutions, and safety anxiety; trustworthy AI

turns those from adoption blockers into manageable governance problems by adding auditability, safe fallback, monitoring, and explanation. It also redistributes accountability, making it clearer when a device, provider, or human operator bears responsibility, while raising certification costs and potentially excluding small innovators. Because safe, governable AI is a precondition for scaling AI assistance in high-stakes daily living, its total impact is transformative.

#### **Weak signals (9):**

- (+) [Regulation] → assistive-AI assurance profiles are published (trust moving from rhetoric to rules)
- (+) [Reimbursement] → public payers restrict coverage to auditable models (funding following assurance)
- (+) [Incident reporting] → AI confidence and fallback logs become mandatory (self-monitoring becoming standard)
- (+) [Procurement] → human override and provenance trails enter tender criteria (buyer expectations hardening)
- (+) [Insurers] → lower premiums offered for verified safe-fallback systems (trust becoming priced)
- (+) [Disability organizations] → rate tools on contestability and explainability (user scrutiny institutionalizing)
- (+) [Providers] → home-care programs expand once audit trails satisfy governance (trust unlocking scale)
- (-) [SME access] → certification costs push smaller vendors out (assurance concentrating the market)
- (-) [Public trust] → scandals reveal explanations not matching behavior (performative trust undermining adoption)

## **ART 03.018 - Automated Machine Learning (AutoML)**

### **Score: 5 (Impact in GVN 13)**

#### **Justification (3–5 sentences):**

AutoML lowers the bottleneck of scarce specialists and allows faster local adaptation of models for different impairments, languages, homes, and device contexts. Its second-order effect is two-sided: small actors can build tailored tools faster, but poorly specified objectives can automate bias or unsafe control policies just as fast. That yields significant impact on pace and spread of personalization, though not enough by itself to redefine the GVN.

#### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Small providers] → municipal care units deploy custom models without in-house data scientists (capability decentralizing)
- (+) [Assistive startups] → device updates are shipped more frequently from automated pipelines (iteration cycles shortening)
- (+) [Localization] → communication and support tools add minority-language variants quickly (inclusion improving operationally)
- (+) [Rehab clinics] → therapists tune prediction models through guided interfaces (specialist bottleneck easing)

- (-) [Bias] → audits find unsafe models traced to poorly framed reward metrics (automation amplifying specification errors)
- (-) [Governance] → documentation lags proliferating model variants (oversight becoming harder)

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Independent living increasingly depends on many coordinated elements: wearables, room sensors, robots, scheduling agents, transport, reminders, and human caregivers. Multi-agent AI can turn these from a patchwork into a coordinated support ecosystem, but it also creates new failure cascades and shifts power toward whoever controls the orchestration layer. The magnitude is significant because coordination, not just individual device capability, is a real bottleneck in disability support.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Home independence] → care platforms start orchestrating sensors, reminders, and mobility aids together (support becoming system-level)
- (+) [Care scheduling] → digital agents negotiate visit timing with user routines (coordination labor dropping)
- (+) [Transport integration] → mobility apps sync accessible rides with therapy and work schedules (daily logistics tightening)
- (+) [Service robots] → household robots share maps and tasks with home sensors (multi-device coordination emerging)
- (-) [Cascading failure] → incident reviews show one bad inference triggering many wrong actions (system coupling becoming risky)
- (-) [Market structure] → single orchestration vendors lock users into whole ecosystems (coordination power centralizing)

## ART 03.020 - Quantum-Accelerated AI Systems

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The plausible path is faster optimization in discovery and perhaps some complex scheduling, not front-line disability support. The GVN benefits only indirectly through better upstream models or research. This stays minor unless quantum advantage appears in widely used assistive planning tools.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Research] → assistive-AI labs test quantum subroutines for difficult optimization (upstream experimentation beginning)



- (+) [Planning] → large care systems run pilot scheduling models with hybrid quantum stacks (niche operations use appearing)
- (-) [Productization] → no user-facing assistive tools depend on quantum acceleration (front-line pathway absent)
- (-) [Procurement] → disability budgets treat quantum access as research, not service infrastructure (institutional boundary holding)

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

This could accelerate the pipeline for new implants, materials, neurotherapies, assistive control strategies, and rare-disease interventions, shortening how long the GVN waits for usable advances. Institutionally, it may shift innovation power toward actors who own data, labs, or closed discovery platforms. The impact is material through the innovation system, but one step removed from everyday service delivery.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Assistive R&D] → discovery platforms begin targeting prosthetic control and neuro-restoration problems (innovation cycle accelerating)
- (+) [Rare diseases] → candidate therapies for disabling conditions emerge from autonomous lab loops (upstream relevance increasing)
- (+) [Funding] → disability innovation programs buy access to autonomous discovery stacks (institutional adoption starting)
- (-) [Ownership] → exclusive data partnerships lock discovery gains inside a few firms (innovation power concentrating)
- (-) [Validation] → regulators demand more human oversight after opaque discovery claims (translation bottleneck persisting)

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Mature AR/VR directly improves rehabilitation intensity, remote expert support, navigation training, social participation, and contextual guidance layered into daily life. It also changes workforce and service models by making remote coaching and virtualized accessible participation more common, while raising risks of exclusion if content standards ignore accessibility. Significant, but not the single linchpin of the GVN.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rehabilitation] → insurers reimburse immersive home therapy sessions (virtual rehab becoming normal service)
- (+) [Navigation] → visually impaired users receive AR wayfinding through public pilots (spatial guidance entering everyday use)
- (+) [Remote expertise] → technicians fit devices through shared first-person mixed reality (expert scarcity easing)
- (+) [Employment / education] → accommodation programs accept immersive participation as standard (participation moving beyond travel)
- (-) [Accessibility] → user groups report major apps fail with sensory or motor adaptations (content standards lagging)
- (-) [Equity] → premium headsets dominate effective deployments (benefits stratifying by income)

**ART 04.023 - Brain-Computer Interfaces (BCI)**

**Score: 10 (Impact in GVN 13)**

**Justification (3–5 sentences):**

For people with severe motor or speech impairments, BCIs move the control channel itself, enabling communication, prosthetic control, environmental control, and some restoration of agency where conventional interfaces fail. Systemically, they shift public debate from care hours toward autonomy rights, consent, neural privacy, and cyber safety, with strong distributional risks if only premium users access them. The change is transformative for a smaller but highly affected population and large enough to alter the GVN's operating model for severe disability.

**Weak signals (9):**

- (+) [Communication access] → public systems reimburse BCI-based communication where eye-gaze fails (last-resort control becoming mainstream)
- (+) [Rehab pathways] → combined neurosurgery-rehab-technology clinics are created (care pathways reorganizing)
- (+) [Prosthetics] → neural-control fitting becomes part of advanced limb programs (direct control entering routine practice)
- (+) [Home independence] → environmental-control platforms add BCI interfaces (agency expanding beyond clinic)
- (+) [Work participation] → supported-employment programs pilot BCI workstations (severe impairment reaching paid work)
- (+) [Rights discourse] → advocacy groups campaign for neural privacy and access rights (governance reframing around the brain)
- (+) [Certification] → regulators define update and safety rules for neural interfaces (institutional normalization starting)
- (-) [Cybersecurity] → advisories on neural-interface spoofing or update risks appear (brain-linked cyber risk materializing)
- (-) [Access inequality] → reimbursement covers only narrow diagnoses while premium markets broaden first (restoration becoming stratified)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 20 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

This is the clearest direct embodiment of the challenger regime described in the GVN: restoring mobility and working capacity, reducing dependence on institutional care and personal assistance, and moving support from protection toward enabled function. Its second- and third-order effects are equally large: employment, insurance, housing adaptation, transport, and care labor all change when physically impaired people can do more themselves, while inequality, stigma, and cyber or maintenance risks become system issues. Because it is a linchpin technology family for the most important shift from care to autonomy, it merits the sparse 20.

### **Weak signals (10):**

- (+) [Reimbursement] → public systems expand coverage from basic devices to powered or neurally integrated versions (funding following functional restoration)
- (+) [Return-to-work] → employment outcomes become core prosthetic and exoskeleton metrics (labor-market impact becoming explicit)
- (+) [Clinical infrastructure] → orthotics-prosthetics centers add AI gait labs and surgical integration teams (service model upgrading)
- (+) [Workplace accommodation] → employers fund wearable support for disabled workers (restoration entering ordinary work)
- (+) [Housing adaptation] → some retrofit budgets shift from structural adaptation to wearable mobility support (environment-versus-device trade-off changing)
- (+) [Public narratives] → disability policy language shifts from care burden to capability recovery (values moving toward empowerment)
- (+) [Procurement] → device subscriptions with upgrades and maintenance replace one-off purchases (assistive tech becoming service-based)
- (+) [Rural provision] → remote fitting, tuning, and follow-up become standard pathways (geographic access broadening)
- (-) [Cybersecurity] → recalls or forced updates affect essential mobility devices (digital dependence becoming bodily risk)
- (-) [Distribution / stigma] → visible divide emerges between premium restorative users and basic-device users (inequality becoming socially salient)

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Better feedback closes the loop in prosthetics, exoskeletons, remote assistance, and sensory substitution, turning crude tool use into safer, more natural function. It also affects training burdens, liability, and user trust because devices feel more predictable and less cognitively exhausting, though premium control stacks could deepen access gaps. Significant as an enabling quality jump, but usually as part of larger assistive systems rather than a standalone transformation.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Prosthetics] → reimbursement starts distinguishing feedback-enabled from passive control systems (feedback becoming functional criterion)
- (+) [Training] → rehabilitation time to proficiency falls in multisensory device pilots (learning burden decreasing)
- (+) [Tele-assistance] → remote manipulation services add force and touch channels (safer remote help emerging)
- (+) [Sensory substitution] → navigation aids add graded tactile or thermal cues (nonvisual guidance getting richer)
- (-) [Cost] → only premium users receive high-fidelity feedback layers (capability stratification growing)
- (-) [Safety] → adverse events trace to overstimulation or wrong force cues (feedback reliability becoming safety issue)

## ART 04.026 - AI Understanding of Human Intent & Context

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

This is a core route from command-based assistance to genuinely adaptive assistance: devices and services that understand when a user is struggling, what help is wanted, and how to communicate it appropriately. It directly supports need-based treatment, cognitive support, communication assistance, and seamless interface use, while also creating deep risks around surveillance, misinterpretation, and paternalistic automation. Because it can reshape how support is delivered across many impairment groups every day, it reaches 10.

### **Weak signals (9):**

- (+) [Communication support] → AAC and assistant tools begin inferring intent from multimodal cues (interaction burden dropping)
- (+) [Cognitive support] → reminder systems adapt prompts to context and stress signs (assistance becoming situationally aware)
- (+) [Mobility aids] → wheelchairs and prosthetics infer user intention before explicit commands (control becoming more natural)
- (+) [Care workflows] → staff dashboards use context-aware alerts instead of generic alarms (attention becoming better targeted)
- (+) [Accessibility settings] → devices auto-switch modalities based on fatigue, environment, or companions (interfaces becoming adaptive)
- (+) [Reimbursement] → payers cover context-aware assistance for independence outcomes (funding following adaptive support)
- (+) [Disability advocacy] → user groups demand override and explanation rights for inferred intent (governance shifting to user control)
- (-) [Misinterpretation] → incident reports cite incorrect intent inference in vulnerable situations (context modeling showing harm)
- (-) [Surveillance] → employers or care providers repurpose intent analytics for compliance monitoring (assistance slipping into control)

## ART 04.027 - Brain-to-Brain Interfaces

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The direct path is narrow: specialized communication or training channels for severe sensory or motor cases. It is not central to the GVN's main operating model, and its ethical and adoption barriers are likely to keep it niche even in mature form. So it remains a limited but nonzero watchpoint.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Severe communication cases] → pilot programs test BBI-assisted cueing or interaction (niche use-case appearing)
- (+) [Rehab research] → labs study direct shared-state support in motor retraining (specialist experimentation growing)
- (-) [Ethics governance] → rules limit use to tightly controlled settings (broad pathway staying blocked)
- (-) [Service demand] → disability providers show little procurement interest (institutional pull remaining weak)

**ART 04.028 - Memory Prostheses**

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Memory prostheses could materially reduce dependence among people with dementia, TBI, and other cognitive impairments by restoring procedural or episodic support that currently drives supervision needs. Their second-order effects include delayed institutionalization and new consent and accountability questions about implanted cognitive assistance. This is potentially large, but because the higher score depends on invasive use reaching broad older populations, 5 is the safer choice.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Active aging] → memory-support implants enter early dementia care pathways (cognitive restoration moving upstream)
- (+) [TBI rehabilitation] → post-injury programs add implanted memory support options (rehab scope widening)
- (+) [Institutional care] → delayed residential placement appears in pilot outcome data (care substitution becoming measurable)
- (+) [Consent governance] → guardianship and advance-consent tools add implant-specific clauses (cognitive agency becoming regulated)
- (-) [Equity] → only private or narrow diagnosis groups get access first (benefit distribution narrowing)
- (-) [Liability] → disputes arise over responsibility for false or missing recall cues (memory support becoming legally salient)

**5. Robotics & Physical Autonomy**

## ART 05.029 - Self-Driving Vehicles

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Autonomous road mobility can convert a large share of transport dependence into independent mobility for people unable to drive, changing access to work, rehab, shopping, and social life. It also shifts liability from individual disabled drivers and informal carers toward platform operators, insurers, fleets, and regulators, while potentially excluding users if geofenced or premium services dominate. Because mobility is a major everyday bottleneck and the weekly-life effect can reach large populations, 10 fits.

### **Weak signals (9):**

- (+) [Mobility independence] → disability transport budgets shift from paratransit to autonomous subscriptions (mobility control moving to users)
- (+) [Supported employment] → job programs fund autonomous commute credits (work barrier dropping)
- (+) [Vehicle standards] → accessible autonomous cabin specs appear in procurement codes (accessibility entering fleet design)
- (+) [Rural access] → autonomous shuttle pilots target areas with scarce assistance (geographic inclusion expanding)
- (+) [Caregiver burden] → time-use data show fewer escort trips by relatives (informal care burden easing)
- (+) [Eligibility rules] → fit-to-drive restrictions are replaced by supervised autonomy profiles (mobility governance changing)
- (+) [Rehab discharge] → transport autonomy is written into independent-living plans (mobility becoming care outcome)
- (-) [Dispatch fairness] → wheelchair users are deprioritized by fleet algorithms (algorithmic exclusion surfacing)
- (-) [Safety] → incident reviews show failures around non-normative movement or wheelchair loading (disabled-body assumptions exposed)

## ART 05.030 - Drone Swarms & Aerial Robots

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The main link is peripheral: rapid delivery of medicines, spare parts, accessibility mapping, and some emergency checks, rather than core functional compensation. These uses are useful but secondary compared with other mobility and care technologies. So this stays in the limited-but-concrete range.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote users] → community-care programs use drones for urgent medication or device-part delivery (logistics niche opening)

- (+) [Accessibility mapping] → municipalities test aerial surveys for barrier detection (environmental monitoring use emerging)
- (-) [Routine care] → no disability-service budgets depend on drone operations (core pathway still absent)
- (-) [Safety rules] → urban airspace restrictions keep assistive use exceptional (deployment staying episodic)

## ART 05.031 - Humanoid and General-Purpose Robots

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Mature general-purpose robots could perform transfers, fetching, cleaning, meal prep, navigation assistance, and some personal support in homes and institutions, directly lowering dependence on scarce human care hours. They would also reshape labor relations, public budgets, housing design, and the balance between care and autonomy, while creating safety, dignity, and substitution risks. That scale of operating-model change is transformative, even if not as singularly foundational as advanced prosthetics.

### **Weak signals (9):**

- (+) [Home care] → public payers reimburse robot-assisted support hours (robotic help entering mainstream service)
- (+) [Supported housing] → redesigns include robot docking, turning, and transfer clearances (built environment adapting)
- (+) [Care labor] → unions negotiate robot-supervision roles and staffing mixes (labor model visibly changing)
- (+) [Independent living] → service plans substitute some housekeeping and transfer hours with robots (care substitution becoming real)
- (+) [Rural shortages] → municipalities deploy tele-supervised home robots (scarcity driving adoption)
- (+) [Safety certification] → intimate-space robotics standards are published (governance catching up)
- (+) [Employment] → disabled users use robots for workplace task assistance (functional gains crossing into work)
- (-) [Dignity] → complaints arise about unwanted robotic monitoring or manipulation (intimate automation meeting resistance)
- (-) [Access inequality] → premium households receive higher-capability robots than public users (service stratification emerging)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Safer compliant robots and wearable actuators matter in personal assistance, rehabilitation, grasp support, and gentle manipulation around vulnerable bodies. Their broader effect is to make automation acceptable in intimate or cluttered settings where rigid machines would be rejected, but



they usually enter the GVN as specialized components. Significant, but mostly as part of broader robotic support systems.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Personal assistance] → lift and transfer devices adopt soft-contact manipulation (human-robot proximity becoming acceptable)
- (+) [Wearables] → textile exosuits enter fatigue and weakness support programs (lighter assistive actuation spreading)
- (+) [Rehab] → clinics deploy soft robotic hands and gait supports (gentle therapy interfaces becoming normal)
- (+) [Home acceptance] → users report higher acceptance than rigid alternatives (social fit improving)
- (-) [Durability] → service logs show material fatigue under daily caregiving loads (maintenance limits surfacing)
- (-) [Procurement] → buyers treat soft systems as experimental accessories (institutional trust still partial)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

In this GVN the linkage is mostly through logistics, remote inspection, and environmental servicing rather than direct functional restoration. That can ease some support bottlenecks, but it does not alter the main operating model of disability redress on its own. Hence a limited score.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Facility operations] → care campuses use autonomous robots for errands and inspection (backstage support use appearing)
- (+) [Disaster response] → vulnerable-user welfare checks include autonomous platforms (emergency niche opening)
- (-) [Front-line care] → no mainstream disability support pathway depends on these systems (direct linkage still weak)
- (-) [Regulation] → unsupervised operation limits keep use behind the scenes (autonomy staying infrastructure-like)

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Accessible environments increasingly need machine-readable markers, docking, localization, and safe shared traffic rules if assistive robots and autonomous mobility are to scale. This is institutionally important because it moves spending from one-off accessibility retrofits toward

autonomy-ready environments, and it changes who gets to define “accessible” space. Significant as a systems enabler, though not the core end-user technology.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Building codes] → new accessible-building guidance includes robot-readable wayfinding and docking (accessibility definition expanding)
- (+) [Public housing] → retrofits add charging, docking, and localization fixtures (homes becoming autonomy-ready)
- (+) [Transport nodes] → stations install mixed human-robot circulation rules (shared-space governance materializing)
- (+) [Procurement] → municipalities ask for infrastructure compatibility across vendors (ecosystem logic entering planning)
- (-) [Exclusion] → older housing stock falls further behind autonomy-ready environments (infrastructure inequality widening)
- (-) [Public resistance] → complaints rise about public space being optimized for machines (accessibility politics shifting)

## **ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics**

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The main relevance is allowing persistent service robots or sensors where charging is difficult, for example in large facilities or remote environments. That is too narrow and infrastructural to move the GVN strongly by itself. So it remains a niche watchpoint.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Large facilities] → care campuses test beam-powered patrol or logistics robots (persistent operation niche appearing)
- (+) [Remote monitoring] → inaccessible locations use beam-powered assistive sensors (serviceability barrier easing)
- (-) [Safety] → radiation-exclusion requirements block use in occupied care spaces (human-environment fit staying poor)
- (-) [Procurement] → assistive buyers keep preferring conventional charging systems (pathway remaining marginal)

## **ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The plausible route is better climbing or manipulation by maintenance and adaptation robots operating in hard-to-reach spaces. That may matter at the margins for home adaptation and facility servicing, but it does not change the main assistive model. Concrete but minor.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Home adaptation] → maintenance robots use dry adhesion for ceiling or wall tasks (adaptation servicing niche opening)
- (+) [Facility safety] → care buildings test residue-free climbing inspection tools (access constraints easing)
- (-) [Direct assistance] → no user-facing disability devices adopt the technology (core pathway absent)
- (-) [Standards] → assistive-device certification ignores dry-adhesion use cases (translation remaining peripheral)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 10 (Impact in GVN 13)

**Justification (3–5 sentences):**

Personalized assistive devices are a direct bottleneck in this GVN, and mature multi-material printing makes sockets, orthoses, custom handles, hearing-device shells, soft-rigid hybrid supports, and embedded-sensor aids faster and cheaper to tailor. Systemically, it shifts value toward digital design files, local fabrication networks, and faster iteration with users, while raising certification, liability, and IP questions around who is allowed to print function-critical aids. Because it changes how assistive products are designed, fitted, and supplied at scale, it reaches transformative magnitude.

**Weak signals (9):**

- (+) [Orthotics / prosthetics clinics] → clinics print multi-material devices on site (fabrication moving to point-of-care)
- (+) [Procurement] → public buyers accept digital prescriptions instead of catalog-only products (customization entering funding logic)
- (+) [User iteration] → fitting cycles shorten from weeks to days (customization speed becoming operationally visible)
- (+) [Embedded sensing] → printed supports integrate pressure or motion sensing (device and monitoring converging)
- (+) [Local production] → regional maker-fabrication hubs win assistive contracts (manufacturing decentralizing)
- (+) [Repair economics] → spare parts and custom grips are printed instead of stocked (inventory logic changing)
- (+) [Training] → rehab technicians retrain in digital design and validation (workforce composition shifting)
- (-) [Certification] → disputes grow over who is liable for printed failures (quality assurance becoming contested)
- (-) [IP / lock-in] → vendors restrict design-file access even when users own devices (control shifting to digital rights)

## ART 06.038 - Digital Twin & Simulation-Driven Production

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

High-fidelity production twins improve fit, reliability, and validation of assistive devices and implants, reducing costly rework and failures. The institutional effect is mostly upstream, higher quality and faster iteration for manufacturers and clinics, rather than a direct change in everyday support. So it is material but indirect.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Device manufacturers] → custom aids are simulated before fabrication as routine (rework starting to fall)
- (+) [Clinics] → fit failures trigger twin-based redesign workflows (evidence loop tightening)
- (+) [Regulators] → digital evidence from simulated production enters submissions (validation practice modernizing)
- (-) [SMEs] → smaller assistive makers cannot afford full twin stacks (quality advantage concentrating)
- (-) [Users] → twin data stay inside vendor tools, not portable to new providers (institutional lock-in persisting)

## ART 06.039 - Reconfigurable & Agile Factories

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Assistive product demand is heterogeneous and often low-volume, which is exactly where agile factories matter: they lower the penalty for customization, small batch runs, and rapid product variation. That can shorten waiting times and improve user-device fit while supporting more local or regional production ecosystems. Significant, but still one step upstream from direct functional support.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Lead times] → wait times for custom devices fall after modular production adoption (small-batch economics improving)
- (+) [Regional manufacturing] → assistive suppliers reshore niche production runs (local resilience increasing)
- (+) [Product variation] → more disability-specific variants appear without long delays (heterogeneity becoming economical)
- (+) [Public tenders] → buyers accept smaller batch lots and faster updates (procurement logic adapting)
- (-) [Validation burden] → frequent reconfiguration triggers repeated certification slowdowns (agility meeting regulation)
- (-) [Market concentration] → only large groups can afford flexible facilities (manufacturing power centralizing)

## ART 06.040 - Circular & Sustainable Manufacturing

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

More circular production can reduce device cost, supply fragility, and waste in wheelchairs, prosthetics, orthotics, and home-support equipment. Its main importance is economic and procurement-related rather than in changing the GVN's core service model. So the impact is real but moderate.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Procurement] → tenders begin rewarding refurbishable or recyclable assistive products (lifecycle value entering buying decisions)
- (+) [Repair ecosystems] → take-back and remanufacture programs expand for mobility aids (device circulation improving)
- (+) [Supply resilience] → recycled material streams are used in standard components (input dependence easing)
- (-) [Quality variation] → complaints arise over inconsistent remanufactured performance (circularity meeting trust issues)
- (-) [Stigma] → users resist visibly reused devices in public provision (acceptability affecting uptake)

## ART 06.041 - Bio-fabrication Technologies

**Score: 10 (Impact in GVN 13)**

**Justification (3–5 sentences):**

This is one of the clearest routes from compensation toward biological restoration: tissue patches, living implants, and eventually organ replacement that reduce functional deficits directly. It also changes public spending, professional roles, and inequality dynamics by shifting some disability support from long-term care toward advanced manufacturing-like therapeutic pipelines. That magnitude is transformative, though not a 20 because the GVN still includes many non-biological disability pathways.

**Weak signals (9):**

- (+) [Clinical pathways] → tissue-patch or organoid implants enter routine rehabilitation programs (restoration moving into standard care)
- (+) [Public funding] → budgets shift from long-term support toward advanced restorative procedures (resource allocation visibly changing)
- (+) [Waiting lists] → disability groups lobby for access to biofabricated replacements (demand becoming political)
- (+) [Manufacturing] → hospital-linked bioprint units are created near rehab centers (production moving closer to care)
- (+) [Outcomes] → independence and work-capacity gains are tracked after implant programs (functional restoration becoming measurable)

- (+) [Professional roles] → rehab teams add biomanufacturing and implant-maintenance specialists (workforce composition changing)
- (+) [Procurement] → reimbursement rules treat living implants as lifecycle services (financing model evolving)
- (-) [Equity] → early access clusters in major urban hospitals or private systems (restoration becoming geographically unequal)
- (-) [Safety / oversight] → post-implant monitoring burdens create new institutional gatekeeping (restoration raising governance load)

## ART 06.042 - 4D Printed & Programmable Materials

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Adaptive printed materials can produce self-adjusting braces, splints, prosthetic liners, seating, and home-access devices that respond to body changes or environment without constant manual retuning. Their second-order effect is to reduce maintenance visits and shift value toward smart material design rather than human adjustment labor. Significant, but usually as a product-performance upgrade within broader assistive systems.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Orthotics] → braces auto-adjust to swelling or posture changes (manual retuning burden dropping)
- (+) [Seating and beds] → pressure-management products adapt shape over time (comfort and skin protection improving)
- (+) [Rural support] → fewer in-person refitting visits are needed (service burden easing geographically)
- (+) [Product catalogs] → adaptive materials replace multiple static size variants (inventory model changing)
- (-) [Durability] → repeated transformations cause unexpected failure rates (material lifecycle becoming bottleneck)
- (-) [Certification] → regulators struggle with devices that change state in use (approval models lagging)

## ART 06.043 - Volumetric Additive Manufacturing

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Faster layerless printing could sharply reduce turnaround time for custom orthoses, prosthetic test parts, surgical guides, and some implant components, which matters in a GVN where fit and iteration dominate value. It also favors more localized production and same-day clinical manufacturing, while putting pressure on certification and QA systems. Significant as a speed-and-customization accelerator, but not by itself the core transformation.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Clinical fabrication] → same-day custom support devices enter outpatient workflows (turnaround time collapsing)
- (+) [Surgical planning] → bespoke guides are printed during treatment windows (coordination delays shrinking)
- (+) [Regional hubs] → compact production units appear in rehab centers (manufacturing localizing)
- (+) [User testing] → rapid prototype loops become part of fitting appointments (co-design cycle tightening)
- (-) [Quality assurance] → regulators demand extra validation for layerless processes (speed meeting oversight friction)
- (-) [Material limits] → only a subset of assistive products can use the process (scope staying bounded)

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The strongest link is better sensing and assistive perception: lighter optics for machine vision aids, better antennas and connectivity in wearables, and possibly more discreet assistive form factors. Those improvements matter, but they are component-level and depend on downstream products to reach users. Material, not central.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Vision aids] → lighter flat-optic assistive headsets reach public pilots (form-factor barrier easing)
- (+) [Wearables] → discreet high-gain antennas improve body-worn connectivity (device usability improving)
- (+) [Hearing / sensing] → compact wave-control components appear in premium aids (component relevance growing)
- (-) [Cost] → metamaterial-enhanced devices stay premium-only (benefits stratifying by price)
- (-) [Procurement] → buyers see gains as optional, not functional essentials (translation remaining partial)

### ART 07.045 - Room-Temperature Superconductors

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The plausible route is smaller high-performance motors, imaging, or sensing systems, not direct



disability redress. Most benefits would arrive indirectly through other industries rather than changing the GVN itself. So the linkage remains limited.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Advanced devices] → elite mobility or neuro systems cite superconducting components (niche performance pathway opening)
- (+) [Imaging / diagnostics] → rehab centers adopt smaller high-field tools (specialist equipment spillover appearing)
- (-) [Assistive products] → mainstream aids remain unaffected in procurement (direct user pathway absent)
- (-) [Infrastructure] → handling constraints keep use outside everyday support settings (practical barrier remaining structural)

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Assistive devices fail through wear, cracking, sweat exposure, and fit drift; self-healing and adaptive polymers could lengthen life, improve comfort, and reduce maintenance in prosthetic liners, wheelchairs, orthoses, footwear, and accessible surfaces. That in turn reduces downtime and service visits and may shift procurement toward lifecycle performance rather than upfront price. Significant, especially for continuity of everyday function.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Prosthetic comfort] → liners and sockets advertise self-repair of microdamage (daily usability improving)
- (+) [Wheelchair durability] → high-wear polymer parts carry much longer warranties (maintenance burden easing)
- (+) [Accessible surfaces] → self-healing coatings enter ramps, grips, and handrails (infrastructure longevity improving)
- (+) [Procurement] → lifecycle durability scores rise in tenders (buyers shifting from upfront-cost logic)
- (-) [Recycling] → complex smart polymers create end-of-life handling disputes (sustainability trade-offs appearing)
- (-) [Verification] → users contest healing claims after real-world wear (trust in material intelligence becoming issue)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Advanced coatings matter through biocompatibility, anti-fouling implants, low-friction mobility aids, easy-clean surfaces, and corrosion resistance in assistive hardware. These are meaningful cost

and reliability gains, but mostly as component improvements within larger device systems. So the score stays moderate.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Implants] → anti-fouling or tissue-friendly coatings become a reimbursed differentiator (component quality becoming clinical issue)
- (+) [Mobility aids] → low-friction coatings extend service intervals on moving parts (reliability gains turning measurable)
- (+) [Care environments] → easy-clean coated surfaces are specified in supported housing (hygiene burden easing)
- (-) [Durability] → coated parts lose function faster than advertised in daily use (real-world robustness questioned)
- (-) [Procurement] → coatings remain hidden and poorly compared across vendors (value capture staying opaque)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Lighter stronger alloys can improve exoskeletons, prosthetics, wheelchairs, joint components, and durable rehabilitation equipment. The main effect is performance and durability rather than a new service model. Material, but not transformative by itself.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Mobility devices] → lighter load-bearing frames enter premium and then public offerings (weight barrier easing)
- (+) [Exoskeletons] → longer duty cycles arrive without bulk increases (performance improving at device level)
- (+) [Repair costs] → fracture-related maintenance declines in metal-intensive aids (durability becoming visible)
- (-) [Material price] → only high-end products adopt advanced alloys first (cost stratification surfacing)
- (-) [Certification] → long-life data requirements slow diffusion into reimbursed devices (institutional drag persisting)

## ART 07.049 - Advanced CO2 Capture Materials for Climate Mitigation

**Score: 0 (Impact in GVN 13)**

**Justification (3–5 sentences):**

I do not see a clear GVN-specific pathway beyond general macroeconomic climate effects, which are too indirect for this scoring task. It does not meaningfully alter how disabilities are redressed. So this stays at zero.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care facilities] → rehab campuses pilot capture-linked air or heat systems (would create a direct facility pathway)
- (+) [Green procurement] → disability buyers weight negative-emissions materials in tenders (would create procurement relevance)
- (-) [Assistive roadmaps] → no aid or care plans mention capture materials (linkage staying absent)
- (-) [Innovation funding] → disability-tech funds ignore capture-material spillovers (attention remaining elsewhere)

## **ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength**

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Lower weight and embedded sensing directly matter in prosthetics, exoskeletons, wheelchairs, orthoses, and assistive sports or work equipment, where grams and fatigue strongly affect real use. Second-order effects include broader work participation and smaller repair burdens, but also higher cost stratification if premium materials are not reimbursed. Significant and widely applicable, though as a component enabler.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Prosthetics] → lighter composite limbs show longer daily wear times (material gains translating to use)
- (+) [Wheelchairs] → smart frames begin self-reporting strain or damage (condition monitoring entering hardware)
- (+) [Work participation] → supported-work programs adopt lightweight assistive gear (function crossing into employment)
- (+) [Durability] → repair intervals lengthen in high-stress devices (fatigue resistance becoming visible)
- (-) [Price] → reimbursement lags advanced-material cost premiums (benefits stratifying by payer)
- (-) [Safety] → regulators raise nanoparticle handling and disposal concerns (materials governance becoming salient)

## **ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling**

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Thermal control matters more than it seems in disability support: comfort, skin integrity, battery management, heat stress, and accessible housing all improve when materials buffer or redirect heat.

The benefits are real across homes and devices, but mostly as incremental reliability and comfort gains rather than a new operating model. So the impact is moderate.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Pressure-ulcer prevention] → seating and bedding products advertise dynamic thermal control (skin protection becoming design variable)
- (+) [Mobility devices] → battery housings use thermal materials for safer all-day use (reliability improving in practice)
- (+) [Accessible housing] → retrofits target passive thermal stability for vulnerable residents (comfort and resilience converging)
- (-) [Fire / toxicity] → safety reviews scrutinize advanced thermal materials in homes (compliance burden growing)
- (-) [Procurement] → buyers struggle to compare real-world thermal claims (value staying under-recognized)

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

More resilient motor supply chains matter for powered wheelchairs, prosthetics, exoskeletons, hearing aids, and service robots, especially if current magnet concentration drives cost or scarcity. The strongest effect is economic and supply-security related rather than direct functional change. Material, but not front-stage.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Powered mobility] → vendors advertise rare-earth-free drive systems (supply resilience becoming user-visible)
- (+) [Public procurement] → tenders start rating component supply risk (motor sourcing entering care economics)
- (+) [Repair markets] → replacement times for motors shorten (supply bottleneck easing)
- (-) [Performance gap] → users report shorter range or lower torque in early deployments (system-level trade-offs surfacing)
- (-) [Market power] → incumbents lock in proprietary motor geometries around new magnets (supply shift not improving openness)

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

**Score: 0 (Impact in GVN 13)**

**Justification (3–5 sentences):**

There is no clear, specific operating-model link to disability redress here beyond very indirect infrastructure effects. That is too weak for a nonzero score in this GVN-specific assessment. So this remains a watchpoint only.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care resilience] → remote disability facilities adopt desalination-linked water autonomy (would create a concrete pathway)
- (+) [Home support] → water-dependent assistive services cite membrane resilience in remote regions (would create operational relevance)
- (-) [Assistive tech] → no product or service roadmaps mention desalination dependence (linkage remaining absent)
- (-) [Funding] → disability innovation programs ignore membrane spillovers (institutional distance persisting)

**ART 07.054 - Ultra-wide-bandgap (UWBG) power semiconductors**

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

More efficient compact power electronics can shrink chargers, extend range, reduce heat, and improve reliability in mobility aids, exoskeletons, lifts, and home-support equipment. These are meaningful operational gains, but mainly as upstream component improvements. The impact is therefore material but indirect.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Chargers] → powered-aid chargers become smaller, cooler, and quieter (power electronics improvement reaching users)
- (+) [Range] → mobility devices gain visible runtime without larger packs (system efficiency becoming functional)
- (+) [Home equipment] → lifts and transfer systems reduce heat-related faults (reliability improving in daily care)
- (-) [Cost] → semiconductor gains stay inside premium devices first (benefits not spreading evenly)
- (-) [Repairability] → power modules become harder for local repair shops to service (component complexity raising dependence)

**ART 07.055 - Solid Hydrogen Storage Materials**

**Score: 0 (Impact in GVN 13)**

**Justification (3–5 sentences):**

I do not see a meaningful direct pathway to disability redress beyond very generic energy or logistics spillovers. It does not substantially change assistive devices, care models, or accessibility systems in this GVN. Score zero.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote services] → disability support fleets test hydrogen cartridge logistics (would create a concrete service link)
- (+) [Facility backup] → high-dependency care sites pilot solid-hydrogen backup systems (would create resilience relevance)
- (-) [Assistive devices] → no mainstream aid category depends on hydrogen storage (core pathway absent)
- (-) [Procurement] → disability buyers continue specifying battery or grid solutions only (institutional interest remaining negligible)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Reliable low-carbon baseload power could help energy-intensive care systems and reduce macro-level electricity fragility, but the link to disability redress is indirect. It would not by itself change how functional ability is compensated or restored. That keeps the score low.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care infrastructure] → disability-service planners explicitly model fusion-backed reliability (would create targeted relevance)
- (+) [Medical-device supply] → manufacturers cite fusion-linked power stability for production (upstream relevance emerging)
- (-) [Service models] → no disability programs depend on fusion timelines (linkage staying indirect)
- (-) [Procurement] → fusion remains outside assistive investment decisions (institutional distance persisting)

### ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

SMRs could improve electricity reliability for care campuses and remote services, but their impact on disability redress is still primarily infrastructural and indirect. They do not by themselves alter the main assistive or therapeutic pathways of the GVN. So the score remains low.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote care regions] → resilience plans for high-dependency services mention SMRs (would create a site-specific pathway)

- (+) [Public facilities] → rehabilitation campuses evaluate SMR-linked energy security (institutional relevance emerging)
- (-) [Assistive programs] → no user-facing disability service depends on SMR deployment (direct pathway absent)
- (-) [Budgeting] → disability spending debates ignore nuclear supply options (linkage staying background-only)

## ART 08.058 - Thin-film Solar Cells

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Thin flexible solar can power small assistive devices, resilient homes, rural care outposts, and sensor-rich accessible environments where installation burden matters. Its main GVN effect is resilience and local autonomy, not direct restoration of function. Material but moderate.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote users] → off-grid disability support kits include flexible solar charging (local energy autonomy growing)
- (+) [Homes] → supported-living retrofits add solar skins for assistive backup loads (resilience entering accessibility budgets)
- (+) [Wearables] → low-power sensors and prompts self-charge in daylight (maintenance burden easing)
- (-) [Reliability] → users report seasonal performance gaps for critical support loads (energy autonomy proving uneven)
- (-) [Procurement] → thin-film systems are treated as optional sustainability add-ons (functional value underweighted)

## ART 08.059 - Bionic Leaf Technology

**Score: 0 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

I do not see a meaningful direct pathway from artificial-photosynthesis panels to the operating model of disability redress. Any effect would be through broad energy or chemical-system spillovers, which is too indirect here. So this stays at zero.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote support sites] → disability-service planners test bionic-leaf energy or fuel modules (would create operational relevance)
- (+) [Assistive manufacturing] → biomaterial supply chains for aids cite bionic-leaf inputs (would create an upstream link)
- (-) [Care roadmaps] → no disability programs mention the technology (linkage staying absent)



- (-) [Procurement] → aid and care buyers ignore the technology entirely (institutional relevance not forming)

## ART 08.060 - Grid-Scale Energy Storage

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

More reliable grids reduce outages that disable powered beds, lifts, refrigeration, communication aids, and home medical or assistive systems. That matters especially as the GVN moves from institution to home, but the effect is infrastructural rather than disability-specific design. Material, yet not central.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Outage-sensitive users] → disability emergency plans begin citing storage-backed resilience zones (vulnerability becoming energy-planning issue)
- (+) [Care campuses] → high-dependency facilities contract long-duration backup capacity (reliability becoming purchasable)
- (+) [Home support] → utilities identify powered-aid users in storage-driven outage priority plans (energy systems seeing disability demand)
- (-) [Cost pass-through] → storage surcharges raise energy poverty concerns among disabled households (resilience costs shifting to users)
- (-) [Service continuity] → outages still disrupt home aids despite grid storage expansion (system benefit not reaching endpoints)

## ART 08.061 - Solid-State Batteries

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Better batteries directly unlock lighter, safer, longer-lasting wheelchairs, exoskeletons, prosthetics, hearing devices, wearables, and service robots, many of the most important technologies in the challenger regime. They also reduce fire and insurance friction and support all-day independence rather than short-duty assistive use, while possibly intensifying access gaps if premium battery systems are not reimbursed. Because energy density and safety are major bottlenecks across many assistive technologies, this reaches transformative scale.

### **Weak signals (9):**

- (+) [Powered mobility] → public tenders start requiring all-day range at current weight (battery bottleneck becoming central procurement issue)
- (+) [Safety] → insurers relax restrictions on indoor charging of advanced aids (fire-risk barrier weakening)
- (+) [Exoskeletons] → duty cycles extend enough for full work shifts (assistive use moving beyond short sessions)
- (+) [Wearables] → hearing and vision aids reduce charging frequency dramatically (daily friction falling)

- (+) [Home care] → fewer battery-related service calls appear in maintenance logs (operational burden decreasing)
- (+) [Second-hand market] → battery health passports appear for assistive devices (asset lifetimes becoming tradable)
- (+) [Public funding] → reimbursement starts distinguishing battery safety and lifetime quality tiers (energy system entering care finance)
- (-) [Equity] → premium batteries reach private markets first (independence gains stratifying by payer)
- (-) [Repairability] → sealed high-density packs make local repair harder (vendor dependence increasing)

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The possible route is resilient energy supply for facilities or heavy logistics, not direct disability compensation. It may matter in the background but does not meaningfully reshape the GVN on its own. Limited score.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote logistics] → disability-service fleets trial hydrogen carriers for long-range support (niche operations link emerging)
- (+) [Facility backup] → high-dependency sites evaluate hydrogen storage for resilience (background infrastructure relevance appearing)
- (-) [Assistive devices] → no mainstream aid category depends on hydrogen fuel pathways (direct pathway absent)
- (-) [Funding] → disability programs do not treat hydrogen as strategic support infrastructure (institutional pull remaining weak)

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 0 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Only general energy-system spillovers are apparent. That is too indirect for this GVN-specific assessment. Zero.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote support regions] → disability resilience plans explicitly rely on local wind assets (would create geographic relevance)
- (+) [Care campuses] → accessible housing projects co-design with on-site wind systems (would create facility pathway)
- (-) [Assistive systems] → no disability technology roadmaps cite wind-specific dependencies (linkage staying absent)

- (-) [Procurement] → care and aid buyers never mention wind generation attributes (institutional relevance missing)

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The niche link is powering remote sensors, isolated facilities, or some hard-to-wire assistive infrastructure. That could matter in exceptional settings, but not enough to alter the main operating model. So it remains minor.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote support sites] → trials power isolated monitoring systems wirelessly (hard-wiring constraint easing)
- (+) [Disaster response] → temporary disability support zones use beamed backup power (emergency relevance appearing)
- (-) [Occupied care spaces] → safety constraints block routine use around people (human-environment fit weak)
- (-) [Assistive-device design] → manufacturers do not redesign around beamed power assumptions (pathway staying niche)

## ART 08.065 - Advanced Geothermal Technology

**Score: 0 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

I do not see a meaningful direct path from deep geothermal systems to the operating model of disability redress beyond broad energy reliability effects. That is too indirect for this task. So this remains zero.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care infrastructure] → high-dependency facilities explicitly rely on geothermal resilience (would create a targeted pathway)
- (+) [Accessible housing] → thermal-retrofit programs pair geothermal with disability resilience goals (would create support relevance)
- (-) [Aid roadmaps] → no assistive device or service strategy mentions geothermal dependence (linkage absent)
- (-) [Funding] → disability innovation funds ignore geothermal spillovers (institutional distance persisting)

## ART 08.066 - Resilient Microgrids

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

As disability support shifts into homes and distributed community settings, resilient local power becomes a functional safety issue, not just an energy issue. Microgrids reduce the risk that outages interrupt powered mobility, ventilation, communication, lifts, refrigeration, or AI-supported home care, while also moving control toward local institutions and communities. Significant because it materially strengthens the feasibility of independence outside institutions.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Home independence] → outage-vulnerable users are mapped into microgrid priority zones (disability demand entering grid planning)
- (+) [Supported housing] → new projects include islandable power as accessibility feature (resilience redefining accessibility)
- (+) [Care campuses] → black-start tests become part of disability-service preparedness (energy continuity becoming care metric)
- (+) [Utility coordination] → health and disability services share critical-load registries (cross-sector coordination tightening)
- (-) [Equity] → microgrid resilience clusters in affluent districts first (energy resilience stratifying access)
- (-) [Governance] → disputes grow over who gets priority during islanding (local control becoming contested)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

Score: 10 (Impact in GVN 13)

**Justification (3–5 sentences):**

This can move some disabilities from lifelong compensation toward molecular correction, especially inherited sensory, neuromuscular, metabolic, or degenerative conditions. The second-order impact is as large as the clinical effect: public funding, disability identity politics, prenatal choices, and inequality may all shift if high-function restorations become feasible but unevenly accessible. Because it can change both prevalence and meaning of disability support at scale, it reaches 10.

**Weak signals (9):**

- (+) [Rare-disease pathways] → disability-linked gene-edit therapies enter routine referral systems (correction moving from experimental to operational)
- (+) [Screening] → genomic diagnostics are tied directly to restorative treatment eligibility (diagnosis becoming intervention gateway)
- (+) [Payer policy] → outcomes-based reimbursement appears for function-restoring edits (public finance adapting to cure logic)
- (+) [Advocacy] → disability organizations split between access-rights and anti-erasure positions (identity politics becoming explicit)

- (+) [Rehab] → post-edit rehabilitation programs are built to convert biological gains into function (care pathways reorganizing)
- (+) [Workforce] → genetic counseling and long-term monitoring expand inside disability services (professional mix shifting)
- (+) [Prenatal medicine] → families are offered early-intervention editing for disabling conditions (timing of support shifting upstream)
- (-) [Equity] → access is concentrated in premium or urban centers first (restorative capability becoming stratified)
- (-) [Safety / trust] → public backlash follows off-target or mosaic outcome cases (correction model meeting legitimacy shocks)

## ART 09.068 - mRNA Therapies & Vaccines

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

mRNA platforms can deliver repeated or personalized treatments for some functional deficits faster than traditional biologics, especially where dosage and target need frequent adjustment. Institutionally, they favor software-like therapeutic iteration and smaller-batch manufacturing, but still depend on diagnosis, delivery, and reimbursement infrastructure. Significant, but not as foundational as gene editing or biofabricated replacement.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rare disabling conditions] → recurring mRNA therapies enter standard care pathways (platform flexibility becoming practical)
- (+) [Dose personalization] → biomarkers are used to tune treatment schedules (therapy becoming more adaptive)
- (+) [Manufacturing] → local or regional batch production supports niche disability indications (supply becoming more responsive)
- (+) [Rehab integration] → therapy outcomes are tracked in functional rather than purely clinical terms (treatment aligning with GVN goals)
- (-) [Cold-chain / delivery] → logistics burdens limit rural access (operational inequality persisting)
- (-) [Funding] → frequent-update therapies trigger reimbursement disputes (platform speed outrunning public payment norms)

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 0 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

I do not see a meaningful pathway from cellular agriculture to the redressing-disabilities operating model beyond diffuse nutrition or macroeconomic spillovers. That is too indirect here. So the score stays at zero.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Clinical nutrition] → disability rehabilitation diets begin using cultivated proteins for targeted formulations (would create a care pathway)
- (+) [Facility procurement] → long-term care menus cite cultured products for specific functional outcomes (would create operational relevance)
- (-) [Assistive policy] → no disability strategy documents mention the technology (linkage absent)
- (-) [Funding] → disability innovation budgets ignore cellular agriculture entirely (institutional distance persisting)

## ART 09.070 - Organoids & Tissue Engineering

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Organoids and engineered tissues improve disease modeling and create some patch-like restorative options, shortening the path from mechanism to intervention for disabling conditions. Most impact is upstream through better therapy selection and validation rather than direct daily-life assistance. Significant but not primary.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Therapy selection] → organoid tests begin guiding treatment for disabling diseases (model-to-care translation starting)
- (+) [Tissue repair] → standardized patches enter niche restorative programs (partial biological replacement emerging)
- (+) [Biobanks] → disability cohorts are linked to organoid platforms (condition-specific evidence improving)
- (+) [Drug development] → trials for function-preserving therapies use organoid response data (iteration cycles shortening)
- (-) [Scale] → manufacturing variability keeps access inside specialist centers (standardization lagging)
- (-) [Ethics / consent] → governance disputes grow around stored patient-derived tissues (institutional friction becoming visible)

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The plausible link is cheaper biomaterials, drugs, or embedded biosensing, not direct disability redress. Useful in the background, but not central to the GVN operating model. Limited score.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Assistive materials] → device makers begin sourcing microbially produced specialty inputs (upstream link opening)

- (+) [Therapeutics] → designer-microbe products target specific disabling conditions (clinical pathway emerging)
- (-) [Front-line support] → disability services show little direct dependence on such systems (operating-model link weak)
- (-) [Governance] → containment and safety rules keep usage narrow (institutional boundaries holding)

## ART 09.072 - Microbiome Engineering

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Some functional deficits may be reduced through microbiome interventions affecting inflammation, metabolism, or neurodevelopment, but the path is condition-specific and indirect. It does not define the main assistive shift in this GVN. So it remains a niche watchpoint.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Neurodevelopment / gut-health programs] → microbiome interventions enter some disability clinics (condition-specific relevance appearing)
- (+) [Home monitoring] → simple microbiome tests are linked to functional support adjustments (measurement-to-support connection emerging)
- (-) [Mainstream rehab] → most disability pathways remain unaffected (system-level impact staying small)
- (-) [Evidence] → outcomes remain inconsistent across users and settings (predictability bottleneck persisting)

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

This directly supports a move from equal treatment to need-based treatment, an explicit value shift in the GVN, by matching people to the interventions, devices, and monitoring regimes most likely to preserve function. Its wider effects include new data-rights politics, earlier interventions, more targeted spending, and possible exclusion if models underrepresent some disability groups. Because it can change how decisions are made across a wide share of the system, it is transformative.

### **Weak signals (9):**

- (+) [Eligibility decisions] → genomic or molecular profiles start shaping assistive and therapeutic pathways (support becoming biologically individualized)
- (+) [Early detection] → functional-risk panels enter routine monitoring for aging populations (disability timing moving earlier)
- (+) [Reimbursement] → payers fund precision diagnostics tied to functional outcomes (testing becoming part of support finance)
- (+) [Care coordination] → portable molecular summaries are used across providers (decision continuity improving)



- (+) [Device matching] → implants or prostheses are matched to tissue or disease profiles (hardware selection becoming personalized)
- (+) [Public messaging] → disability services reframe from standard packages to tailored pathways (institutional language shifting)
- (+) [Counseling] → genomics counseling enters disability service ecosystems (new professional roles forming)
- (-) [Representation] → minority or rare-body groups challenge poor model performance (equity gap surfacing)
- (-) [Data use] → insurers or employers seek access to predictive disability markers (personalization drifting into discrimination risk)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

These platforms mainly accelerate testing and personalization of therapies for disabling conditions and reduce trial-and-error in development. Important for innovation and some precision decisions, but still mostly upstream from direct support. Material, not central.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Drug testing] → disability-focused therapeutics use organ-on-chip evidence in development (translation cycles shortening)
- (+) [Personalization] → some treatment choices are screened on patient-derived chip systems (therapy selection becoming more informed)
- (+) [Regulators] → chip data are accepted in submissions for disabling conditions (institutional legitimacy increasing)
- (-) [Clinical reach] → use stays within research hospitals and specialized labs (service impact bounded)
- (-) [Standardization] → chip-to-chip variability slows routine deployment (upstream uncertainty persisting)

## ART 09.075 - Biological Aging & Longevity Barriers

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Active aging is explicit in the challenger regime, and therapies that delay frailty, neurodegeneration, sensory decline, or recovery loss would strongly reshape disability prevalence, timing, and care demand. They could shift public spending from long-term care toward periodic maintenance therapies, while raising major equity and norm conflicts around what counts as normal aging or “deserved” support. Because the weekly-life effects could reach very large older populations, this is transformative.

### **Weak signals (9):**

- (+) [Aging services] → functional-maintenance therapies enter older-adult care pathways (frailty prevention becoming operational)
- (+) [Budget shifts] → spending moves from residential care growth to preventive maintenance programs (care economics visibly rebalancing)
- (+) [Workforce participation] → later-life work and volunteering rise after functional-aging interventions (capacity effects leaving clinics)
- (+) [Outcome metrics] → public systems track mobility, cognition, and independence years gained (function replacing survival-only focus)
- (+) [Insurance] → preventive longevity-style therapies get disability-relevant coverage categories (financing model broadening)
- (+) [Rehab timing] → earlier treatment is offered before major decline thresholds (support moving upstream)
- (+) [Public debate] → “aging as treatable decline” enters disability policy discourse (normative frame shifting)
- (-) [Inequality] → affluent groups gain prolonged function well before public coverage catches up (life-course inequality widening)
- (-) [Legitimacy] → disability groups contest narratives that equate support needs with treatment failure (identity conflict surfacing)

## ART 09.076 - Engineered Living Materials

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The only meaningful routes here are specialized wound care materials, adaptive surfaces, or self-healing accessible environments. Those are real but peripheral compared with the main assistive, robotic, and biomedical pathways. So it stays minor.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Wound care] → living-material dressings enter pressure-ulcer management (niche clinical pathway opening)
- (+) [Accessible surfaces] → self-maintaining handrails or ramps are piloted (infrastructure maintenance link emerging)
- (-) [Assistive devices] → mainstream aid manufacturers do not adopt living materials (core relevance staying small)
- (-) [Regulation] → biosecurity requirements keep materials in specialist categories (institutional barrier remaining high)

## ART 09.077 - Gene Drive Pest Control

**Score: 0 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

This is more about disability prevention through public health and environmental control than about redressing existing disabilities. That is too indirect relative to this GVN’s operating model. So score zero.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Public health] → disability-prevention strategies cite gene-drive effects on specific disabling diseases (would create indirect relevance)
- (+) [Care planning] → long-term disability incidence forecasts begin incorporating gene-drive scenarios (would create system planning linkage)
- (-) [Assistive services] → no disability support models depend on gene-drive deployment (redress pathway absent)
- (-) [Governance] → ecological controversy keeps the issue inside public-health debate only (institutional separation persisting)

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

It could affect extreme prematurity outcomes, developmental research, and some prenatal intervention pathways, but it does not materially change how existing disability is compensated or supported. Any impact is indirect and ethically gated. Limited score.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Neonatal medicine] → disability-prevention programs discuss ex-vivo support for prematurity (upstream relevance emerging)
- (+) [Developmental research] → synthetic-embryo findings alter understanding of disabling conditions (knowledge pathway opening)
- (-) [Redress services] → no assistive-service pathway changes because of the technology (direct impact remaining absent)
- (-) [Ethics] → strict legal limits keep deployment far from routine care (institutional barrier staying dominant)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

As a specific route to resilient, wide-area connectivity, mega-constellations support remote rehab, tele-assistance, device updates, peer support, and continuity in rural or disrupted settings. They also shift bargaining power toward constellation operators and raise surveillance, affordability, and dependency risks. Significant, but only one pathway among several to the broader connectivity effect.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rural disability services] → satellite terminals are bundled into home-support packages (coverage barrier easing fast)
- (+) [Emergency continuity] → care plans for vulnerable users include satellite failover links (resilience becoming service design)
- (+) [Remote fitting] → device vendors support remote updates over satellite backhaul (geography mattering less operationally)
- (+) [Public programs] → subsidies target disconnected disabled households specifically (inclusion becoming policy-visible)
- (-) [Affordability] → recurring terminal and subscription costs block uptake (connectivity inequality persisting)
- (-) [Market power] → a few constellation firms dominate disability-critical connectivity contracts (dependency concentrating)

**ART 10.080 - Space Resource Utilization (SRU)**

**Score: 0 (Impact in GVN 13)**

**Justification (3–5 sentences):**

I do not see a meaningful direct pathway from returned space-mined materials to the disability-redress operating model within this scope. Any materials spillovers would be too contingent and indirect. So it remains at zero.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Assistive materials] → prosthetic or implant suppliers cite SRU-derived inputs (would create a direct materials path)
- (+) [Public R&D] → disability-tech programs reference SRU material-security spillovers (would create upstream relevance)
- (-) [Procurement] → no disability buyers or standards mention SRU-based materials (linkage absent)
- (-) [Certification] → medical pathways ignore extraterrestrial-source materials (translation barrier remaining complete)

**ART 10.081 - Closed-Loop Life Support System**

**Score: 0 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Closed-loop life support is highly relevant to space habitats but has no clear, meaningful pathway into the dominant operating model of disability redress here. Indoor-environment control spillovers are too indirect for a nonzero score. So it stays at zero.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [High-dependency housing] → autonomous habitat-control systems are ported into disability settings (would create a direct path)
- (+) [Environmental support] → care campuses adopt life-support-style closed loops for vulnerable residents (would create institutional relevance)
- (-) [Assistive ecosystems] → no major disability supplier references space life-support architectures (linkage absent)
- (-) [Funding] → disability innovation programs ignore the technology entirely (attention not forming)

## ART 10.082 - High-Altitude Platforms & Balloons

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The relevant path is temporary connectivity and sensing in remote or disrupted regions, which can support vulnerable users during outages or disasters. But that role is episodic rather than structural within this GVN. So the score remains low.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Disaster support] → emergency disability communication plans add HAP connectivity options (episodic relevance becoming concrete)
- (+) [Remote areas] → pilots restore care links through stratospheric relays (coverage niche appearing)
- (-) [Routine services] → day-to-day disability support does not depend on HAPs (operating-model linkage weak)
- (-) [Regulatory access] → airspace and deployment limits keep HAP use exceptional (scale staying constrained)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Shared ledgers and verifiable credentials could help with consent, device logs, funding flows, maintenance history, and user-controlled data across fragmented disability services. They also redistribute trust and auditability, but at the cost of new complexity, key-management risks, and speculative platform capture. Material in some institutional layers, yet not a core driver of functional improvement.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Consent and rights] → disability-service portals issue verifiable permissions or records (trust infrastructure entering workflows)

- (+) [Device maintenance] → assistive-device histories become tamper-evident and portable (service continuity improving)
- (+) [Direct payments] → support budgets use programmable release conditions (administration becoming more automated)
- (-) [Usability] → account recovery failures lock vulnerable users out of services (trust stack creating new exclusion)
- (-) [Intermediaries] → managed wallets dominate, re-centralizing control (decentralization not shifting power as promised)

## ART 11.084 - Platform Cooperatives & Fair Work

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Cooperative digital platforms could rebalance power in home-care labor, peer support, personal assistance, and supported work for disabled people themselves. That matters because the GVN is not only about devices but about who controls services and who benefits from them. Material, though more institutional than direct.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Personal assistance] → worker- or user-owned scheduling platforms appear (service governance starting to shift)
- (+) [Supported work] → disabled workers join platform co-ops with transparent algorithm rules (income mediation becoming contestable)
- (+) [Care quality] → members vote on matching, rates, or cancellation policies (rule-setting moving closer to users)
- (-) [Capital] → cooperative platforms struggle to scale against venture-backed incumbents (ownership shift meeting finance limits)
- (-) [Fragmentation] → too many local co-ops reduce service continuity across regions (fairness gains trading against scale)

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Better access to device, outcome, and service data can improve personalization and innovation, but marketplaces also risk commodifying sensitive disability data and privileging large buyers. The effect sits mainly at the institutional and innovation layer. Moderate score.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Assistive analytics] → de-identified device and outcome datasets are listed with common schemas (data liquidity starting to rise)
- (+) [Small innovators] → startups use marketplace access instead of exclusive hospital partnerships (entry barriers lowering)

- (+) [Public buyers] → procurement requests machine-readable evidence from marketplace-linked datasets (data markets entering decisions)
- (-) [User rights] → advocacy groups protest monetization of disability-related traces (commodification becoming visible)
- (-) [Access inequality] → only large firms can afford premium data tiers (marketplaces reinforcing concentration)

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 3 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Secure social platforms support peer coordination, community troubleshooting, advocacy, and remote participation for disabled users who are often dependent on stable communication communities. They also reduce harassment or outage risk but can fragment support networks across incompatible ecosystems. Material, though not central.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Peer support] → disability communities migrate to encrypted resilient group spaces (support continuity becoming a design issue)
- (+) [Crisis coordination] → outage-resistant channels are used for assistive-device incident coordination (resilience gaining practical value)
- (+) [Accessibility] → platforms compete on screen-reader, caption, and low-motor-friction support (inclusive communication becoming visible)
- (-) [Fragmentation] → support groups scatter across incompatible secure nodes (network effects weakening peer reach)
- (-) [Moderation] → abuse or misinformation persists despite technical resilience (safety remaining partly social, not technical)

## ART 11.087 - Collective Open Innovation Networks

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The GVN explicitly mentions crowdsourcing and community support; open innovation networks are a direct mechanism for that, allowing users, families, clinicians, makers, and firms to co-develop and validate assistive solutions. This can shorten adaptation cycles, reduce vendor blind spots, and shift innovation power toward users, while creating IP and quality-control challenges. Significant and very aligned with the challenger regime.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [User-led innovation] → disability communities post challenge briefs and prototype requests (need discovery becoming more open)
- (+) [Validation] → maker-built solutions gain shared benchmark and test pathways (community ideas becoming more trustworthy)



- (+) [Clinician collaboration] → rehab professionals contribute openly to design iterations (expertise flowing into collective networks)
- (+) [Procurement] → public buyers source from community-validated solutions, not only incumbents (innovation path widening)
- (-) [IP conflict] → disputes rise over ownership of user-contributed improvements (collaboration meeting extractive incentives)
- (-) [Quality control] → some widely shared hacks fail in real use (open innovation needing stronger assurance)

## ART 11.088 - Scalable Decentralized Governance

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

It may help govern shared data trusts or community device ecosystems, but the link to actual disability redress is secondary. Useful in some ecosystem designs, not a main driver. Low score.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Data trusts] → disability organizations pilot member-governed data rules (governance relevance appearing)
- (+) [Community support funds] → pooled assistive budgets are allocated through transparent digital governance (niche institutional use opening)
- (-) [User fatigue] → participation in governance remains low among service users (coordination model staying brittle)
- (-) [Service delivery] → core disability outcomes do not improve measurably from governance tooling alone (direct linkage weak)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

One of the GVN's inhibitors is limited awareness and professional familiarity with new assistive technologies. Digital learning networks can spread device-use skills, caregiver training, accessibility practices, and employment credentials for disabled users at scale, thereby changing adoption speed and proactivity. Significant because knowledge diffusion is a real bottleneck here.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Care workforce] → micro-credentials for assistive-tech setup and support become standard (professional familiarity scaling)
- (+) [Users and families] → self-paced device-use training is bundled with public provision (proactivity becoming systematized)
- (+) [Employment] → portable skill credentials help disabled users prove capability remotely (labor-market entry easing)

- (+) [Rural services] → specialists support local teams through networked learning rather than travel (expert scarcity easing)
- (-) [Quality] → course completion outpaces actual practical competence (credential inflation risk surfacing)
- (-) [Exclusion] → low-digital-literacy users fall behind in training-heavy systems (knowledge diffusion becoming unequal)

## ART 11.090 — Prediction-Market Forecasting Platforms

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Forecast platforms may improve planning for disability budgets, technology uptake, or demand, but they do not directly change functional support. Their effect is mostly managerial and contingent. Limited score.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Public planning] → disability agencies start using forecast markets for demand or rollout timing (managerial relevance appearing)
- (+) [Technology adoption] → large providers compare procurement scenarios through live forecasts (decision support niche opening)
- (-) [Service delivery] → user outcomes show little direct change from better forecasting alone (direct linkage weak)
- (-) [Participation] → markets lack enough informed disability stakeholders to stay credible (signal quality remaining thin)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 10 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The smart-home and assistive-device ecosystem only scales if wheelchairs, hearing devices, environmental controls, wearables, sensors, and care platforms can work together without bespoke integration. Mature interoperability standards directly reduce lock-in, setup burden, and fragmentation, explicit blockers in a conservative, guideline-driven system, while also redistributing power toward users and public buyers who can demand mix-and-match ecosystems. Because this is a major enabling condition for widespread assistive environments, it reaches transformative magnitude.

### **Weak signals (9):**

- (+) [Procurement] → municipal tenders require open device protocols and certified compatibility (buyers enforcing interoperability)
- (+) [User setup] → one dashboard begins controlling mixed-vendor assistive devices (integration burden visibly falling)
- (+) [Certification] → “works with assistive home systems” labels appear (compatibility becoming market signal)
- (+) [Home adaptation grants] → funding is tied to non-proprietary installations (public money pushing openness)
- (+) [Care workflows] → providers swap sensors and devices without replatforming whole systems (service flexibility improving)
- (+) [Advocacy] → disability groups publish lock-in scorecards by vendor (user power organizing around openness)
- (+) [SME innovation] → plug-ins and niche devices flourish on shared standards (entry barriers dropping)
- (-) [Vendor strategy] → major firms keep premium features proprietary despite baseline compliance (partial openness preserving lock-in)
- (-) [Safety] → emergency failures expose interoperability gaps between compliant devices (paper standards meeting real-world complexity)

## ART 12.092 — Interoperable Digital Twin Ecosystems

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Portable digital twins of bodies, devices, homes, and rehab plans can make personalization continuous rather than episodic and let different providers collaborate around the same evolving representation. That can improve fit, maintenance, and remote support, though it also raises data-control and model-liability issues. Significant, especially for complex multi-device users.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Complex users] → providers share evolving body-device-environment twins across services (coordination becoming model-based)
- (+) [Maintenance] → prosthetic and wheelchair service histories link to user-specific twins (failure prevention improving)
- (+) [Home adaptation] → housing and care teams co-plan from shared digital replicas (silo boundaries softening)
- (+) [Remote support] → troubleshooting is done against user twins rather than static records (service efficiency improving)
- (-) [Liability] → disputes arise when twin predictions and real outcomes diverge (model accountability becoming legal issue)
- (-) [Data control] → users cannot easily move twins across vendor ecosystems (portability gap surfacing)

## ART 12.093 — Global Supply Chain Traceability Networks

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Traceability improves safety, authenticity, and reliability of implants, spare parts, batteries, and assistive devices, which matters in a sector vulnerable to procurement opacity and maintenance delays. The change is meaningful but upstream and governance-oriented. Moderate score.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Safety] → batteries, actuators, and implant components get full digital provenance in tenders (trust moving upstream)
- (+) [Repairs] → spare-part authenticity checks become routine in mobility-aid maintenance (counterfeit risk becoming operational)
- (+) [Recalls] → root-cause analysis times shrink because custody records are searchable (quality response improving)
- (-) [Supplier burden] → smaller component vendors struggle to join traceability networks (compliance raising concentration)
- (-) [Data opacity] → commercial secrecy limits what users can actually verify (traceability not fully empowering end users)

## ART 12.094 — Personal Data Portability & Trust Frameworks

**Score: 10 (Impact in GVN 13)**

**Justification (3–5 sentences):**

This directly addresses a core GVN problem: people with disabilities repeatedly prove the same needs to different organizations while their device settings, risk profiles, accommodations, and care data remain trapped in silos. Portable trusted data radically improves personalization, continuity, and user agency, while also shifting power from institutions toward individuals and exposing new exclusion risks if sharing becomes quasi-mandatory. Because it can alter daily interaction across the system for large populations, it is transformative.

**Weak signals (9):**

- (+) [Accommodation continuity] → users carry machine-readable support profiles across providers (repeated assessment burden dropping)
- (+) [Device settings] → wheelchairs, AAC tools, and home systems import prior user preferences (personalization becoming portable)
- (+) [Consent] → disability-service portals issue time-bound reusable permission receipts (sharing becoming user-directed)
- (+) [Employment / education] → portable accommodation credentials are accepted across institutions (participation friction falling)
- (+) [Family support] → delegated data permissions become routine for caregivers (governance adapting to shared care)
- (+) [Public procurement] → tenders require import and export of user profiles (buyers pushing against lock-in)
- (+) [Advocacy] → “my data, my settings” campaigns gain traction (power shift becoming organized)
- (-) [Conditional access] → providers pressure users to share more than necessary (portability turning quasi-mandatory)

- (-) [Risk scoring] → third parties build vulnerability profiles from portable data flows (agency gains meeting new exploitation risk)

## ART 12.095 — Interoperable Digital Currency Payment Networks

**Score: 1 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

Easier cross-system payments can help reimburse aids, cross-border services, or direct payments, but this is not a central bottleneck in disability redress compared with data, devices, and skills. The pathway is real but narrow. Low score.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Direct payments] → users can route support budgets across providers more easily (administrative friction easing)
- (+) [Cross-border care] → foreign assistive services become easier to settle (niche mobility pathway opening)
- (-) [Core services] → most disability bottlenecks remain unchanged despite payment interoperability (direct linkage weak)
- (-) [Compliance] → identity and fraud controls make disability-specific use cumbersome (narrow benefit staying bounded)

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

**Score: 5 (Impact in GVN 13)**

### **Justification (3–5 sentences):**

The GVN explicitly highlights conservative regulated culture and guideline-based measures; machine-readable rules can make funding, compliance, safety checks, and eligibility for assistive solutions faster and more consistent. That can speed adoption of individualized technologies and reduce bureaucratic overhead, while also hardening whatever biases are encoded in the rules. Significant because governance friction is a real bottleneck, but still not the primary functional layer.

### **Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Eligibility] → assistive funding rules are published with executable logic (bureaucratic interpretation burden dropping)
- (+) [Procurement] → vendors test compliance against public rule APIs before tendering (market-entry friction easing)
- (+) [Case handling] → disability officers use decision traces generated from coded rules (auditability improving)
- (+) [Update speed] → policy changes reach service systems much faster (governance lag shrinking)
- (-) [Bias] → automated rules replicate old equal-treatment assumptions (bad policy getting codified)

- (-) [Appeals] → users challenge rigid machine-executed interpretations (consistency colliding with individual need)

## ART 12.097 — Open Metaverse Interoperability Protocols

**Score: 3 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Interoperable immersive environments can widen accessible work, education, therapy, and social participation for people with mobility or sensory constraints, especially when physical access remains hard. Their effect is meaningful but depends on uptake of remote or virtual participation and accessible content standards. Material, though not central.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote participation] → accessible work or rehab spaces become portable across virtual platforms (participation lock-in easing)
- (+) [Assistive identity] → users keep accessibility settings across immersive environments (friction dropping across platforms)
- (+) [Education / therapy] → interoperability is demanded in publicly funded virtual services (public buyers pushing openness)
- (-) [Accessibility] → many worlds still ignore captions, input alternatives, or sensory limits (content barrier persisting)
- (-) [Economics] → major platforms resist portability of assets and settings (interoperability politics becoming visible)

## ART 12.098 — Content Authenticity Infrastructure

**Score: 1 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Provenance systems help trust tele-assessment media, remote incident evidence, and AI-generated support content, but the role is narrow. They improve one layer of governance rather than the core support model. Low score.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Tele-assessment] → remote eligibility or rehab reviews require signed provenance on media (trust entering workflow)
- (+) [Incident evidence] → assistive-device failure reports include credentialed video chains (verification burden easing)
- (-) [Adoption] → most disability services ignore provenance tooling (institutional pull remaining weak)
- (-) [False trust] → authenticated but misleading content still causes disputes (provenance not solving truth problems)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

Disability support is split across organizations that often cannot or will not share raw data; privacy-preserving collaboration lets them coordinate analytics, eligibility, and model improvement without centralizing the data. That materially improves cross-organizational intelligence and can reduce one of the biggest blockers to need-based support, though complexity may favor large intermediaries. Significant, but a layer below the front-end assistive shift.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Cross-provider coordination] → hospitals, municipalities, and device firms run joint analyses without pooling raw data (fragmentation cost falling)
- (+) [Eligibility] → sensitive support decisions use shared encrypted computations (cooperation becoming technically feasible)
- (+) [Model improvement] → device performance is benchmarked across organizations without raw-data transfer (shared learning broadening)
- (+) [Regulatory comfort] → data protection authorities explicitly bless such collaborations (trust barrier weakening)
- (-) [Complexity] → only big intermediaries can operate collaboration networks (privacy gains concentrating power)
- (-) [Latency] → secure computation slows time-critical support decisions (privacy trade-offs becoming operational)

## ART 12.100 — Manufacturing standards + conformance testing + certification infrastructure

**Score: 5 (Impact in GVN 13)**

**Justification (3–5 sentences):**

The GVN's conservative culture and public financing mean new assistive products spread only when buyers, regulators, and clinicians can trust performance claims. Strong conformance and certification infrastructure can drastically shorten the path from innovation to procurement, improve safety, and lower rework, while also raising barriers for small entrants. Significant because institutional adoption, not just invention, is a central bottleneck.

**Weak signals (6):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Procurement] → buyers accept standardized test results in place of bespoke evidence packages (adoption friction dropping)
- (+) [Custom devices] → certified conformance suites emerge for printed and personalized aids (innovation gaining institutional pathway)
- (+) [Insurance] → reimbursement is linked to certified performance classes (trust becoming financially operational)



- (+) [Repair markets] → service shops use standardized diagnostic artifacts and certificates (quality assurance spreading downstream)
- (-) [SME access] → smaller assistive makers struggle with certification cost and paperwork (assurance raising entry barriers)
- (-) [Innovation speed] → rapidly iterating products wait for slow conformance updates (standards lagging technology)

## GVN 14: Acquiring Information ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 — Global Broadband Connectivity

**Score: 20 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This is a linchpin for the shift from institution-mediated information to ubiquitous, direct, peer-to-peer information acquisition. First-order, it expands access to raw sources, local reporting, search, AI assistance, and direct observation in places where access is now poor or absent. Second-order, it redistributes power from incumbent broadcasters and gatekeepers toward platforms, communities, and network operators. Third-order, it also scales misinformation, foreign interference, and attention capture. In a 5.5M-person society this plausibly changes the weekly information routines of hundreds of thousands to millions of people and is a necessary part of the >€1B-scale operating-model shift, so 20 fits.

**Weak signals (9):**

- (+) [Access/local information] → rural libraries, schools, and community centers add satellite or mesh terminals (access bottleneck easing)
- (+) [Crowdsourced observations] → emergency maps begin using media from previously offline areas (more direct local evidence)
- (+) [Relevance] → search and social products add hyperlocal feeds in weak-coverage regions (more situation-specific information)
- (+) [Dependency on established sources] → local news startups target newly connected communities (source diversity widening)
- (+) [Public services] → agencies publish raw local sensor/video feeds over new links (fewer intermediary distortions)
- (-) [False information] → misinformation spikes track new connectivity rollouts (friction scales with access)
- (-) [External interference] → jamming, throttling, or politically targeted blocking complaints rise (control battles emerging)
- (+) [Usefulness in disruption] → disaster-response plans assume satellite fallback by default (continuity becoming normal)

- (–) [Equality/power] → premium connectivity tiers create visible information access gaps (uneven informational advantage)

## ART 01.002 — Ultra-Low Latency Networks

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Ultra-low latency matters where information has to be shared, interpreted, and acted on in near real time, such as telepresence, live verification, and remote expert assistance. The biggest second-order effects are in premium access tiers, new expectations for synchronized live evidence, and platform power over time-critical information flows. It is material but not foundational across the whole GVN. It plausibly sits in the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Situational awareness] → public-safety and field-service tools start buying bounded-latency network guarantees (real-time judgment becomes viable)
- (+) [Relevance] → live AR/tele-expert services advertise millisecond-grade response (information becomes action-ready)
- (+) [Credibility] → courts and inspectors accept synchronized remote evidence feeds (timing integrity gains value)
- (+) [Human-machine interaction] → major venues deploy low-latency zones for immersive guidance (shared live context expanding)
- (+) [Media] → interactive broadcasts add ultra-synced audience and reporter layers (less delay between observation and interpretation)
- (–) [Equality/access] → low-latency access is sold as a premium information tier (speed advantage concentrates)
- (–) [Manipulation/security] → latency spoofing or desynchronization attacks enter incident reports (timing becomes a trust surface)
- (+) [Governance] → procurement standards start specifying latency ceilings for civic systems (institutionalization begins)
- (+) [Edge infrastructure] → edge nodes are placed near courts, hospitals, and media hubs (time-critical information demand visible)

## ART 01.003 — Edge AI for Sensor Data

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART changes the GVN from raw-data collection toward local machine interpretation at the point of capture, which is a major shift in how information becomes usable. Second-order, it moves power to device vendors and model owners who decide thresholds, summaries, and alerts. Third-order, billions of distributed classifiers can reshape what gets noticed, escalated, ignored, or believed. Because it can change weekly information routines across households, workplaces, mobility, and public services at very large scale, it clears the transformative anchor, so 10 fits.

**Weak signals (9):**

- (+) [Relevance] → cameras, meters, and wearables output summaries instead of raw streams (interpretation moves to capture point)
- (+) [Privacy] → procurement rules start preferring on-device analysis with minimal upload (local processing unlocks deployment)
- (+) [Credibility] → public agencies accept edge-generated anomaly alerts as operational evidence (machine interpretation becomes authoritative)
- (+) [Access] → offline tools provide meaningful local insights without cloud dependence (less network dependence)
- (–) [Interpretation difficulty] → incident reports cite missed events caused by model thresholds (local judgment can fail)
- (+) [Governance] → standards require uncertainty scores and audit logs from edge models (oversight enters devices)
- (+) [Institutional economics] → insurers reward edge-monitored sites and vehicles (information becomes insurable)
- (–) [Security/dual use] → adversarial attacks target embedded classifiers in public devices (trust layer becomes attack surface)
- (+) [Media practices] → newsrooms and field teams use device-native event summaries (faster triage and filtering)

## ART 01.004 — Quantum & High-Precision Sensing

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Quantum and high-precision sensing materially improve the ability to observe subtle or previously invisible phenomena, especially in infrastructure, health, environment, and navigation. The main second-order effects are new authorities around calibration, admissibility, and instrument access rather than a society-wide change in information habits. That is material in specialist domains. It plausibly fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Original observations] → public labs and utilities pilot portable quantum-grade instruments (new evidence classes emerging)
- (+) [Credibility] → courts, insurers, or regulators reference high-precision readings in decisions (measurement authority shifting)
- (+) [Local usefulness] → handheld ultra-precise tools are marketed to non-expert field users (precision leaving the lab)
- (+) [Institutionalization] → calibration labs and certification schemes appear for new sensor classes (evidence rules forming)
- (–) [Interpretation] → disputes rise over opaque high-precision outputs and their meaning (precision does not equal clarity)
- (+) [Citizen science] → advanced sensing rental programs reach municipalities or NGOs (access broadening)
- (+) [Operational change] → maintenance programs replace sampling with continuous subtle detection (information frequency increasing)
- (+) [Cross-sector sharing] → agencies exchange high-precision measurements through common platforms (data becomes reusable)
- (–) [Access inequality] → premium instrument access concentrates among large operators (precision advantage can centralize)

## ART 01.005 — Micro/Nano Sensor Networks

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Micro/nano sensor constellations greatly expand the granularity and continuity of physical-world observation, making many more conditions visible than today. Second-order, they shift power toward operators who control interpretation layers and storage, and they create new surveillance and disposal concerns. Third-order, they normalize dense measurement as baseline evidence rather than exceptional data. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Local relevance] → buildings, vehicles, and packaging ship with embedded micro-sensor arrays (observation becomes built in)
- (+) [Situational awareness] → public dashboards show block-level physical condition data (more granular local awareness)
- (+) [Product credibility] → goods expose lifetime handling histories to buyers (provenance becomes experiential)
- (+) [Institutional monitoring] → landlords, employers, or operators add ambient micro-sensing routinely (continuous monitoring normalizing)
- (–) [Privacy/power] → complaints about invisible tracking in homes and workplaces rise (observation becomes contentious)
- (+) [Insurance] → insurers price assets using dense monitoring completeness (fine-grained evidence gains market value)
- (+) [Citizen use] → NGOs deploy speck-sensor networks for pollution or noise evidence (lower-cost civic verification)
- (+) [Governance] → radio, disposal, and calibration rules appear for micro-sensor fleets (ecosystem becoming official)
- (–) [Security] → tamper kits and spoofing tools appear for tiny sensor networks (evidence can be gamed)

## ART 01.006 — Privacy-Preserving Pervasive Sensing

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The central impact is not merely more sensing, but making large-scale sensing socially and legally deployable in places where privacy would otherwise block it. Second-order, it reshapes accountability around what is collected, how long it is kept, and which outputs can leave a device. Third-order, it can expand trust in ambient observation while also enabling new forms of “acceptable” surveillance. Because privacy acceptance is a key bottleneck for many information-rich environments, this is transformative, so 10 fits.

**Weak signals (9):**

- (+) [Trust/credibility] → transit, schools, and buildings buy sensing systems with default local redaction (privacy design unlocking deployment)

- (+) [Governance] → public tenders require minimization and policy-based sharing by default (rules becoming standard)
- (+) [Civil legitimacy] → civil liberties groups conditionally endorse some sensing deployments (social license forming)
- (+) [Institutional practice] → regulators accept aggregate outputs without raw retention (new compromise model)
- (–) [Privacy risk] → lawsuits target re-identification from supposedly protected streams (trust claims being tested)
- (+) [User control] → consumer devices expose granular sensing and retention settings (consent becoming operational)
- (+) [Public accountability] → municipalities publish privacy impact ledgers for sensor networks (oversight becomes visible)
- (–) [Security] → attackers market techniques to reconstruct redacted data (protection layers contested)
- (+) [Cross-border use] → international collaborations switch to local-only sensing modes (data governance friction easing)

## ART 01.007 — Quantum-Resilient and Secure Communication Networks

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Reliable information acquisition depends on source integrity, confidentiality, and resistance to tampering, especially for journalism, civic communications, and sensor control. Second-order effects include new compliance tiers, higher-assurance communications markets, and stronger bargaining power for secure infrastructure providers. Third-order, actors with long-lived sensitive data will change behavior earlier than consumers. That is significant but mostly mediated through institutions, so 5 fits.

### **Weak signals (9):**

- (+) [Credibility/source integrity] → public-sector and media contracts require post-quantum channels (source protection becoming operational)
- (+) [Archival trust] → long-retention archives are re-encrypted with migration plans (future decryption risk taken seriously)
- (+) [Journalistic usefulness] → secure messaging tools advertise quantum-resilient provenance features (sensitive sourcing adapts)
- (+) [Institutional governance] → algorithm-agility reporting becomes part of telecom and cloud audits (transition formalizing)
- (–) [Operational fragility] → outages or failures arise during cryptographic migration (transition itself affects trust)
- (+) [Insurance] → high-assurance communications receive differentiated premiums or risk treatment (security gets priced)
- (+) [Civil society] → journalist and activist groups receive secure communications grants (sensitive users move first)
- (–) [Access inequality] → high-assurance channels are concentrated in premium tiers (security advantage centralizes)

- (+) [Standards] → certification schemes appear for post-quantum endpoints and network gear (ecosystem maturing)

## ART 01.008 — Integrated Sensing and Communication (ISAC)

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

ISAC materially expands ambient situational awareness by letting communication infrastructure double as a sensing layer. Second-order, it gives telecom and infrastructure operators new power over occupancy, movement, and anomaly data, while raising privacy and evidentiary questions. Third-order, it can normalize inferred physical awareness in ordinary spaces. That is significant but still limited by the coarseness and interpretive nature of the data, so 5 fits.

### **Weak signals (9):**

- (+) [Situational awareness] → telecom trials expose occupancy and motion APIs to third parties (network becomes a sensor)
- (+) [Local relevance] → building systems buy radio-sensing add-ons instead of separate hardware (lower-cost ambient awareness)
- (+) [Emergency usefulness] → crowd-flow and evacuation tools rely on comms-derived sensing (new public-safety function)
- (–) [Privacy] → regulators classify RF-derived presence as personal data (invisible observation becomes contested)
- (+) [Institutional markets] → advertisers, retailers, or venues pilot footfall analytics from network sensing (commercial pull emerging)
- (+) [User control] → routers or phones add opt-out controls for ambient radio sensing (public visibility increasing)
- (–) [External interference] → spoofing or signal-distortion incidents target ISAC environments (sensed reality can be manipulated)
- (+) [Governance] → spectrum rules start addressing sensing duties and limits (policy recognizes hybrid role)
- (+) [Legal use] → courts begin testing whether RF-sensed motion is admissible evidence (new evidentiary layer)

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 — Compute-in-Memory & Neuromorphic Chips

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

These chips significantly expand always-on, low-power interpretation of images, sound, motion, and other signals near where they are captured. Second-order, they shift leverage toward chip vendors and device ecosystems that control local intelligence. Third-order, they make continuous

personalization and filtering economically normal. That plausibly reaches the €100M–1B or 50–500M person-hour band through phones, wearables, sensors, and cameras, so 5 fits.

### Weak signals (9):

- (+) [Access] → phones and cameras advertise always-on local understanding with large battery gains (continuous interpretation becomes practical)
- (+) [Privacy] → audits and procurement start preferring local inference hardware (less raw data export)
- (+) [Monitoring] → public infrastructure pilots ultra-low-power anomaly detection chips (edge intelligence diffusing)
- (+) [Developer ecosystem] → open toolchains add neuromorphic support for sensing tasks (software barrier easing)
- (–) [Market power] → a small set of chip vendors define supported local intelligence stacks (control concentrates)
- (+) [Benchmark shift] → performance metrics emphasize sparse event-stream tasks (new computing style becoming normal)
- (+) [Institutional practice] → offline multimodal tools enter fieldwork and emergency kits (cloud dependence declining)
- (–) [Security] → specialized chips become targets for model extraction and tampering (local trust layer attacked)
- (+) [Procurement] → low-power always-on capture and triage features appear in tenders (operational demand visible)

## ART 02.010 — Novel transistor technologies and materials beyond silicon CMOS

### Score: 3 (Impact in GVN 14)

#### Justification (3–5 sentences):

Better transistor technologies reduce heat, energy, and size constraints for the devices that search, rank, capture, and analyze information. The main impact is enabling more capable edge and mobile systems, with second-order effects in supply concentration and faster device turnover rather than a direct new information regime. That is material and plausibly in the €10–100M or 5–50M person-hour band. So 3 fits.

### Weak signals (9):

- (+) [Edge capability] → on-device model sizes jump without battery penalties (local information tools get stronger)
- (+) [Access] → rugged field devices gain near-server-class processing (remote use cases broaden)
- (+) [Cost curve] → public and private roadmaps assume cloud-to-edge workload shifts (compute placement changing)
- (–) [Market structure] → antitrust debates center on new chip process monopolies (hardware power concentrates)
- (+) [Infrastructure] → information-heavy sectors shorten device refresh cycles for new chips (capability diffusing)



- (+) [Developer behavior] → toolkits target multimodal local inference as default (software follows hardware)
- (+) [Energy] → energy-per-query disclosures fall sharply in information services (cheaper high-volume processing)
- (–) [Geopolitics] → export controls cover next-gen transistor components (information capacity becomes strategic)
- (+) [Products] → always-on translation, recognition, and summarization reach mid-range devices (capability broadens)

## ART 02.011 — Quantum Computing Platforms

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The link to this GVN is narrow and mostly indirect, through specialized optimization, scenario exploration, or future security disruption. Effects would be concentrated in elite analytics and high-end AI pipelines rather than broad everyday access, credibility, or source structure. That keeps it below the €10–100M or 5–50M person-hour material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Credibility/specialist analysis] → intelligence or science platforms market quantum-assisted inference services (specialist info advantage emerging)
- (+) [Institutional verification] → policy labs test quantum-enhanced scenario exploration (elite analysis tools broadening)
- (–) [Security/integrity] → archive-risk warnings tie source confidentiality to quantum timelines (future trust pressure visible)
- (+) [Search bottlenecks] → niche knowledge-graph vendors pilot quantum subroutines for ranking (small workflow foothold)
- (–) [Equality/access] → access concentrates in premium compute contracts (benefits stay highly unequal)

## ART 02.012 — Photonic and Optical Computing

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Photonic computing materially lowers the cost and heat of high-volume search, inference, and media processing. Its second-order impact is mostly on who can afford to run very large ranking, moderation, and translation systems continuously, rather than on creating new information channels itself. That is a material enabling shift. It fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Search/processing] → cloud providers launch optical inference tiers for ranking and media tasks (high-volume processing cheaper)
- (+) [Media infrastructure] → translation and moderation stacks advertise optical acceleration (more real-time analysis)

- (+) [Edge-to-core flow] → hybrid optical modules appear in camera and sensor backends (data movement bottlenecks easing)
- (–) [Market power] → optical packaging and laser supply bottlenecks shape information service capacity (new chokepoints emerge)
- (+) [Public research] → open dataset platforms adopt optical backends for faster access (shared knowledge infrastructure benefits)
- (+) [Latency] → interactive media tools market lower jitter and better throughput (timing quality improves)
- (+) [Sustainability] → cost-per-analysis drops for video and multimodal workloads (more processing becomes routine)
- (–) [Security] → attacks and failures target electro-optic conversion layers (new reliability surface appears)
- (+) [Procurement] → hyperscalers specify optical interconnects in information-heavy deployments (capital demand visible)

## ART 02.013 — Next-Gen Memory & Storage

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Better memory and storage materially improve retrieval, provenance, context retention, and long-lived evidence. Second-order, they shift power toward custodians who can cheaply retain and search vast histories, while third-order they increase pressure around deletion, consent, and persistent machine memory. That is material rather than transformative. It plausibly fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Credibility/provenance] → always-on provenance logs become cheap enough to keep by default (auditability expands)
- (+) [Relevance] → personal and enterprise tools retain much longer multimodal histories (context-rich retrieval grows)
- (+) [Public archives] → institutions keep raw media and sensor data instead of sparse summaries (original sources expand)
- (–) [Privacy] → deletion disputes rise as systems preserve more context by default (retention becomes contested)
- (+) [Portability] → standards emerge for portable machine memory packages (context becomes transferable)
- (+) [Institutional practice] → breach investigations and compliance rely on far deeper retained logs (evidence richness rises)
- (–) [Power concentration] → storage-rich platforms gain a stronger advantage in personalized information services (memory becomes market power)
- (+) [Consumer behavior] → lifetime search and recall features become product differentiators (long-memory tools normalize)
- (–) [Security] → incidents increasingly involve theft of dense context stores rather than isolated files (more valuable archives form)

## ART 02.014 — Molecular Computing

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

As framed here, molecular computing does not map clearly onto broad societal information acquisition. Any plausible linkage is highly indirect and niche, such as future embedded biochemical sensing. That keeps it below the threshold for a concrete non-trivial GVN effect. So 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Measurement bottleneck] → chemical labs market molecular processors as in-sample interpreters (would create direct sensing linkage)
- (+) [Credibility/original sources] → field assays produce machine-readable outputs without external instruments (embedded info path forming)
- (–) [Interpretation difficulty] → regulators classify outputs as too opaque for routine use (adoption path stalled)
- (+) [Access/local relevance] → low-infrastructure diagnostics pair computation with sampling kits (linkage would strengthen)

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 — Causal Learning & Reasoning

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART directly addresses a core bottleneck in the GVN: distinguishing correlation, persuasion, and causal explanation. Second-order, it changes accountability in journalism, policy, and decision support by rewarding systems that can explain why and what-if. Third-order, it privileges actors who control intervention data and causal models. If embedded in assistants, search, and public-facing analysis tools, it plausibly changes the weekly information routines of hundreds of thousands of people. So 10 fits.

**Weak signals (9):**

- (+) [Credibility] → search assistants start showing intervention effects and counterfactuals (explanation becomes causal)
- (+) [Public authority] → agencies publish causal models alongside major policy claims (official reasoning made inspectable)
- (+) [Media practice] → newsrooms hire or contract causal-model reviewers (narratives need deeper validation)
- (+) [Consumer usefulness] → reviews shift from averages to “what changed outcomes” views (decision support deepens)

- (–) [Manipulation] → model-poisoning tactics target intervention data and causal graphs (explanations become attack targets)
- (+) [Governance] → high-stakes AI rules begin requiring intervention reasoning, not just prediction (regulatory expectations rise)
- (+) [User behavior] → people compare assistants on “why” and “what if” performance (new quality criterion emerges)
- (–) [Power] → a few platforms control the best causal world models (interpretive authority can centralize)
- (+) [Interface change] → APIs expose causal graphs and uncertainty traces to other tools (causal infrastructure spreads)

## ART 03.016 — Federated & Privacy-Preserving Learning

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

This ART significantly expands personalized and localized information services without requiring sensitive data to be centralized. Second-order, it lowers the advantage of the biggest data hoarders while creating new governance issues around aggregation quality, representation, and auditability. Third-order, it can normalize cross-institution learning where data pooling was previously blocked. That plausibly reaches the significant anchor, so 5 fits.

### **Weak signals (9):**

- (+) [Local relevance] → hospitals, schools, or municipalities join federated model consortia (shared intelligence without raw data pooling)
- (+) [Privacy] → devices market personalization without cloud upload (trust barrier lowering)
- (+) [Access] → smaller organizations gain shared models while keeping local custody (benefit diffuses beyond giants)
- (–) [Bias/power] → weakly represented participants report poor model fit (shared learning can still exclude)
- (+) [Governance] → procurement increasingly demands secure aggregation or differential privacy (institutional norms forming)
- (+) [Security] → breach narratives shift from data exfiltration to model-update leakage (new risk surface visible)
- (+) [Standards] → auditable logs for federated training and model lineage appear (trust layer hardening)
- (+) [Cross-border use] → collaborations use federated approaches to avoid transfer restrictions (jurisdiction friction easing)
- (–) [Performance dispute] → organizations publicly compare local vs centralized model quality (adoption trade-offs becoming visible)

## ART 03.017 — Trustworthy AI Systems

**Score: 10 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Once AI mediates large shares of what people read, compare, and believe, trustworthiness becomes

a central operating condition of this GVN. Second-order effects include major shifts in procurement, liability, and labor oversight. Third-order public willingness to use AI as an information gatekeeper depends on whether these systems are auditable and robust. That plausibly affects the weekly information routines of hundreds of thousands of people, so 10 fits.

### **Weak signals (9):**

- (+) [Credibility] → search/chat tools expose citations, provenance, and confidence by default (trust features become baseline)
- (+) [Governance] → public-sector and enterprise procurements require fallback modes and audit trails (trustworthiness becomes contractual)
- (+) [Insurance] → insurers price AI information systems based on auditability and incident history (risk becomes quantifiable)
- (–) [Failure visibility] → public incident registries track hallucination harms in operational workflows (trust failures become measurable)
- (+) [Labor] → unions and professions negotiate human-override rights in AI-mediated information tasks (oversight institutionalizing)
- (–) [Security] → adversarial attack reports become mainstream procurement criteria (robustness becomes a market battleground)
- (+) [User behavior] → retention and satisfaction correlate with auditability features (trust directly affecting usage)
- (+) [Standards] → model cards and provenance records move from voluntary to required (soft norms hardening)
- (–) [Power] → audited trust layers are dominated by a few large platform vendors (credible AI can still centralize control)

## **ART 03.018 — Automated Machine Learning (AutoML)**

### **Score: 3 (Impact in GVN 14)**

#### **Justification (3–5 sentences):**

AutoML materially lowers the barrier to building information ranking, prediction, and monitoring tools across many organizations. The second-order downside is a flood of mediocre or weakly governed models that can still shape access and interpretation at scale. That is material and plausibly within the €10–100M or 5–50M person-hour band. So 3 fits.

### **Weak signals (9):**

- (+) [Access] → small municipalities and firms launch in-house predictive dashboards without data scientists (model creation diffuses)
- (+) [Media operations] → newsroom and civic-tech stacks add no-code model builders (specialist bottlenecks easing)
- (–) [Credibility] → more public model failures involve auto-generated pipelines (quality risks becoming visible)
- (+) [Governance] → procurement increasingly demands guardrails around automated model creation (oversight catching up)
- (+) [Templates] → platform ecosystems sell domain-specific AutoML packages for information tasks (standardization expanding)
- (–) [Bias/power] → low-code systems replicate biased defaults across many organizations (errors scale faster)

- (+) [Training] → workforce programs shift from coding to model oversight skills (role structure adapting)
- (+) [Operations] → rollback and auto-retraining become default features in low-code AI (lifecycle management standardizing)
- (–) [Accountability] → audit tools increasingly inspect generated pipelines rather than hand-built ones (responsibility becomes harder to trace)

## ART 03.019 — Collaborative Multi-Agent AI

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Coordinated agents can gather, cross-check, summarize, and route information at scales beyond human attention, especially across dispersed sources and sensors. Second-order, they shift power toward the operators of orchestration platforms. Third-order, they can amplify shared blind spots and cascading errors if agents learn from each other too quickly. That plausibly reaches the significant anchor through monitoring, search, triage, and coordination. So 5 fits.

### **Weak signals (9):**

- (+) [Situational awareness] → organizations deploy agent teams for monitoring and source cross-checking (parallel information work scales)
- (+) [Public dashboards] → incident triage is increasingly agent-generated before human review (automation enters interpretation loop)
- (+) [Platformization] → vendors expose orchestration tools for many small AI workers (coordination layer commercializing)
- (–) [Failure amplification] → reports show agent-to-agent errors cascading across workflows (shared blind spots matter)
- (+) [Governance] → tenders require human override and swarm audit logs (oversight begins)
- (+) [Labor] → roles shift from manual review to agent supervision (attention allocation changing)
- (–) [Security] → prompt contagion and collusion become distinct attack categories (multi-agent trust surface expands)
- (+) [Standards] → shared task/map schemas emerge for multi-agent information work (ecosystem interconnecting)
- (+) [Insurance] → autonomous triage systems receive differentiated risk treatment (market recognizing new model)

## ART 03.020 — Quantum-Accelerated AI Systems

**Score: 1 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

The likely effect on this GVN is indirect, mainly through faster optimization inside frontier AI stacks. Benefits would accrue to a small number of high-end providers rather than changing everyday access, credibility, or source structure. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Information intermediaries] → frontier labs market quantum-backed search or ranking modules (niche platform differentiation)
- (+) [Complex planning] → premium forecasting tools cite hybrid quantum optimization (elite-use signal)
- (–) [Equality/access] → only hyperscalers can afford deployments (impact stays concentrated)
- (–) [Credibility] → providers struggle to explain quantum-assisted outputs to auditors (trusted use limited)
- (+) [Compute bottleneck] → benchmark wins appear on combinatorial information-routing tasks (relevance would broaden)

## ART 03.021 — AI-Driven Autonomous Scientific Discovery

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART materially accelerates the production of reliable knowledge in science-intensive domains, which feeds downstream into the broader information ecosystem. Second-order, it shifts authority toward labs and platforms that can continuously generate and validate findings. Third-order, it can flood public channels with semi-validated claims faster than human review can stabilize them. That is material to the knowledge supply side and fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Knowledge production] → funders require machine-readable negative results and autonomous lab logs (learning loops tightening)
- (+) [Media relevance] → specialist media subscribe to AI-discovery monitoring feeds (knowledge enters public channels faster)
- (+) [Speed] → time from hypothesis to public result shrinks in data-rich fields (evidence cycles compressing)
- (–) [Credibility] → retractions and validation bottlenecks grow after machine-generated result surges (knowledge quality pressure)
- (+) [Public agencies] → health and climate bodies use autonomous discovery dashboards (institutional uptake visible)
- (–) [Authorship/governance] → disputes over who owns and verifies AI-generated findings increase (accountability unsettled)
- (+) [Infrastructure] → research procurement bundles robotics with discovery models (autonomous knowledge production operationalized)
- (+) [Peer review] → reviewers ask for machine audit trails and experiment provenance (verification norms shifting)
- (+) [Information labeling] → media create explicit “AI-discovered” evidence tags (public interpretation adapting)



## 4. Human-Machine Interaction & Augmentation

### ART 04.022 — Immersive Augmented & Virtual Reality

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

AR/VR significantly changes how information is experienced by making it situated, shared, and spatial rather than flat and separate. Second-order, it creates new platform control over overlays, spatial annotations, and attention markets. Third-order, it can deepen both understanding and manipulation in context-rich environments. That plausibly reaches the significant anchor in fieldwork, training, guidance, education, and journalism, so 5 fits.

**Weak signals (9):**

- (+) [Situational awareness] → field teams adopt AR overlays for live contextual guidance (information becomes place-bound)
- (+) [Remote presence] → expert support shifts from video calls to shared first-person views (distance barrier easing)
- (+) [Public information] → museums, retail, and transit add persistent spatial information layers (ambient digital guidance grows)
- (–) [Credibility/manipulation] → lawsuits challenge misleading or unsafe overlays (annotation trust becoming contested)
- (+) [Accessibility] → public programs fund spatial navigation and guidance tools (access route widening)
- (–) [Attention/power] → ad markets emerge for location-locked overlays (attention capture follows immersion)
- (+) [Education/media] → schools and newsrooms publish immersive explainers as routine formats (new interpretive norm)
- (–) [Privacy] → backlash rises against always-on capture glasses in public spaces (co-presence triggers surveillance concerns)
- (+) [Governance] → platform policies begin defining who may annotate shared physical spaces (spatial information rights emerging)

### ART 04.023 — Brain-Computer Interfaces (BCI)

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

BCIs could improve access and attention management for some users, but the linkage to broad societal information acquisition remains narrow. The strongest pathways are accessibility and specialized high-focus contexts rather than general source discovery or credibility. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Accessibility/access] → assistive reading and navigation BCIs enter routine procurement (niche information access gains)
- (+) [Attention bottleneck] → high-focus workstations use neural-state adaptation tools (specialist relevance emerging)
- (–) [Privacy] → neural data governance rules tighten around workplace use (trust barrier visible)
- (+) [Human-machine interaction] → consumer devices add low-bandwidth intent shortcuts (small interface foothold)
- (–) [Equality/access] → reimbursement gaps keep adoption clinical or elite (broad impact limited)

## ART 04.024 — Advanced Prosthetics & Exoskeletons

**Score: 0 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

This ART mainly changes mobility and physical task performance, not how society acquires, verifies, or distributes information. Any informational effect would be indirect, through greater participation in some roles. That keeps it below the threshold for a concrete non-trivial GVN effect. So 0 fits.

### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Access/participation] → field-inspection and reporting roles become more accessible through assistive wearables (would create labor linkage)
- (+) [Local observation] → exoskeleton use expands safe access to inspection environments (information-gathering niche)
- (–) [Cost bottleneck] → devices remain framed only as mobility aids (linkage stays weak)
- (+) [Inclusion] → disability-tech programs tie wearables to citizen monitoring or reporting tasks (pathway would strengthen)

## ART 04.025 — Haptic and Multi-Sensory Feedback Systems

**Score: 1 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Richer haptic and multisensory feedback improves remote inspection, telepresence, and interpretation of difficult environments, but it is an interface refinement rather than a new information regime. The main effects remain concentrated in accessibility, training, and specialist control tasks. That keeps it below the material anchor but above zero. So 1 fits.

### **Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote inspection] → operators adopt haptic dashboards for infrastructure or evidence review (better mediated judgment)
- (+) [Accessibility] → multisensory navigation and alert tools gain reimbursement (access channel widening)

- (+) [Credibility] → teleoperation tools add tactile confirmation for evidence collection (remote trust improving)
- (–) [Scale] → most consumer information apps remain visual-only (broad effect stays small)
- (–) [Standards] → no shared haptic vocabularies emerge for public systems (interoperability bottleneck persists)

## ART 04.026 — AI Understanding of Human Intent & Context

**Score: 10 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

This ART changes information acquisition from explicit search toward continuous inference about what a user needs, can handle, and likely means. Second-order, it gives platforms and devices deep agenda-setting power over timing, tone, and framing. Third-order, it can both improve relevance and intensify manipulation or bubble formation. Because it can mediate everyday information exposure for very large populations, the impact is transformative, so 10 fits.

### **Weak signals (9):**

- (+) [Relevance] → assistants surface task- and location-specific information without explicit queries (search shifts toward anticipation)
- (+) [Data access] → devices request broader multimodal permissions for context inference (context becomes the new input)
- (+) [Platform behavior] → products market “understands what you mean” over keyword search (interface paradigm changing)
- (–) [Manipulation] → complaints rise about emotional or situational targeting (context becomes a persuasion channel)
- (+) [Governance] → regulators ask for override and contestability of context inferences (institutional friction becoming visible)
- (+) [Workflows] → organizations use context-aware briefing tools in frontline operations (relevance automation diffusing)
- (–) [Bias] → audit firms test models for cultural and neurodivergent misreads (context inference can misrecognize people)
- (+) [Labor] → roles shift toward training and supervising contextual models (human work reorganizing around inference)
- (–) [Dependence] → user metrics show less search effort but more platform reliance (convenience deepens gatekeeping)

## ART 04.027 — Brain-to-Brain Interfaces

**Score: 1 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

BBIs may eventually transfer tacit knowledge or internal states, but their direct role in mainstream information acquisition is still narrow and speculative. Early use would likely be specialist collaboration or accessibility rather than broad public information flows. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Tacit knowledge transfer] → pilot systems target specialist coordination or training (niche info-sharing channel)
- (+) [Accessibility] → disability research frames BBIs as communication aids (limited relevance path)
- (–) [Privacy/safety] → ethics rules focus on psychological integrity and consent (adoption constrained)
- (+) [Remote collaboration] → labs test shared neural-state cues in demanding tasks (small workflow foothold)
- (–) [Public legitimacy] → no non-clinical governance framework appears (broad impact blocked)

**ART 04.028 — Memory Prostheses**

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Memory prostheses improve retention and recall rather than directly changing the external information environment. Their main GVN linkage is better continuity in high-stakes information work and accessibility for people with cognitive impairment. That keeps them below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Recall continuity] → assistive memory implants pair with secure personal knowledge logs (supports reliable recall)
- (+) [Accessibility] → cognitive-support reimbursement includes information-work use cases (niche adoption route)
- (+) [Professional reliability] → high-stakes occupations test memory aids after interruptions (workflow signal)
- (–) [Privacy/governance] → regulations restrict export or sharing of prosthetic memory data (network effects limited)
- (–) [Equality/access] → use stays clinical and expensive (broad impact remains small)

**5. Robotics & Physical Autonomy****ART 05.029 — Self-Driving Vehicles**

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Autonomous vehicles materially expand continuous street-level observation and localized hazard information because fleets become moving sensor networks. Second-order, this shifts data power

toward fleet operators and raises new privacy and evidentiary questions. Third-order, live urban data can be both stabilizing and manipulative depending on access control. That plausibly fits the €10–100M or 5–50M person-hour band, so 3 fits.

#### **Weak signals (9):**

- (+) [Local observation] → cities negotiate access to autonomous fleet sensor data (street-level evidence becoming marketized)
- (+) [Relevance] → mapping and logistics services sell near-real-time street condition feeds (current local information improves)
- (+) [Insurance] → pricing starts using continuous vehicle telemetry (observations gain institutional weight)
- (–) [Privacy] → public complaints rise over ambient capture by autonomous fleets (street sensing becomes contentious)
- (+) [Public safety] → emergency services pull incident evidence from fleet networks (new source layer enters operations)
- (+) [Media] → local news services subscribe to traffic and disruption feeds from fleets (street reporting becomes automated)
- (–) [Security] → spoofing and sabotage target vehicle observation systems (mobility data becomes attack surface)
- (+) [Labor] → remote monitoring roles grow as direct driving roles shrink (attention shifts from driving to interpretation)
- (+) [Governance] → rules emerge on when fleet data must be shared or retained (urban observability institutionalizing)

## **ART 05.030 — Drone Swarms & Aerial Robots**

### **Score: 5 (Impact in GVN 14)**

#### **Justification (3–5 sentences):**

Drone swarms significantly lower the cost of current, localized, visual information from above, especially in disasters, agriculture, infrastructure, and crowd settings. Second-order, they redistribute power toward whoever controls aerial access and interpretation. Third-order, they can speed both correction of false narratives and mass surveillance. That plausibly lands in the significant anchor, so 5 fits.

#### **Weak signals (9):**

- (+) [Original observations] → municipalities contract swarm services for incident mapping (aerial evidence routine)
- (+) [Media] → newsrooms and insurers use routine drone feeds instead of one-off flights (lower-cost visual verification)
- (+) [Emergency usefulness] → crisis dashboards integrate contractor and citizen drone layers (multi-source situational awareness)
- (–) [Privacy] → neighborhood and event overflight complaints increase (persistent aerial observation contested)
- (+) [Governance] → airspace rules add persistent swarm corridors and no-capture zones (institutionalization begins)

- (+) [Markets] → annotated aerial evidence marketplaces emerge (observation becomes a service)
- (–) [Security/dual use] → anti-drone countermeasures spread around sensitive sites (observation becomes conflictual)
- (+) [Expectation shift] → public expects live aerial confirmation during disruptions (verification norms rising)
- (+) [Legal use] → courts test admissibility and chain-of-custody for swarm-collected media (new evidence class formalizing)

## ART 05.031 — Humanoid and General-Purpose Robots

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

General-purpose robots materially improve information collection in human-designed spaces where permanent sensors are sparse or access is hard. Second-order, they affect labor, chain-of-custody, and accountability for robot-collected evidence more than they affect mass public information habits. That is material and fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Observation access] → facilities deploy humanoid inspectors for routine documentation (human-space sensing scales)
- (+) [Hazard reduction] → agencies pilot robots for dangerous on-site evidence collection (more original sources in risky zones)
- (+) [Remote expertise] → experts supervise embodied robots across multiple sites (distance bottleneck easing)
- (–) [Accountability] → rules are written for when robot observations count as official inspection (responsibility becoming formal)
- (+) [Ecosystem] → vendors ship inspection/reporting task libraries for general robots (information work commoditized)
- (–) [Safety] → incidents involving robot-collected evidence trigger public scrutiny (trust depends on operations)
- (+) [Insurance] → sites receive monitoring-related discounts when robot rounds replace sparse visits (continuous documentation gains value)
- (+) [Public visibility] → citizens increasingly encounter robots gathering civic or environmental data (robot observation normalized)
- (+) [Standards] → chain-of-custody schemes emerge for robot-captured media (evidence legitimacy hardening)

## ART 05.032 — Soft Robotics & Bio-Inspired Machines

**Score: 1 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

The main relevance is niche access to delicate, cluttered, or hazardous environments where information collection is otherwise hard. That matters in some inspections and ecological observations, but it does not reshape the wider information regime. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Hard-to-reach observation] → utilities and labs test soft robots for delicate inspection (niche access gain)
- (+) [Environmental sensing] → bio-inspired crawlers sample fragile ecosystems or ruins (specialist evidence path)
- (+) [Safety] → human entry protocols are replaced by compliant inspection robots (localized substitution)
- (–) [Scale] → deployments stay bespoke rather than platformized (broad effect stays small)
- (–) [Market structure] → no common data interfaces emerge from soft-robot vendors (weak ecosystem effects)

## **ART 05.033 — Fully Autonomous Drones, Robots & Underwater Vehicles**

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART extends reliable information gathering into remote, underwater, dangerous, or unmapped places where human presence is intermittent. Second-order, it creates strong asymmetries between operators who own autonomous fleets and those who do not. Third-order, it can normalize persistent machine observation in previously opaque domains. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Remote observation] → utilities, ports, and municipalities buy long-duration autonomous inspection services (continuous hard-to-reach sensing)
- (+) [Environmental relevance] → marine and remote-area monitoring feeds become subscription products (new source markets forming)
- (+) [Operational change] → autonomous mapping replaces periodic human site visits (manual sampling declining)
- (–) [Security] → spoofing and interference target remote vehicles and mission logs (machine evidence contested)
- (+) [Public sharing] → data portals begin exposing autonomous survey outputs (specialist evidence becoming reusable)
- (+) [Insurance] → continuous robotic monitoring changes premiums and maintenance schedules (observations monetized)
- (–) [Power] → access to remote knowledge concentrates in fleet owners (informational inequality widens)
- (+) [Procurement] → tenders require resilience to comms loss and autonomous logging (trust and uptime emphasized)
- (+) [Labor] → field roles shift toward mission planning and remote oversight (attention moves from travel to interpretation)



## ART 05.034 — Supportive Infrastructure for Autonomy

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This infrastructure can make robotic information gathering cheaper and safer, but only in deliberately prepared environments. Its impact is therefore indirect and localized to specific sites such as campuses, hospitals, ports, and warehouses. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Observation cost] → facilities add robot-readable markers and docking for inspection fleets (localized sensing scale-up)
- (+) [Governance] → building codes mention autonomy-ready infrastructure (institutional foothold appearing)
- (+) [Site transparency] → campuses expose shared robot telemetry layers to managers or occupants (new local info services)
- (–) [Retrofitting cost] → deployments stay confined to premium high-utilization sites (breadth remains low)
- (–) [Interoperability] → vendor-specific infrastructure fragments data access (weak network effects)

## ART 05.035 — Optical/Microwave Power Beaming for Persistent Robotics

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The relevant pathway is longer-duration remote sensing and communications in places where battery swaps or fuel delivery are the main bottlenecks. That matters in disaster response and a few industrial settings, but it does not broadly alter how society acquires reliable information. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Monitoring persistence] → remote sensor or drone pilots run for weeks without battery swaps (duty-cycle bottleneck easing)
- (+) [Hazard access] → critical sites adopt beamed-power monitoring corridors (remote observation niche)
- (–) [Safety] → beam-exclusion incidents or strict rules slow civilian deployments (adoption constrained)
- (+) [Emergency response] → temporary beam stations support disaster-area reconnaissance (situational awareness boost)
- (–) [Economics] → only defense and industrial sites justify infrastructure (breadth remains low)

## ART 05.036 — Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The most relevant role is niche inspection and evidence collection on smooth, vertical, or delicate surfaces where conventional approaches are cumbersome. It improves access in specialist settings but does not alter the wider information operating model. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Hard-surface inspection] → climbing robots with dry adhesion enter routine asset inspections (new evidence access)
- (+) [Damage-free observation] → heritage or cleanroom sites approve adhesive robots (sensitive-site foothold)
- (+) [Safety] → rope-access inspections are partly replaced by wall-climbing robots (niche substitution)
- (–) [Surface limits] → rough or dirty environments keep use specialized (linkage stays narrow)
- (–) [Data standards] → no mainstream inspection platforms integrate this robot class (small ecosystem impact)

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 — Multi-Material & Hybrid 3D Printing

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The main linkage is faster fabrication of custom sensors, housings, interfaces, and specialist tools for information collection. Effects are mostly upstream in equipment iteration and niche access rather than in broad public information behavior. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Measurement tools] → labs print custom sensor assemblies in-house (equipment iteration quickens)
- (+) [Access] → local makerspaces produce bespoke assistive information devices (small democratization effect)
- (+) [Supply bottlenecks] → field teams print replacement parts for monitoring systems (resilience niche)
- (–) [Quality] → certification hurdles keep printed sensors out of routine use (impact capped)

- (–) [Visibility] → benefits remain hidden inside specialist workflows (public linkage weak)

## ART 06.038 — Digital Twin & Simulation-Driven Production

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Industrial digital twins increase information about factories and supply conditions, but their effect on this GVN is mostly indirect unless those outputs are broadly shared. The main value is sector-specific transparency and forecasting rather than a new public information regime. That keeps it below the material anchor but above zero. So 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Operational transparency] → manufacturers publish live production status or disruption forecasts from twins (supply information spillover)
- (+) [Credibility] → buyers request twin-backed claims on reliability and delivery (evidence quality improving)
- (–) [Access] → twin data stays proprietary and internal-only (linkage remains narrow)
- (+) [Coordination] → logistics and analysis tools begin consuming twin-derived alerts (information crossover emerging)
- (–) [Auditability] → disputes grow over unverifiable vendor simulations (trust bottleneck visible)

## ART 06.039 — Reconfigurable & Agile Factories

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Agile factories mainly change manufacturing responsiveness, not how society acquires, verifies, or shares information. Any benefit to this GVN would be indirect through faster availability of devices or sensors. That keeps it below the threshold for a concrete non-trivial GVN effect. So 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Device availability] → sensor and communication hardware shortages ease because lines retool faster (would create indirect benefit)
- (+) [Local production] → emergency information devices are manufactured regionally on short notice (niche linkage path)
- (–) [Public relevance] → factory agility is discussed only in industrial cost terms (linkage remains distant)
- (–) [Data sharing] → no new information rights or observability norms follow from reconfigurability (systemic pathway absent)

## ART 06.040 — Circular & Sustainable Manufacturing

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART changes material flows, waste, and sourcing more than it changes how information is acquired or trusted. Traceability effects are real, but they belong more to traceability networks than to circular production itself. Any linkage to the GVN is therefore secondary and indirect. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product information] → recycled-content markets expose rich provenance data to buyers (would create niche information services)
- (+) [Credibility] → circularity claims require machine-readable disclosure and audits (possible info spillover)
- (–) [Operating model] → benefits remain framed as materials savings, not knowledge access (direct linkage absent)
- (–) [Adoption] → no new public-facing information services emerge from circular plants (impact stays weak)

## ART 06.041 — Bio-fabrication technologies

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Bio-fabrication is primarily about producing tissues and biological materials, not acquiring information. It may indirectly aid research instrumentation, but that is too remote to score as a meaningful GVN impact. There is no clear pathway to broad changes in access, credibility, or information-sharing routines. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Measurement tools] → bio-fabricated sensing tissues enter diagnostics or monitoring platforms (would create direct linkage)
- (+) [Research information] → standardized tissue models replace some slow testing workflows (specialist knowledge path)
- (–) [Public information] → deployments remain production-focused, not information-focused (linkage stays distant)
- (–) [Governance] → no broader data-rights or transparency effects emerge (systemic impact absent)

## ART 06.042 — 4D Printed & Programmable Materials

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Programmable materials can make objects and structures act as passive or semi-passive information carriers by changing state in response to conditions. The main impact is enabling adaptive indicators, signage, and sensor housings rather than changing the broader information regime. This is concrete but narrow, mostly affecting low-maintenance local information cues. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Local awareness] → buildings and products adopt materials that visibly indicate stress or exposure (low-cost condition signals)
- (+) [Safety information] → passive self-deploying markers appear in emergency kits (accessibility gain)
- (+) [Monitoring cost] → owners replace some manual inspections with state-changing materials (niche substitution)
- (–) [Interpretation] → users still need external systems to read complex state changes (limits autonomy)
- (–) [Standardization] → few shared schemas exist for programmable material outputs (weak interoperability)

**ART 06.043 — Volumetric Additive Manufacturing****Score: 0 (Impact in GVN 14)****Justification (3–5 sentences):**

Faster layerless printing may help equipment supply chains, but it does not directly change information access, credibility, or interpretation. The pathway to this GVN is too indirect and generic. Its effects stay upstream in manufacturing rather than in how reliable information is produced or consumed. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Device supply] → rapid printing is used for emergency sensor or comms components (would create indirect benefit)
- (+) [Field repair] → compact printers support remote information infrastructure maintenance (niche relevance path)
- (–) [Public information] → adoption remains inside manufacturing workflows (direct linkage absent)
- (–) [Systemic effects] → no new data rights or trust mechanisms appear (weak GVN connection)

**7. Advanced Materials & Nano-engineering**

## ART 07.044 — Metamaterials for Novel Optics & Connectivity

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Metamaterials materially improve antennas, lenses, and wave control, which lowers cost and expands placement of sensing and communication devices. Second-order, they shift leverage toward operators who can shape coverage and visibility, and they introduce new stealth and privacy issues. Their main effect is as an enabling layer for broader observability and connectivity. That is a material enabling effect and fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Connectivity bottleneck] → buildings deploy reconfigurable surfaces to fix dead zones (coverage becomes programmable)
- (+) [Observation quality] → compact flat optics appear in cameras and wearables (better sensing in smaller forms)
- (+) [Public procurement] → infrastructure tenders specify smart RF surfaces for sensing/coverage (wave control institutionalizing)
- (–) [Privacy] → debates shift to “walls that see and route” (environment itself becomes informational)
- (+) [Markets] → firms sell metamaterial-enhanced indoor mapping and observability services (new service layer emerging)
- (–) [Security] → attacks target programmable surfaces to distort coverage or sensing (wave control becomes attack surface)
- (+) [Maintenance] → weak-signal zones become cheaper to service through passive surfaces (deployment friction dropping)
- (+) [Standards] → controllable-surface telemetry and control schemes appear (ecosystem forming)
- (–) [Geopolitics] → export controls begin covering advanced wave-control surfaces (strategic value rising)

## ART 07.045 — Room-Temperature Superconductors

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

If mature, room-temperature superconductors materially lower power losses and improve sensing, timing, and high-performance information infrastructure. The main GVN effect is through denser, more reliable compute and measurement capacity, with second-order impacts on who can operate these upgraded systems. This is material but indirect, not a direct shift in information behavior. That fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Infrastructure cost] → data centers and telecom backbones pilot superconducting power or switching elements (information systems get denser)
- (+) [Measurement] → compact ultra-sensitive instruments become practical outside labs (precision evidence broadens)

- (+) [Access] → new sensing tools move from elite labs to utilities and municipalities (capability diffusing)
- (–) [Market power] → material IP and manufacturing control concentrate among few suppliers (capacity can centralize)
- (+) [Energy] → carriers and compute operators publicize lower losses for information infrastructure (economics shifting)
- (+) [Standards] → safety and performance certification schemes appear for high-field public equipment (adoption becoming formal)
- (+) [Siting] → location choices for compute and networks shift around upgraded power density (infrastructure geography changing)
- (–) [Security] → high-field equipment becomes a new failure and sabotage concern (criticality rising)
- (+) [Planning] → infrastructure roadmaps assume much denser sensing and compute loads (expectations changing)

## ART 07.046 — Self-Healing & Smart Polymers

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The most relevant effect is more durable sensors, wearables, cables, and housings, which reduce maintenance and downtime in information systems. That is concrete but mostly upstream and operational rather than transformative for information access or credibility. The benefits are real in remote and harsh environments but narrow in their GVN effect. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Infrastructure uptime] → comms cables, wearables, and sensor housings shift to self-healing polymers (less maintenance downtime)
- (+) [Monitoring] → smart coatings signal damage before sensor failure (reliability improves)
- (+) [Access] → ruggedized low-service devices reach remote users and sites (small coverage gain)
- (–) [Cost] → materials stay confined to premium hardware lines (limits breadth)
- (–) [Standards] → no common repair-status reporting emerges (weak information-layer effects)

## ART 07.047 — Nano-Catalysts & Advanced Coatings

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Direct effects on acquiring information are modest, mainly through better sensor surfaces, optics, corrosion resistance, or device reliability. Broader societal information behavior is not significantly altered by this ART alone. The linkage is mostly an equipment-performance enabler. That keeps it below the material anchor but above zero, so 1 fits.



**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Measurement quality] → sensor makers market nano-coated surfaces with higher stability (incremental data quality gain)
- (+) [Field reliability] → anti-fouling and corrosion-resistant monitoring gear expands remote deployments (service intervals lengthen)
- (+) [Public evidence] → low-maintenance environmental sensors appear in harsher locations (coverage improves slightly)
- (–) [Visibility] → benefits remain buried inside component specifications (weak behavioral change)
- (–) [Supply risk] → scarce coating inputs keep adoption narrow (limits scale)

**ART 07.048 — High-Entropy Alloys & Advanced Metals**

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Stronger, more heat-stable materials improve sensors, satellites, and infrastructure, but the effect on information acquisition is indirect. It supports reliability in harsh environments rather than changing how reliable information is produced or consumed. The main impact is on durability and uptime. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Harsh-environment sensing] → instrument makers shift to HEA components for long-life monitoring (uptime in extremes)
- (+) [Remote access] → observation platforms extend maintenance intervals in difficult sites (coverage improves marginally)
- (+) [Credibility] → fewer sensor drifts are attributed to advanced materials (evidence becomes more stable)
- (–) [Diffusion] → material use stays hidden in aerospace and industrial niches (broad effect limited)
- (–) [Cost] → premium alloys remain confined to mission-critical devices (scale stays small)

**ART 07.049 — Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation**

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

CO<sub>2</sub> capture materials matter for climate mitigation, but they do not directly change how people acquire or verify information. Any linkage would come through carbon monitoring and disclosure, which is secondary to the core ART. There is no clear operating-model shift here for the GVN. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Environmental information] → capture systems publish continuous audited carbon-flow data (would create niche data services)
- (+) [Credibility] → buyers demand machine-readable proof of removed CO<sub>2</sub> (possible disclosure pathway)
- (–) [Public use] → deployments remain industrial climate infrastructure, not information tools (direct linkage absent)
- (–) [Systemic change] → no broad source, credibility, or platform effects follow (weak GVN connection)

## ART 07.050 — Graphene and Nanotube Composites for Lightweight Strength

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

These materials can materially enable lighter, tougher, self-sensing devices and structures, including drones, wearables, and embedded monitoring surfaces. Second-order, they make persistent observation cheaper while raising new data-rights issues around self-reporting products and infrastructure. Their role is enabling, but material at system level. That fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Hardware form factor] → drones and wearables adopt conductive composite structures with embedded sensing (lighter devices observe more)
- (+) [Access] → consumer devices market lighter always-on capture hardware (continuous observation broadens)
- (+) [Infrastructure visibility] → materials start reporting strain or damage electrically (structures become information sources)
- (+) [Credibility] → regulators or insurers accept composite-embedded condition data (self-sensing evidence legitimized)
- (–) [Privacy] → concern rises about sensorized clothing, furniture, or buildings (materials become covert observation surfaces)
- (+) [Maintenance] → repair models shift around self-reporting materials (continuous diagnostics normalizing)
- (+) [Procurement] → tenders emphasize weight plus data capability (materials chosen for information value)
- (–) [Supply] → nanotube and graphene bottlenecks affect sensor and device rollout (new chokepoints)
- (+) [Recycling/governance] → labeling rules begin covering nanocomposite sensor materials (ecosystem formalizing)

## ART 07.051 — Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART mainly improves energy efficiency and thermal stability. Any effect on information acquisition is indirect through better uptime of devices or sites, which is too generic for a meaningful standalone GVN impact. It does not materially change access, relevance, or credibility pathways. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Infrastructure reliability] → data closets or base stations gain passive thermal retrofits (would create uptime link)
- (+) [Remote access] → extreme-climate communication sites stay online longer (niche relevance)
- (–) [Public information] → adoption is framed only as energy savings (direct linkage absent)
- (–) [Behavior] → no new credibility, provenance, or interpretation practices emerge (weak systemic pathway)

## ART 07.052 — Rare-Earth-Free Magnets for Sustainable Motors

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The main relevance is stabilizing supply for motors, speakers, actuators, and sensors used in information infrastructure. That can reduce hardware bottlenecks but does not directly alter how reliable information is produced or consumed. The effect stays upstream in equipment resilience and availability. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Hardware supply] → device vendors advertise rare-earth-free components (supply resilience improving)
- (+) [Access] → fewer shortages affect communication or monitoring hardware deliveries (small availability gain)
- (+) [Geopolitics] → procurement shifts away from vulnerable magnet supply chains (infrastructure risk reduced)
- (–) [User behavior] → information services show no direct feature change from magnet substitution (effect remains upstream)
- (–) [Performance] → high-end device classes still rely on legacy magnets (limits breadth)

## ART 07.053 — Nano-Engineered Membranes for Low-Energy Desalination

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Desalination membranes affect water systems more than information systems. Any linkage would be through supporting remote settlements or facilities, which is too indirect for this GVN. There is

no clear information-regime shift here. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote infrastructure] → off-grid communications sites pair desalination with operations (would create support link)
- (+) [Local relevance] → water-quality data services grow around advanced treatment plants (possible niche path)
- (–) [Direct effect] → the technology remains utility-focused, not information-focused (linkage absent)
- (–) [Systemic change] → no broad source, credibility, or platform effects emerge (weak GVN connection)

## ART 07.054 — Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Better power semiconductors improve efficiency and compactness of comms, edge compute, and sensing nodes where heat and voltage are constraints. The impact on this GVN is real but upstream and enabling rather than directly user-facing. It mainly supports deployment into harsher and tighter environments. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Edge infrastructure] → base stations and sensor gateways shrink or harden thanks to new power modules (deployment gets easier)
- (+) [Remote access] → harsh-environment comms hardware operates with less cooling (site viability expands)
- (+) [Reliability] → uptime improves in data-heavy equipment previously limited by heat (service continuity rises)
- (–) [Visibility] → benefits stay buried in infrastructure procurement (indirect effect)
- (–) [Supply] → packaging and materials bottlenecks slow broad rollout (scale stays modest)

## ART 07.055 — Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART is about fuel handling, not information acquisition. It may support remote systems indirectly, but the link to this GVN is too weak to count as a meaningful standalone effect. The pathways are generic infrastructure support rather than GVN-specific change. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote monitoring] → long-duration sensing or comms sites adopt solid hydrogen cartridges (would create support role)
- (+) [Resilience] → emergency information hubs use safer hydrogen storage (niche linkage)
- (–) [Direct relevance] → deployment remains in energy logistics, not information workflows (pathway weak)
- (–) [Behavior] → no new trust, verification, or access mechanisms follow (impact absent)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 — Fusion Energy Reactors

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Fusion could lower long-run power cost and fragility for compute-heavy information infrastructure, but the linkage to this GVN is indirect. Benefits would mainly show up through energy price, uptime, and siting rather than new information channels or trust mechanisms. Its role is potentially large for infrastructure, but not directly for this GVN's operating model. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Compute bottleneck] → data-center planning begins around fusion-backed sites (energy constraints easing)
- (+) [Resilience] → telecom and AI operators sign long-term firm-power deals with fusion projects (indirect support growing)
- (+) [Public services] → high-energy public analytics infrastructure becomes politically feasible (cost barrier softens)
- (–) [Timing] → information-sector roadmaps do not yet depend on fusion availability (current linkage weak)
- (–) [Access] → benefits accrue first to major compute actors (uneven spillovers)

### ART 08.057 — Small Modular Fission Reactors (SMRs)

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

SMRs can support reliable power for data centers, telecom, and remote public infrastructure, but the effect on information acquisition remains indirect. The strongest pathways are resilience and cost stability rather than changed source credibility or access models. This is an infrastructure support effect, not a core GVN transformation. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Infrastructure uptime] → telecom and data operators explore SMR-backed campuses (firm-power support path)
- (+) [Remote access] → isolated regions pair SMRs with communications expansion plans (localized enabling effect)
- (+) [Governance] → critical-information facilities are listed as anchor SMR loads (sector link appearing)
- (–) [Public perception] → debates stay about energy and safety, not information access (direct linkage thin)
- (–) [Scale] → long licensing cycles delay spillovers into info systems (impact constrained)

## ART 08.058 — Thin-film solar cells

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Thin-film solar materially expands off-grid and distributed power for sensors, access points, wearables, and information surfaces. Second-order, it increases autonomy for households and communities while also creating uneven quality and maintenance outcomes across regions. Its main GVN effect is enabling local and mobile information access where wired power is inconvenient or absent. That is a material enabling role and plausibly fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Access] → shelters, windows, wearables, and asset labels begin powering local sensors or displays (distributed information power growing)
- (+) [Community networks] → local relay points use thin-film retrofits for power (low-cost access expanding)
- (+) [Public procurement] → tenders bundle solar skins with environmental or safety information systems (integration becoming standard)
- (+) [Humanitarian use] → emergency kits include solar-powered local information devices (off-grid relevance visible)
- (–) [Credibility] → low-quality laminates create trust issues in remote monitoring (power source affects data reliability)
- (+) [Building rules] → codes allow power-generating information surfaces (new form factors legalized)
- (+) [Consumer behavior] → devices market longer capture or communication time from integrated films (continuous use easier)
- (+) [Civic tech] → local journalism and civic sensor kits adopt rollable solar packages (grassroots observability expands)
- (–) [Equity] → access gains appear first in self-provisioning communities and premium products (benefits can distribute unevenly)

## ART 08.059 — Bionic Leaf Technology

**Score: 0 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Bionic leaf systems focus on chemical production rather than information production or

distribution. Any linkage to this GVN is remote and indirect. It does not directly change how people access, verify, or compare information. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

#### **Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote systems] → chemical-output panels start powering isolated sensing nodes (would create support link)
- (+) [Environmental information] → deployments expose live operating data as public evidence of carbon flows (niche information service)
- (–) [Direct relevance] → market messaging stays on fuels and molecules, not information access (linkage absent)
- (–) [Systemic effects] → no platform, trust, or sensing regime change follows (weak GVN connection)

## **ART 08.060 — Grid-Scale Energy Storage**

**Score: 3 (Impact in GVN 14)**

#### **Justification (3–5 sentences):**

Reliable information systems increasingly depend on stable power for telecom, sensors, and AI services, and long-duration storage reduces outage-driven fragility. Second-order, it shifts bargaining power toward operators who can guarantee continuity during disruptions, which matters for trusted information access. The main impact is resilience of access, not a direct change in interpretation or source diversity. That is material and plausibly in the €10–100M or 5–50M person-hour band, so 3 fits.

#### **Weak signals (9):**

- (+) [Continuity] → telecom and cloud contracts start specifying storage-backed uptime (information reliability tied to energy buffering)
- (+) [Civic access] → municipalities pair community information hubs with long-duration storage (local resilience strengthening)
- (+) [Outage response] → communications resilience improves first in storage-rich service areas (continuity becomes visible)
- (+) [Governance] → regulators treat data centers and communications as critical flexible loads (information infrastructure prioritized)
- (+) [Insurance] → storage-backed information facilities receive lower continuity-risk premiums (resilience gets priced)
- (–) [Equity] → resilient information access diverges by neighborhood or operator investment (continuity inequality emerges)
- (+) [Planning] → utilities prioritize storage near network nodes and emergency services (co-location becoming intentional)
- (+) [Drills] → black-start exercises include civic information platforms (continuity treated as a public-information issue)
- (–) [Narrative instability] → outage-related panic and rumor spikes drop unevenly based on storage presence (information trust linked to power continuity)



## ART 08.061 — Solid-State Batteries

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Safer, denser batteries materially improve mobile devices, drones, wearables, and field communications used to gather and share information. Second-order, they enable new always-on device categories and longer-lived hardware while shifting supply and recycling governance. Their main role is enabling more continuous and mobile observation, not directly changing credibility rules. That is a material enabling effect and fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Mobile access] → field devices and wearables advertise multi-day continuous sensing (always-on use becomes practical)
- (+) [Remote reporting] → drones and portable comms vendors move to safer high-density packs (mobility of observation expands)
- (+) [Public procurement] → safer batteries enter civic kiosks and public sensors (deployment friction drops)
- (+) [Insurance] → constraints ease for battery-backed public information infrastructure (safety risk falls)
- (+) [Emergency kits] → journalism and response kits get lighter with longer runtime (field information work expands)
- (+) [Consumer behavior] → users leave capture and sensor features on continuously (information frequency rises)
- (–) [Supply] → new chemistry bottlenecks or battery passport rules shape rollout (control points shift)
- (+) [Form factors] → thinner sensor-rich devices reach mainstream markets (more embedded information tools)
- (–) [Waste/governance] → recycling and lifecycle data become part of procurement and public scrutiny (energy storage becomes accountable)

## ART 08.062 — Green Hydrogen & Power-to-X

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The direct linkage is narrow, mostly via backup or remote energy for information infrastructure. It does not itself change relevance, credibility, or source access. Its influence is as an energy support layer for continuity in specific hard-to-wire settings. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Resilience] → remote telecom or media sites adopt hydrogen backup systems (continuity support path)

- (+) [Access] → isolated regions combine power-to-X storage with communications expansion (localized enabling effect)
- (+) [Governance] → critical information infrastructure appears in hydrogen resilience planning (sector link emerging)
- (–) [Direct use] → deployments remain framed as energy storage, not information tools (linkage thin)
- (–) [Cost] → complex handling keeps systems out of most civic information networks (impact modest)

## ART 08.063 — High-Efficiency Wind Turbines

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Better wind power supports cheaper electricity for information infrastructure, but the effect is indirect and generic. The strongest relevance is to remote or coastal communications and sensing sites. It does not materially reshape source diversity, trust, or interpretation patterns. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Remote access] → wind-backed systems support rural or coastal communications nodes (local continuity gain)
- (+) [Monitoring] → turbine condition data becomes an open operational dataset (niche information service)
- (+) [Energy cost] → information operators sign direct contracts with wind projects (indirect support path)
- (–) [Direct relevance] → no change occurs in source verification or information governance (linkage remains upstream)
- (–) [Variability] → benefits depend on separate storage or grid solutions (impact constrained)

## ART 08.064 — Wireless & Space-Based Power Transfer

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The main GVN pathway is enabling temporary or hard-to-reach sensing and communication without wiring or fuel logistics. That matters in disasters and certain remote operations, but not as a broad shift in information acquisition. The effect is operational and episodic rather than systemic. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Rapid deployment] → emergency comms and sensing kits adopt beamed-power receivers (faster field setup)

- (+) [Remote monitoring] → isolated sites run longer without fuel deliveries (service continuity improves)
- (–) [Safety/governance] → strict beam rules limit civilian information uses (adoption constrained)
- (+) [Dual use] → disaster-response pilots spill over from defense programs (niche capability transfer)
- (–) [Economics] → infrastructure costs confine use to special cases (broad effect small)

## ART 08.065 — Advanced geothermal technology

**Score: 1 (Impact in GVN 14)**

### Justification (3–5 sentences):

Advanced geothermal can provide firm local power for data centers, telecom, and civic infrastructure, but that remains an indirect support function for this GVN. It improves continuity more than it changes information access or credibility directly. The pathway is meaningful but narrow. That keeps it below the material anchor but above zero, so 1 fits.

### Weak signals (5):

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Continuity] → information infrastructure clusters near geothermal sites (firm-power support appearing)
- (+) [Remote regions] → geothermal-backed communities extend local communications services (localized enablement)
- (+) [Public services] → emergency information hubs appear in geothermal microgrid plans (sector link forming)
- (–) [Direct linkage] → discussions stay about heat and power, not information rights or trust (weak regime effect)
- (–) [Diffusion] → site-specific geology limits broad spillovers into information systems (impact bounded)

## ART 08.066 — Resilient microgrids

**Score: 3 (Impact in GVN 14)**

### Justification (3–5 sentences):

Resilient microgrids materially improve continuity of communications, local sensing, and public information access during outages and crises. Second-order, they increase local autonomy over information infrastructure while also creating resilience gaps between places that can and cannot finance them. Their biggest GVN effect is maintaining trusted access when centralized systems fail. That is material and plausibly in the €10–100M or 5–50M person-hour band, so 3 fits.

### Weak signals (9):

- (+) [Public access] → libraries, community centers, and telecom nodes are designated as microgrid-backed information hubs (continuity becomes intentional)
- (+) [Emergency use] → outage response plans prioritize keeping local data and communications live (information resilience recognized)

- (+) [Procurement] → resilience grants bundle power, Wi-Fi, and public displays (integrated civic infrastructure forming)
- (+) [Drills] → emergency exercises test islanded information services, not just power (operational relevance rising)
- (+) [Insurance] → continuity audits start rating information resilience alongside electrical resilience (risk model expanding)
- (+) [Transparency] → public dashboards show which information services stay live during outages (continuity visible to citizens)
- (–) [Equality] → neighborhoods without resilient microgrids face deeper information blackouts (resilience inequality emerges)
- (+) [Governance] → utilities formalize islanding rules for civic communication assets (institutionalization growing)
- (–) [Narrative control] → rumor spikes after outages fall unevenly where local hubs stay powered (truth becomes resilience-dependent)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 — Next-Generation Gene Editing

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The main linkage is indirect, through better biological measurement, diagnostics, and public debates about evidence and bio-risk. It does not itself create major new information channels for the broader population. Its relevance to the GVN is mostly specialist and institutional. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Health information] → edited-cell diagnostics enter clinical monitoring workflows (niche data pathway)
- (+) [Credibility] → public disputes increasingly hinge on genomic edit verification (specialist evidence relevance)
- (–) [Public routine] → most citizens encounter the ART as therapy news, not information infrastructure (broad impact low)
- (+) [Governance] → consent and audit trails for editing programs become machine-readable (limited data-governance spillover)
- (–) [Trust] → controversies over hidden edits erode confidence in bio-data claims (acceptance constrained)

### ART 09.068 — mRNA Therapies & Vaccines

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART changes therapeutic delivery more than it changes information acquisition. The relevant pathway is the expansion of biomarker-driven, rapidly updated health information loops around treatment and monitoring. That can matter in health contexts, but not across the full GVN. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Personal relevance] → treatment platforms expose biomarker-driven update schedules to patients (health info loop tightening)
- (+) [Public dashboards] → rapid mRNA updates rely on real-time molecular surveillance feeds (niche information demand)
- (–) [General GVN] → broader information markets remain unchanged outside health contexts (impact bounded)
- (+) [Credibility] → provenance and cold-chain data become visible to users and clinicians (trust signal improving)
- (–) [Polarization] → misinformation around tailored updates intensifies (health-only regime conflict)

**ART 09.069 — Cellular Agriculture & Cultured Meat**

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Cellular agriculture mainly changes food production, not the acquisition of reliable information. It may generate new labeling and traceability needs, but those are secondary rather than a core GVN shift. The pathways to source access, interpretation, or trust are indirect. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Product information] → cultured-food markets rely on rich provenance dashboards (would create niche info services)
- (+) [Credibility] → consumers demand machine-readable process and composition data (possible linkage path)
- (–) [Public routine] → changes stay within food supply and regulation, not information access (direct effect absent)
- (–) [Systemic] → no broader sensing/search/trust infrastructure grows out of the ART (weak GVN connection)

**ART 09.070 — Organoids & Tissue Engineering**

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Organoids improve biomedical evidence and could expand personalized diagnostic information, but the effect remains sector-specific. They change research and some clinical evidence pipelines more

than society-wide information acquisition. The GVN relevance is real but narrow. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Health evidence] → patient-derived organoid readouts enter treatment decisions (personalized information path)
- (+) [Research information] → toxicology and drug pipelines publish organoid-derived evidence routinely (knowledge supply shift)
- (+) [Credibility] → regulators specify when organoid results count as acceptable evidence (institutional foothold)
- (–) [Scale] → use remains confined to specialized labs and hospitals (broad impact capped)
- (–) [Interpretation] → conflicting organoid models create trust disputes (mainstream diffusion limited)

## ART 09.071 — Synthetic Biology & Designer Microbes

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Designer microbes can act as living sensors or reporters, but in this GVN their main effect is niche measurement and environmental monitoring rather than broad social information flows. Institutional impacts remain limited to specific sectors and biosecurity governance. The relevance is concrete but narrow. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Measurement] → biosensor microbes are used in water, soil, or contamination monitoring (new data source)
- (+) [Local relevance] → field kits report environmental conditions via engineered biology (niche citizen use)
- (–) [Biosecurity] → strict containment rules block routine public deployments (adoption constrained)
- (+) [Credibility] → regulators define validation methods for living-sensor outputs (institutional entry point)
- (–) [Public trust] → communities resist microbial sensors despite utility (limits scale)

## ART 09.072 — Microbiome Engineering

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The strongest link is the growth of personal and environmental information services built around microbial measurement and intervention. That can matter for health, agriculture, and water, but it does not broadly transform the overall information regime. Its GVN impact is narrow and domain-bound. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Personal relevance] → routine microbiome dashboards guide interventions (niche information service)
- (+) [Environmental monitoring] → utilities or farms use microbiome control panels (localized evidence source)
- (+) [Authority shift] → consumer platforms interpret invisible microbial states for lay users (new intermediary power)
- (–) [Trust] → weakly reproducible microbiome claims trigger skepticism (credibility barrier)
- (–) [Scale] → services remain premium or domain-specific (broad GVN impact limited)

**ART 09.073 — Precision Medicine & Genomic Diagnostics**

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART gives people and institutions direct access to highly relevant, previously invisible information about health risk, treatment response, and biological state. Second-order, it shifts authority from generalized expertise toward data-rich diagnostic platforms while raising major privacy, discrimination, and consent issues. Third-order, it can normalize continuous molecular monitoring and personalized guidance. In a 5.5M society that plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Personal relevance] → routine care includes genomic profiles and recurring molecular monitoring (personal biology becomes a standing data source)
- (+) [Interpretation] → consumer platforms translate genomic results into plain-language guidance (lay access to complex evidence widening)
- (–) [Power/distribution] → employers or insurers seek access to diagnostic-derived risk signals (data asymmetry intensifies)
- (+) [Institutionalization] → health systems build APIs around standardized genomic records (bio-information becoming infrastructural)
- (+) [Temporal dynamics] → variant reinterpretation notices become common consumer events (knowledge about the self stays updateable)
- (–) [Privacy] → lawsuits target secondary use of genomic data (control over sensitive information contested)
- (+) [Daily workflow] → pharmacies and clinicians use pharmacogenomic flags routinely (diagnostic info directly shapes decisions)
- (–) [Equity] → underrepresented groups challenge biased risk predictions (authority depends on representation quality)
- (+) [Portability] → data wallets market selective sharing of genomic findings (individual control becomes operational)

**ART 09.074 — Organs-on-Chips & Bio-Computational Hybrids**

**Score: 1 (Impact in GVN 14)**



**Justification (3–5 sentences):**

These systems mainly affect research and specialist testing, with limited spillover into mainstream information acquisition. The most relevant pathway is faster, richer biomedical evidence and some new machine-readable biological outputs. That is valuable but narrow within the GVN. It keeps the score below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Research evidence] → safety and drug-screening decisions routinely reference chip outputs (specialist information source)
- (+) [Monitoring] → chips stream machine-readable biological state data into lab platforms (new evidence format)
- (+) [Credibility] → regulators publish acceptance criteria for chip-derived results (institutional foothold)
- (–) [Scale] → use stays inside labs rather than public-facing services (broad effect capped)
- (–) [Interpretation] → disagreement between chip models reduces trust in outputs (diffusion limited)

**ART 09.075 — Biological Aging & Longevity Barriers**

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The direct effect is not on information acquisition, but on human capacity, continuity, and attention in information-intensive work. That matters at the margin in aging or expert populations, yet it does not create new source, credibility, or access architectures. The linkage is indirect and limited. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Human capacity] → high-cognition professions track biomarkers after longevity treatments (workforce continuity signal)
- (+) [Access] → older adults retain digital information participation longer (small inclusion effect)
- (–) [Direct linkage] → changes are framed as healthspan, not information systems (pathway remains indirect)
- (+) [Labor structure] → expertise-retention strategies include longevity interventions (niche knowledge continuity)
- (–) [Inequality] → access is elite, limiting broad GVN effects (scale remains small)

**ART 09.076 — Engineered Living Materials**

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The most relevant effect is structures that self-report condition or preserve sensor function, improving visibility of infrastructure and environments. That creates some new local information

channels but mostly as embedded monitoring rather than broad social change. It is a narrow but plausible GVN linkage. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Infrastructure visibility] → self-reporting living materials appear in buildings or water systems (new condition signals)
- (+) [Maintenance] → inspections shift toward embedded indicator monitoring (localized substitution)
- (+) [Credibility] → audit protocols are created for signals from living materials (evidence legitimacy growing)
- (–) [Durability] → variable biological behavior undermines trust in outputs (adoption constrained)
- (–) [Scale] → use remains confined to specialist pilots (broad effect limited)

## ART 09.077 — Gene Drive Pest Control

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Gene drives change ecological control strategies, not how society acquires or verifies information. The closest link is through monitoring programs and public controversy, which is too indirect for a meaningful GVN score. It does not materially alter the operating model of acquiring information. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Environmental information] → gene-drive programs require public real-time spread dashboards (would create niche data services)
- (+) [Credibility] → ecological monitoring standards become machine-readable and transparent (possible information spillover)
- (–) [Public routine] → effects remain in biosurveillance and policy, not general information access (direct linkage absent)
- (–) [Trust] → controversy centers on ecology and governance, not new information architectures (weak GVN fit)

## ART 09.078 — Artificial Wombs & Synthetic Embryos

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

The main linkage is richer, continuous information about developmental processes and associated governance debates, not broad public information acquisition. It may materially affect specialist clinical and research evidence but remains narrow. The GVN impact is domain-specific rather than system-wide. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Clinical evidence] → developmental support systems expose continuous machine-readable state data (specialist information channel)
- (+) [Governance] → dashboards and audit logs become mandatory in regulated trials (institutional evidence path)
- (+) [Research information] → synthetic embryo models shorten developmental research cycles (knowledge supply niche)
- (–) [Public routine] → use remains highly specialized and regulated (broad impact low)
- (–) [Ethics conflict] → governance disputes overshadow practical information applications (diffusion limited)

## 10. Space & Aeronautical Engineering

### ART 10.079 — Satellite Mega-Constellations & Space Internet

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART strongly expands both information access and original-source observation by combining connectivity, positioning, and Earth observation at near-global scale. Second-order, it shifts power toward constellation operators and away from terrestrial bottlenecks. Third-order, it can amplify surveillance, geopolitical interference, and platform dependence even as access widens. For a 5.5M society it plausibly affects everyday information routines across households, logistics, public safety, and remote areas, so 10 fits.

**Weak signals (9):**

- (+) [Access] → remote households, vessels, and field teams adopt satellite terminals at consumer scale (coverage gap closing)
- (+) [Original observations] → agencies integrate constellation imagery and alerting into routine operations (space sensing becomes ordinary)
- (+) [Product integration] → services bundle connectivity with localized Earth-observation products (infrastructure stacking begins)
- (+) [Resilience] → terrestrial outage plans assume satellite fallback by default (continuity expectations changing)
- (–) [Geopolitics/security] → governments issue new rules on foreign dependence, spectrum, and resilience (control conflicts surfacing)
- (+) [Civic intelligence] → OSINT communities rely on cheaper, faster imagery refresh (public-source analysis accelerates)
- (–) [Interference] → jamming and spoofing incidents against civilian links rise (space links become contested)
- (+) [Local economies] → newsrooms and service businesses launch in previously underserved regions (information access reshapes local markets)
- (–) [Market power] → competition scrutiny targets vertically integrated constellation operators (information access centralizing)

## ART 10.080 — Space Resource Utilization (SRU)

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Returning space-mined materials to Earth does not directly change how information is acquired or trusted in society. Any later benefit through cheaper satellites or electronics is too indirect for this GVN. The link is infrastructural and speculative rather than operational. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Indirect infrastructure] → space-mined materials are explicitly earmarked for communication or observation hardware (would create later linkage)
- (+) [Supply chain] → satellite makers treat SRU as a future materials source (early indirect path)
- (–) [Direct relevance] → projects are framed around commodities, not information access (linkage absent)
- (–) [Time horizon] → no current information service depends on SRU output (impact not meaningful)

## ART 10.081 — Closed-Loop Life Support System

**Score: 0 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Closed-loop life support is important for remote habitation but does not directly affect this GVN in a terrestrial 5.5M society. Any spillovers into sensing or monitoring are too indirect and specialized. It does not materially shift access, credibility, or source structure. That keeps it below the threshold for a concrete non-trivial GVN effect, so 0 fits.

**Weak signals (4):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Monitoring techniques] → life-support sensing stacks get reused in remote terrestrial facilities (would create niche linkage)
- (+) [Resilience] → isolated shelters adopt habitat-style information dashboards (possible spillover)
- (–) [Public relevance] → the ART remains tied to habitats, not mainstream information services (direct link absent)
- (–) [Systemic effects] → no broad change occurs in search, media, or source credibility (weak fit)

## ART 10.082 — High-Altitude Platforms & Balloons

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

HAPs can provide rapidly deployable connectivity and persistent regional sensing where terrestrial networks are weak or disrupted. Second-order, they create new control points over regional visibility and communications, with civil-military overlap and privacy tensions. Third-order, they can shift expectations toward temporary but always-available regional observation. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Rapid access] → disaster-response agencies precontract HAP coverage for communications and imaging (deployment time falling)
- (+) [Remote coverage] → underserved regions receive recurring HAP service (regional information access expanding)
- (+) [Public safety] → regional dashboards combine HAP and terrestrial feeds (layered situational awareness emerging)
- (–) [Privacy] → airspace and privacy rules update for persistent stratospheric observation (visibility becoming contested)
- (+) [Continuity] → carriers use HAPs as temporary capacity during outages and major events (resilience function growing)
- (+) [Civic oversight] → environmental groups use HAP imagery in disputes (new accessible evidence source)
- (+) [Processing] → vendors market regional AI processing at altitude (faster local signal triage)
- (–) [Security] → spoofing, takedown, or interference incidents target HAP service areas (regional info layer becomes vulnerable)
- (+) [Policy comparison] → communities compare HAP coverage against terrestrial rollout promises (new benchmark for access)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 — Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Decentralized trust layers can materially improve provenance, tamper resistance, and shared records across actors who do not trust one another, which matters for media, archives, credentials, and data exchange. Second-order, they also create new centers of power in wallet providers, protocols, and tokenized attention markets. Third-order, they can amplify scams and speculative distortions alongside traceability gains. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Credibility/provenance] → media archives and registries anchor records on shared ledgers (tamper resistance becomes routine)
- (+) [Cross-platform trust] → verifiable claims travel between services without one operator (shared truth layer emerging)

- (+) [User control] → wallets become common containers for rights, credentials, or permissions (identity and trust tools diffusing)
- (–) [Fraud] → phishing and provenance scams grow around credential tools (trust layer attracts exploitation)
- (+) [Public institutions] → agencies test tamper-evident records for permits or evidence (official use cases forming)
- (+) [Legal practice] → courts and auditors selectively accept ledger-backed timestamps (evidence norms shifting)
- (+) [Platform interfaces] → consumer services expose “verify on-chain” features (verification becomes user-facing)
- (–) [Governance] → protocol upgrades create visible fights over trust rules (decentralization still political)
- (–) [Infrastructure risk] → bridges and oracles become high-profile points of failure (interoperability becomes vulnerability)

## ART 11.084 — Platform Cooperatives & Fair Work

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Ownership and governance of platforms materially shape what information is surfaced, how local knowledge is monetized, and whether contributors can contest ranking rules. Cooperative models could alter local news, labor, and review ecosystems in selected domains, but likely not across all information flows. The main impact is second-order, through power and rule-setting rather than new technical information channels. That fits the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Source diversity] → local marketplaces launch member-governed rating and information rules (ranking becomes contestable)
- (+) [Media access] → journalists, creators, or workers form cooperatively owned distribution platforms (intermediary power redistributed)
- (+) [Transparency] → payout and ranking logic becomes inspectable in member dashboards (information governance made legible)
- (+) [Institutional support] → cities, unions, or foundations fund cooperative alternatives (new governance models entering practice)
- (–) [Scale] → financing bottlenecks stall growth despite local adoption (institutional model struggles to scale)
- (+) [Dispute resolution] → appeals shift from opaque platform tickets to member forums (rule legitimacy increases)
- (+) [Retention] → contributor retention improves when users own part of the platform (incentive alignment visible)
- (–) [Competitive response] → incumbents copy transparency features without ownership shifts (co-op pressure affects mainstream models)
- (+) [Regulation] → policymakers treat co-op data governance as a distinct platform model (institutional recognition emerging)

## ART 11.085 — Open Data Sharing Marketplaces

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART directly broadens access to fragmented data and reduces dependence on bespoke bilateral relationships, which is central to the challenger regime for this GVN. Second-order, it creates new data intermediaries, pricing power over scarce datasets, and sharper conflicts over consent and unequal access. Third-order, it can both enrich local information services and deepen information inequality when premium data dominates. Because many public and private information services could be restructured around these exchanges, 10 fits.

**Weak signals (9):**

- (+) [Access] → sectors publish machine-readable data listings with quality scores and usage terms (data discoverability becoming systematic)
- (+) [Privacy] → compute-to-data becomes standard in regulated data exchanges (sharing without copying normalizing)
- (+) [Smaller actors] → smaller organizations buy datasets previously available only through privileged partnerships (access barrier dropping)
- (+) [Procurement] → public tenders require marketplace-compatible schemas (institutional adoption formalizing)
- (–) [Ownership conflict] → disputes over withdrawal, provenance, and resale become common (data becomes a contested asset)
- (–) [Inequality] → premium data bundles create visible performance gaps between services (access stratification emerging)
- (–) [Re-identification risk] → privacy advocates track misuse of exchanged derivatives (safety friction rising)
- (+) [Insurance/finance] → risk models begin using data provenance scores from marketplaces (trust becomes monetized)
- (+) [Accreditation] → industry bodies certify data sellers and brokers (market infrastructure maturing)

## ART 11.086 — Secure & Resilient Social Platforms

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Peer-to-peer and resilient social platforms sit directly inside the challenger regime for this GVN because they change how observations are shared, compared, and trusted outside established intermediaries. Second-order, they redistribute power around moderation, identity, and governance. Third-order, they can amplify both civic coordination and misinformation resilience or contestation at very large scale. Because social platforms structure everyday information exposure for broad populations, 10 fits.

**Weak signals (9):**

- (+) [Source plurality] → communities and public-interest groups migrate to federated or resilient platforms (channel diversification accelerating)



- (+) [Portability] → users increasingly move contacts and archives between compatible services (social lock-in weakening)
- (+) [Institutional use] → public bodies open official nodes on interoperable networks (legitimacy moving beyond incumbents)
- (+) [Resilience] → censorship or outage events trigger visible migration waves (continuity value becoming salient)
- (+) [Governance] → moderation logs and policy changes become inspectable by default (rules becoming legible)
- (–) [Abuse] → harmful networks exploit federation gaps and mirrored routes (resilience helps both good and bad actors)
- (+) [Public-interest investment] → grants fund resilient civic communication infrastructures (institutional support growing)
- (–) [Commercial tension] → app stores, ISPs, or regulators contest decentralization and security choices (infrastructure politics intensifying)
- (+) [Creator economics] → advertisers and creators test monetization outside dominant platforms (attention markets decentralizing)

## ART 11.087 — Collective Open Innovation Networks

**Score: 3 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Open innovation networks expand the production and sharing of problem-specific knowledge across organizational boundaries. That matters for the supply of reliable information and faster validation of claims, but it is more about knowledge creation than everyday information acquisition. The strongest effects are around coordination and evidence reuse. That is material and plausibly in the €10–100M or 5–50M person-hour band, so 3 fits.

### **Weak signals (9):**

- (+) [Knowledge production] → agencies and firms run recurring challenge platforms with evidence trails (distributed problem-solving scaling)
- (+) [Access] → open problem marketplaces attract cross-sector contributors (expertise discovery improving)
- (+) [Reuse] → failed approaches are preserved as searchable assets (negative knowledge stops disappearing)
- (–) [IP conflict] → provenance logs replace informal claims in ownership disputes (collaboration needs traceability)
- (+) [Public procurement] → challenge participation becomes part of innovation funding criteria (institutional support visible)
- (+) [Reputation] → contributors build portable records from verified solution history (merit signals becoming datafied)
- (+) [Automation] → AI agents join human contributors in challenge platforms (knowledge production becomes hybrid)
- (+) [Validation markets] → services arise around benchmark, test, and replication support (evidence quality industrializing)
- (+) [Inclusion] → smaller actors gain visibility through portable contribution records (access to innovation networks widens)

## ART 11.088 — Scalable Decentralized Governance

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Governance systems shape who sets platform rules, moderation boundaries, and shared data rights, so their GVN relevance is real. The biggest effects are second-order, around institutional coordination and legitimacy, rather than first-order consumer information flows. They can reduce coordination costs while also opening new manipulation and accountability risks. That is material and fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Rule legitimacy] → online communities adopt software-mediated rule changes and voting (governance becomes machine-readable)
- (+) [Public-interest platforms] → moderation or funding decisions use delegated voting systems (collective rule-setting scales)
- (+) [Auditability] → bylaws, treasury moves, and rule changes become user-facing logs (governance visibility increases)
- (–) [Manipulation] → vote-buying, fake identities, or bloc capture drive redesigns (decentralization remains vulnerable)
- (+) [Regulation] → authorities examine whether automated governance meets accountability standards (institutional scrutiny growing)
- (+) [Participation] → rule changes become visible user-facing events rather than opaque admin actions (users see governance directly)
- (+) [Co-op/union spillover] → labor and community groups adopt decentralized governance for data and payout rules (model diffusing)
- (–) [Inequality] → participation asymmetry drives delegation and sampling reforms (scalability depends on design changes)
- (+) [Insurance/audit] → governance quality becomes part of platform risk assessment (rules affect trust economics)

## ART 11.089 — Digital Learning Networks and Skill Credentialing

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Better digital learning and portable skill credentials materially improve the public's ability to interpret information, judge expertise, and access niche sources. Second-order, they shift authority from traditional institutions toward platform-based credential and tutoring systems. Third-order, they can reduce or amplify inequality depending on quality and access. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Information literacy] → AI tutors for media literacy, data interpretation, and civic skills enter mainstream use (interpretive capacity scales)
- (+) [Authority] → employers and agencies accept wallet-based skill credentials (credential power shifting)

- (+) [Transparency] → professional bodies publish machine-readable skill rubrics (competence becomes inspectable)
- (–) [Fraud] → impersonation and credential gaming trigger stronger identity and proctoring rules (trust remains contested)
- (+) [Local expertise] → communities use portable credentials to validate peer experts (authority becomes more distributed)
- (+) [Public institutions] → libraries and schools adopt portable credential systems (learning networks become civic infrastructure)
- (+) [Ranking systems] → platforms incorporate verified skills rather than pedigree alone (expertise signals diversify)
- (–) [Platform power] → backlash grows against opaque private credential monopolies (new gatekeepers emerge)
- (+) [Workflow integration] → learning modules tie directly to evidence tasks and real-world practice (knowledge becomes operational)

## ART 11.090 — Prediction-Market Forecasting Platforms

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Prediction markets generate structured, continuously updated probabilistic information that can materially improve decisions under uncertainty. Second-order, they shift authority toward calibrated performance and away from rhetoric, while also raising manipulation, settlement, and incentive questions. Third-order, organizations can learn from repeated forecasting loops. That plausibly reaches the significant anchor, so 5 fits.

### **Weak signals (9):**

- (+) [Forecast quality] → organizations run internal prediction markets on policy or operational questions (probabilistic intelligence institutionalizing)
- (+) [Media integration] → news outlets publish market probabilities alongside reporting (narrative meets quantified belief)
- (+) [Governance] → regulators clarify what counts as forecasting rather than gambling (legal footing forming)
- (+) [Expert reputation] → accuracy leaderboards affect analyst status and demand (calibration gains social weight)
- (–) [Manipulation] → insiders or coordinated actors target settlement events (incentivized information can be gamed)
- (+) [Public planning] → agencies use markets as one input to preparedness decisions (decision workflows changing)
- (+) [API embedding] → live probabilities feed planning software directly (forecasting becomes infrastructural)
- (+) [Local use] → civic groups create markets on local issues and timelines (collective intelligence localizing)
- (–) [Trust conflict] → users compare media narratives against market odds and escalate disputes (new legitimacy contest emerges)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 — Universal IoT Interoperability Standards

**Score: 10 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Interoperability is a practical bottleneck for turning many sensors into a usable information environment, so this ART directly enables the challenger regime's vision of comparable, localized, multi-source observation. Second-order, it lowers custom integration costs for smaller actors while concentrating influence in standard-setters and certifiers. Third-order, it can scale both civic sensing and pervasive surveillance very quickly. Because it changes how sensor-derived information becomes accessible and combinable at population scale, 10 fits.

**Weak signals (9):**

- (+) [Access] → public tenders require open IoT schemas and certification (interoperability becomes a procurement norm)
- (+) [Legibility] → devices auto-publish capabilities into shared dashboards (sensor behavior becomes machine-readable)
- (+) [Market entry] → smaller vendors plug into major platforms without custom gateways (barriers drop for new sources)
- (–) [Governance] → regulators start treating non-interoperable devices as a policy problem (fragmentation becomes unacceptable)
- (+) [Tool ecosystem] → open-source sensor fusion tools flourish across mixed fleets (combining data gets easier)
- (+) [User behavior] → device migration and combined local views become noticeably easier (cross-device context improves)
- (–) [Security] → incidents trace back to poor standard conformance (baseline rules become critical trust layer)
- (+) [Insurance] → interoperable and auditable deployments receive better risk treatment (standardization gets priced)
- (+) [Civic sensing] → mixed low-cost device networks scale without bespoke integration (grassroots observability expands)

### ART 12.092 — Interoperable Digital Twin Ecosystems

**Score: 3 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Portable shared twins improve remote inspection, diagnosis, and coordination around physical assets, which feeds more reliable operational information into the GVN. The biggest effects are institutional—less vendor lock-in and better cross-organization data flow—rather than direct changes in public information behavior. It is material mainly as a coordination and observability infrastructure. That is material and fits the €10–100M or 5–50M person-hour band, so 3 fits.

**Weak signals (9):**

- (+) [Coordination] → asset owners require twin portability in procurement (lock-in starts to weaken)
- (+) [Information reuse] → maintenance and public-works data move between tools without rebuilds (shared understanding improving)
- (+) [Preparedness] → incident exercises rely on shared twin packages across vendors (remote planning gets easier)
- (–) [Liability] → disputes cite twin provenance and update histories (model state becomes evidentiary)
- (+) [Access] → smaller operators buy services built on portable twins rather than one vendor stack (benefits diffuse)
- (+) [Governance] → regulators ask for uncertainty and provenance fields inside twins (quality norms hardening)
- (+) [Labor] → worker roles shift toward remote twin supervision and intervention rehearsal (interpretive work changes)
- (+) [Standards] → open twin schemas gain certification programs (ecosystem formalizing)
- (–) [Security] → attackers target twin synchronization and model tampering (virtual state becomes a trust surface)

## ART 12.093 — Global Supply Chain Traceability Networks

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Traceability networks directly improve the reliability of product-related information by making provenance, composition, handling, and compliance more visible. Second-order, they change bargaining power between large buyers and smaller suppliers while raising selective-disclosure and surveillance concerns. Third-order, they can normalize machine-readable provenance as a baseline expectation. That plausibly reaches the significant anchor, so 5 fits.

### **Weak signals (9):**

- (+) [Credibility] → consumer apps and procurement systems routinely scan portable product histories (provenance becomes everyday evidence)
- (+) [Institutionalization] → customs and regulators require interoperable traceability records (network becomes compliance infrastructure)
- (+) [Quality response] → recalls and fraud cases are resolved faster through shared custody data (root-cause analysis accelerates)
- (–) [Power] → smaller suppliers are pressured to adopt expensive tagging and disclosure systems (informational burden can concentrate)
- (+) [Market behavior] → premium products market verified origin and handling in real time (trust becomes monetized)
- (–) [Selective disclosure] → disputes rise over what can remain hidden in shared chains (commercial secrecy clashes with transparency)
- (+) [Investigative use] → journalists and NGOs mine traceability networks for investigations (public oversight capability expands)
- (+) [Counterfeit control] → verification shifts from lab checks to network verification (authenticity becomes network-native)
- (+) [Finance/insurance] → supply risk pricing uses traceability completeness (information quality affects capital access)

## ART 12.094 — Personal Data Portability & Trust Frameworks

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART materially shifts information power from platforms toward individuals by making permissioned reuse, comparison, and movement of personal data easier. Second-order, it creates new wallet intermediaries and consent markets while exposing users to manipulation through sharing interfaces. Third-order, it can both strengthen competition and intensify surveillance if poorly governed. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [User control] → major services accept standardized data import/export and consent receipts (portability becoming operational)
- (+) [Access] → personal data wallets become default on devices or browsers (control layer moving to users)
- (+) [Competition] → people move histories between health, finance, search, or learning services routinely (lock-in weakening)
- (–) [Manipulation] → regulators audit dark patterns in consent dashboards (sharing control becomes contested)
- (+) [Workflow change] → support cases increasingly concern revocation and sharing scopes (user control becoming normal work)
- (+) [Service creation] → startups build comparison tools around user-carried data (new information services emerging)
- (–) [Platform resistance] → platforms degrade imported data quality or experience (portability triggers strategic pushback)
- (–) [Security] → breach reports emphasize wallet or consent-token theft (new attack surfaces emerging)
- (+) [Advocacy] → public scorecards rate services on portability quality (rights become comparable)

## ART 12.095 — Interoperable Digital Currency Payment Networks

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

Payment interoperability affects transaction data and access to paid information services, but it does not directly transform how reliable information is acquired. The main linkage is smoother monetization and cross-border coordination. This remains a supporting economic layer rather than a core GVN change. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Access] → cross-platform micropayments make niche information services easier to buy (revenue friction falling)
- (+) [Coordination] → civic alert or data services settle small payments across systems instantly (supporting ecosystem effect)

- (–) [Direct relevance] → most changes concern settlement, not source credibility or sensing (linkage narrow)
- (+) [Platform power] → wallet operators start influencing access terms for information apps (small governance spillover)
- (–) [User behavior] → information discovery patterns stay largely unchanged despite payment upgrades (impact capped)

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

**Score: 5 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

This ART makes official rules and administrative logic directly queryable, testable, and comparable, reducing dependence on slow human interpretation of bureaucratic sources. Second-order, it creates more transparent but also more rigid rule mediation and shifts power toward compliance software providers. Third-order, it can normalize continuous rule-checking in ordinary decisions. That plausibly reaches the significant anchor, so 5 fits.

### **Weak signals (9):**

- (+) [Certified information] → regulators publish official APIs or test suites alongside legal text (authoritative rules become machine-consumable)
- (+) [Administrative access] → businesses and public services auto-check forms or transactions against coded rules (interpretation cost falling)
- (+) [Citizen usefulness] → assistants explain eligibility and obligations from official rule packages (bureaucratic knowledge becoming accessible)
- (–) [Legal ambiguity] → disputes emerge when coded rules diverge from legal intent (machine interpretation challenged)
- (+) [Change visibility] → version-change alerts become routine public events (rule updates become trackable)
- (+) [Smaller actors] → smaller firms gain cheaper access to compliance-grade interpretation (expertise bottleneck easing)
- (+) [Publishing shift] → legal publishers pivot from commentary to executable rulesets (information products changing)
- (+) [Appeals/evidence] → execution logs of rule decisions appear in appeals (administrative accountability deepening)
- (–) [Power] → a few vendors dominate rule runtimes and policy profiles (certified interpretation can centralize)

## ART 12.097 — Open Metaverse Interoperability Protocols

**Score: 1 (Impact in GVN 14)**

### **Justification (3–5 sentences):**

Interoperable virtual worlds could create new channels for information exchange, presence, and learning, but their relevance to this GVN remains contingent and secondary. The main effects would be on interface and platform structure rather than core source credibility or sensing. Adoption may matter in some domains, but not enough to shift the GVN broadly. That keeps it below the material anchor but above zero, so 1 fits.



**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Access] → training, civic, or information services become portable across virtual spaces (niche participation gain)
- (+) [Platform power] → users carry identity and reputation between immersive environments (intermediary control shifts)
- (–) [Mainstream relevance] → most public information activity remains outside immersive worlds (impact bounded)
- (+) [Learning] → educational and collaborative environments rely on interoperable assets and identities (sector-specific adoption)
- (–) [Governance] → moderation and provenance rules stay fragmented despite portability (trust effects limited)

**ART 12.098 — Content Authenticity Infrastructure**

**Score: 20 (Impact in GVN 14)**

**Justification (3–5 sentences):**

In a world of abundant synthetic and manipulable media, provenance becomes a linchpin for reliable information acquisition, and this ART directly targets source lineage, edit history, and attribution. Second-order, it redistributes power toward capture-device vendors, verification intermediaries, and platforms that decide when credentials matter. Third-order, it can either restore trust or exclude uncertified grassroots evidence if badly governed. Because credibility is central to this GVN's goal, a broadly deployed authenticity layer is a necessary part of the most important transformative shift, so 20 fits.

**Weak signals (9):**

- (+) [Credibility] → cameras, editing tools, and generative systems ship with default content credentials (provenance becoming native)
- (+) [Ranking power] → major platforms privilege or label credentialed media in feeds (authenticity affects visibility)
- (+) [Institutional use] → public agencies and courts require provenance chains for sensitive evidence (credentialed media becomes official)
- (+) [Media practice] → newsrooms build verification desks around authenticity metadata (workflow shift from ad hoc checks)
- (+) [Grassroots access] → creators demand low-cost ways to sign content without revealing identity (authenticity broadens beyond elites)
- (–) [Security] → credential stripping and counterfeit provenance services appear (trust layer becomes a new battleground)
- (+) [User interface] → browsers and phones expose provenance summaries as normal UI (public interpretation changes)
- (+) [Contracts] → legal, insurance, and procurement rules reference authenticity infrastructure (credibility becomes contractual)
- (–) [Geopolitics] → disinformation campaigns explicitly target provenance trust chains (authenticity becomes strategic terrain)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

**Score: 5 (Impact in GVN 14)**

**Justification (3–5 sentences):**

These protocols materially expand the set of actors who can jointly generate useful information from fragmented data without central pooling. Second-order, they create new neutral computation intermediaries and governance rules over acceptable queries. Third-order, they can make previously blocked cross-sector intelligence routine. That plausibly reaches the significant anchor, so 5 fits.

**Weak signals (9):**

- (+) [Cross-organizational insight] → competitors or agencies run joint analytics without sharing raw records (new collaboration regime forming)
- (+) [Regulated sectors] → health and public-sector consortia procure MPC-style collaboration layers (blocked data uses opening up)
- (+) [Workflow change] → analysts submit queries to neutral compute enclaves instead of requesting copies (access model shifting)
- (–) [Governance] → disputes move from data-access denial to output-permission rules (policy shifts to query control)
- (+) [Inclusion] → smaller actors join collaborations previously open only to trusted giants (access barrier easing)
- (+) [Regulatory guidance] → formal rules appear for auditable privacy-preserving computation (institutional acceptance growing)
- (–) [Trust challenge] → watchdogs question whether outputs are truly non-reidentifying (safety claims being tested)
- (+) [Vendor ecosystem] → safe-query templates and audit tooling become standard products (market layer maturing)
- (+) [Cross-border use] → international collaborations choose privacy-preserving protocols over transfers (jurisdiction friction easing)

## ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

**Score: 1 (Impact in GVN 14)**

**Justification (3–5 sentences):**

This ART mainly affects the quality and comparability of manufacturing technologies, not information acquisition directly. The relevant spillover is better trust in sensor and device performance claims and faster qualification of information hardware. Its effect is upstream, through procurement and reliability rather than everyday information behavior. That keeps it below the material anchor but above zero, so 1 fits.

**Weak signals (5):**

Signal density: LOW (linkage weak; additional signals would be speculative).

- (+) [Credibility] → sensor and communication hardware claims rely on machine-readable conformance certificates (evidence quality improving)

- (+) [Access] → smaller buyers adopt new information devices faster because certification is standardized (qualification friction falling)
- (+) [Governance] → insurers and regulators accept standardized test suites for information hardware (institutional trust support)
- (–) [Public routine] → benefits remain upstream in procurement, not user behavior (direct effect limited)
- (–) [Scope] → certification focuses on manufacturing process, not information integrity itself (GVN linkage narrow)

## GVN 15: Proficiency and its Proof ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART expands reliable access to online learning, remote practice, rich simulations, and portable assessment beyond specific campuses or urban centers; the strongest pathway is richer remote learning and assessment for rural, mobile, and adult learners rather than basic email-level inclusion. Around the GVN, it weakens location-based institutional advantage and makes employer-recognized remote proof more plausible. In feedback-loop terms, once remote study, work trials, and assessments become routine, more providers can compete on pedagogy and skill proof rather than campus presence. The main downsides are infrastructure dependence, platform concentration, and new forms of exclusion for learners lacking premium devices or service quality. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Flexibility and accessibility] → public procurement bundles ubiquitous connectivity with national learning platforms (access barrier falls)
- (+) [Location-based limitations] → remote schools and apprenticeship sites stop maintaining offline-only teaching schedules (place constraint weakens)
- (+) [Recognizability of proficiency] → employers accept remotely supervised skills tests from rural and mobile learners (proof travels farther)
- (+) [Private sector and on-the-job learning] → firms open live remote observation of workplace tasks for trainees (work-based learning scales)
- (+) [Modernization and relevance] → course providers shift from low-bandwidth video to interactive simulation and labs (richer pedagogy normalizes)

- (+) [Learning to learn] → adult learners study during commuting and distributed work intervals (learning time expands)
- (-) [Equality in access] → high-value credential pathways begin to require premium terminals or service tiers (device gap widens)
- (-) [Institutional resistance] → universities keep physical-attendance rules after network reliability improves (campus gatekeeping persists)
- (-) [Quality assurance and trust] → credential disputes are traced to outages, latency spikes, or routing failures (infrastructure trust matters)

## ART 01.002 - Ultra-Low Latency Networks

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART enables remote labs, haptic supervision, collaborative XR practice, and other skill-building tasks that fail when network delay is noticeable; its main relevance is for remote practical training where milliseconds matter: telesupervision, haptics, shared simulation, and live equipment use. Around the GVN, that weakens the need to co-locate expertise, expensive equipment, and trainees for some high-value procedural learning. In feedback-loop terms, if latency-sensitive remote practice becomes credible, more sectors can mix scarce expert oversight with distributed competence-based assessment. The main downsides are expensive infrastructure, unequal availability, and overconfidence that remote simulation fully substitutes for local practice. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

### **Weak signals (6):**

- (+) [Procedural and systemic skills] → remote labs and telesupervision are used for tasks previously reserved for on-site training (distance barrier falls)
- (+) [Contextuality] → haptic or multi-user XR drills become normal in apprenticeship and clinical rehearsal (richer remote practice appears)
- (+) [Recognizability of proficiency] → employers accept low-latency remote performance logs for selected practical roles (proof travels with less lag)
- (+) [Private sector and on-the-job learning] → scarce experts supervise many distributed learners in real time (mentoring scales outward)
- (-) [Equality in access] → premium low-latency zones become a new quality divider between providers (infrastructure stratifies)
- (-) [Quality assurance] → sectors dispute whether remote low-latency practice counts as equivalent to local hands-on time (transfer validity is contested)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.003 - Edge AI for Sensor Data

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART turns real-world practice into machine-readable evidence through instrumented tools, spaces, and workflows; the most important use is immediate feedback on tool handling, workflow execution, and anomaly response in real settings. Around the GVN, that supports competence-based qualifications and on-the-job learning, but also shifts power toward whoever owns the sensors, models, and performance logs. In feedback-loop terms, if employers start trusting observed performance traces, portfolios and live task data can displace some classroom-only credentials. The largest risk is normalization of continuous surveillance, especially for trainees with less bargaining power. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Procedural and systemic skills] → tools or workspaces start issuing task-performance summaries automatically (practice becomes measurable)
- (+) [Private sector and on-the-job learning] → apprenticeships use equipment logs in progression decisions (work evidence grows)
- (+) [Recognizability of proficiency] → employers request machine-captured task traces for selected roles (proof moves beyond paper)
- (+) [Contextuality] → assessment shifts from classroom-only tasks to real environment performance snapshots (situated proof appears)
- (-) [Quality assurance] → disputes arise over sensor calibration or model interpretation in skill scoring (measurement trust matters)
- (-) [Equality in access] → high-quality instrumented learning environments cluster in large firms and elite institutions (evidence quality stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 01.004 - Quantum & High-Precision Sensing**

**Score: 1 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART primarily creates new specialist domains that require updated curricula, licenses, and professional standards. Around the GVN, the GVN effect comes through niche credential markets and the need to prove competence in new technical tasks, not through mass learning-system redesign. In feedback-loop terms, spillovers rise only if the technology becomes a widely deployed platform that many occupations must understand or supervise. Fragmented vendor certificates and unequal access to expensive training are the main negatives. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new specialist platforms practitioners (new skill market forms)

- (+) [Recognizability of proficiency] → employers mention new specialist platforms experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART turns real-world practice into machine-readable evidence through instrumented tools, spaces, and workflows. Around the GVN, that supports competence-based qualifications and on-the-job learning, but also shifts power toward whoever owns the sensors, models, and performance logs. In feedback-loop terms, if employers start trusting observed performance traces, portfolios and live task data can displace some classroom-only credentials. The largest risk is normalization of continuous surveillance, especially for trainees with less bargaining power. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for micro/nano sensor networks practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention micro/nano sensor networks experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART makes continuous observation of practice and workplace learning more acceptable by keeping raw personal data local or heavily minimized; here the breakthrough is legitimacy: continuous competence evidence becomes thinkable without demanding raw video, audio, or biometric centralization. Around the GVN, that directly addresses one of the biggest blockers to competence-based proof outside formal exams: trust from workers, unions, regulators, and learners. In feedback-loop terms, if accepted, continuous skill evidence can spread from pilots into hiring, certification renewal, and apprenticeships, accelerating the shift away from title-only proof. Risks remain around opaque scoring, false reassurance about privacy, and unequal access to higher-trust implementations. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Procedural and systemic skills] → unions or works councils approve privacy-preserving skill capture pilots (continuous evidence becomes acceptable)
- (+) [Recognizability of proficiency] → employers accept device-generated task evidence without storing raw video/audio (proof without raw surveillance)
- (+) [Private sector and on-the-job learning] → apprenticeship programs use on-device assessment logs for progression decisions (workplace learning formalizes)
- (+) [Regulatory barriers] → sector regulators publish conditions for privacy-safe continuous assessment (compliance pathway opens)
- (+) [Contextuality] → portfolios start including in-situ performance summaries from real work settings (skill proof becomes contextual)
- (-) [Quality assurance] → legal challenges target false or biased summaries produced by privacy-preserving monitors (validity gets tested)
- (-) [Equality in access] → privacy-safe implementations appear only in large employers and elite providers (trust becomes unequal)
- (-) [Authority of educational institutions] → schools reject workplace evidence they cannot audit in raw form (institutional trust mismatch)
- (-) [Security and dual-use] → tampering or spoofing incidents hit device-side assessment logs (integrity remains fragile)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mainly improves the integrity and longevity of credentials, exams, and remote collaboration rather than the pedagogy itself. Around the GVN, its institutional effect is to reduce backend security objections to digital proof systems, especially for high-stakes records held over



decades. In feedback-loop terms, this only meaningfully changes the GVN if learning and credentialing ecosystems become more networked and long-lived. The main risk is expensive compliance and vendor lock-in without corresponding gains in perceived legitimacy. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for secure credential infrastructure practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention secure credential infrastructure experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 01.008 - Integrated Sensing and Communication (ISAC)**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART turns real-world practice into machine-readable evidence through instrumented tools, spaces, and workflows. Around the GVN, that supports competence-based qualifications and on-the-job learning, but also shifts power toward whoever owns the sensors, models, and performance logs. In feedback-loop terms, if employers start trusting observed performance traces, portfolios and live task data can displace some classroom-only credentials. The largest risk is normalization of continuous surveillance, especially for trainees with less bargaining power. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for integrated sensing and communication (isac) practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention integrated sensing and communication (isac) experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)

- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART makes always-on tutoring, feedback, translation, and assistive learning tools cheaper to run locally on personal devices and work equipment. Around the GVN, that lowers dependence on central platforms and can widen access to privacy-preserving personalized support. In feedback-loop terms, if low-cost local AI becomes standard, personalized learning can move from elite services into everyday schooling and adult reskilling. The downside is fragmentation across vendors and a tendency to over-automate feedback without equivalent investment in pedagogy. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Flexibility and accessibility] → low-cost devices ship with capable offline tutoring and translation features (support becomes portable)
- (+) [Learning to learn] → learners keep persistent local study assistants across platforms and jobs (continuity improves)
- (+) [Private sector and on-the-job learning] → wearable or device-based coaching is deployed in routine workplace training (embedded support scales)
- (+) [Privacy] → institutions market on-device learning support as a trust feature (local processing becomes valued)
- (-) [Market structure] → proprietary chip-software stacks determine which learning tools work well (vendor dependence rises)
- (-) [Quality assurance] → low-power shortcuts produce uneven coaching quality across devices (support consistency fragments)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly matters through cheaper compute for AI, simulation, and rich digital content rather than through any learning-specific mechanism. Around the GVN, its main institutional effect would be to lower costs for platforms that deliver tutoring, assessment, or credential services. In feedback-loop terms, unless those downstream systems change hiring and accreditation practices, the GVN impact stays indirect. The main downside is concentration of capability in firms controlling specialized hardware stacks. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced compute stacks practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced compute stacks experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART primarily creates new specialist domains that require updated curricula, licenses, and professional standards. Around the GVN, the GVN effect comes through niche credential markets and the need to prove competence in new technical tasks, not through mass learning-system redesign. In feedback-loop terms, spillovers rise only if the technology becomes a widely deployed platform that many occupations must understand or supervise. Fragmented vendor certificates and unequal access to expensive training are the main negatives. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new specialist platforms practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new specialist platforms experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 02.012 - Photonic and Optical Computing****Score: 1 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART mostly matters through cheaper compute for AI, simulation, and rich digital content rather than through any learning-specific mechanism. Around the GVN, its main institutional effect would be to lower costs for platforms that deliver tutoring, assessment, or credential services. In feedback-loop terms, unless those downstream systems change hiring and accreditation practices, the GVN impact stays indirect. The main downside is concentration of capability in firms controlling specialized hardware stacks. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced compute stacks practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced compute stacks experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)

- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly matters through cheaper compute for AI, simulation, and rich digital content rather than through any learning-specific mechanism. Around the GVN, its main institutional effect would be to lower costs for platforms that deliver tutoring, assessment, or credential services. In feedback-loop terms, unless those downstream systems change hiring and accreditation practices, the GVN impact stays indirect. The main downside is concentration of capability in firms controlling specialized hardware stacks. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced compute stacks practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced compute stacks experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score: 0 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

**Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for molecular computing roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on molecular computing use (training base widens)
- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to molecular computing (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)

Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

**Score: 10 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART strengthens the GVN's “understanding of meanings” and big-picture reasoning by letting tutors and decision tools explain mechanisms, counterfactuals, and system interactions; that is unusually well aligned with this GVN because “understanding meanings” and seeing larger interactions are explicit target values. Around the GVN, that shifts value away from memorized answers and toward demonstrable intervention reasoning in schools, workplaces, and professional assessment. In feedback-loop terms, as employers reward causal understanding, curricula and credentialing can move toward simulations, scenario tests, and explainable problem-solving. The main negative is persuasive but incorrect causal guidance being treated as authoritative. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

**Weak signals (10):**

- (+) [Understanding of meanings] → assessment rubrics start requiring causal explanations, not only correct outputs (reasoning becomes visible)
- (+) [Procedural and systemic skills] → simulator vendors add intervention-and-outcome trace reports (system thinking gets measured)
- (+) [Learning to learn] → AI tutors routinely generate what-if paths after learner errors (feedback deepens)
- (+) [Contextuality] → employers request scenario-reasoning logs alongside grades or certificates (proof shifts from recall)

- (+) [Modernization and relevance] → curricula are rewritten around system maps and counterfactual drills (content logic changes)
- (+) [Recognition of diverse proficiencies] → portfolios include causal analyses from work, civic, and hobby contexts (informal reasoning counts)
- (-) [Quality assurance] → disputes emerge over confident but wrong causal tutoring advice (false explanation harms trust)
- (-) [Overemphasis on technology] → students optimize for explaining to AI rubrics rather than real stakeholders (proxy gaming appears)
- (-) [Authority of educational institutions] → faculty bodies cap automated causal scoring in high-stakes exams (acceptance bottleneck persists)
- (-) [Equality in access] → top-tier causal tutors remain far better in premium subscriptions (reasoning support stratifies)

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 5 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART lets personalized learning and assessment models improve across many institutions without centralizing raw learner or worker data; its biggest value is making shared improvement and benchmarking politically acceptable across schools, employers, and public systems. Around the GVN, that reduces a major governance barrier to nationwide skill analytics, portability, and shared quality improvement. In feedback-loop terms, if sector bodies trust the setup, better models feed broader adoption, which in turn improves model quality and makes alternative pathways more legible. The main downsides are coordination overhead and the risk that only large institutions can afford compliant participation. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

### **Weak signals (9):**

- (+) [Flexibility and accessibility] → municipal schools, employers, and universities join shared learning-model federations (cross-site improvement begins)
- (+) [Recognizability of proficiency] → sector bodies accept federated benchmarking for competency frameworks (shared evidence becomes credible)
- (+) [Private sector and on-the-job learning] → firms participate in shared skill-model updates without exporting raw worker traces (workplace data becomes usable)
- (+) [Regulatory barriers] → privacy authorities approve federated learner analytics in sensitive domains (compliance friction drops)
- (+) [Learning to learn] → personal study models follow users across devices while staying local (lifelong profile stabilizes)
- (-) [Equality in access] → smaller providers cannot afford participation in federated infrastructure (quality gap widens)



- (-) [Quality assurance] → model drift or site bias is documented across federated partners (trust depends on governance)
- (-) [Market structure] → a few orchestration providers dominate federation governance and metrics (new gatekeepers emerge)
- (+) [Authority of educational institutions] → cross-institution learner-model agreements replace one-off data-sharing contracts (coordination cost falls)

## ART 03.017 - Trustworthy AI Systems

**Score: 10 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART makes AI tutoring, scoring, recommendation, and credential decisions auditable enough for high-stakes use; for this GVN, trust is not a side issue: without it, AI-based proof and AI-mediated teaching remain stuck at the margins. Around the GVN, that is pivotal for whether regulators, employers, and public institutions accept AI-mediated proof of proficiency at all. In feedback-loop terms, once trusted systems enter accreditation, hiring, and licensure, they can rapidly scale alternative assessment and continuous verification. The biggest risks are false confidence, biased governance choices baked into “trustworthy” pipelines, and expensive compliance that advantages incumbents. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

### **Weak signals (10):**

- (+) [Authorized evaluation of formal learning] → public exam bodies certify AI-assisted scoring under explicit audit rules (high-stakes adoption begins)
- (+) [Recognizability of proficiency] → employers publish hiring policies that accept auditable AI-mediated skill assessments (labor market trust grows)
- (+) [Resistance to change] → teacher and professional bodies shift from outright bans to bounded-use frameworks (institutional resistance softens)
- (+) [Quality assurance] → routine third-party bias and robustness audits become a procurement requirement (trust becomes operationalized)
- (+) [Modernization and relevance] → curriculum updates accelerate because AI-generated materials pass formal review faster (content lag shrinks)
- (+) [Learning to learn] → learners receive confidence-calibrated study guidance with appealable explanations (support becomes contestable)
- (-) [Fairness and accountability] → lawsuits target biased automated credential or placement decisions (legitimacy gets stress-tested)
- (-) [Market structure] → only large vendors can afford full assurance pipelines (trust layer centralizes)
- (-) [Security and dual-use] → prompt-injection or red-teaming failures lead to credential revocations (integrity incidents shape adoption)

- (-) [Authority of educational institutions] → institutions keep human-only review for prestige pathways (dual-track legitimacy emerges)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score: 5 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART dramatically lowers the cost of building domain-specific tutors, simulators, and skill-assessment systems; the main leverage is rapid creation of sector-specific tutors, simulators, and competency tests by organizations that cannot afford bespoke ML teams. Around the GVN, that helps smaller providers, employers, and sector bodies update content faster and create competence-based pathways outside major institutions. In feedback-loop terms, faster tool creation can produce a dense market of micro-credentials and contextual assessments, which then pulls more learning into modular formats. Poorly specified objectives can industrialize low-quality or biased assessments at scale. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

### **Weak signals (9):**

- (+) [Modernization and relevance] → niche fields begin shipping updated tutor and simulator modules within weeks, not years (content refresh accelerates)
- (+) [Private sector and on-the-job learning] → employers generate task-specific training copilots for local workflows (workplace learning customizes)
- (+) [Recognition of diverse proficiencies] → small providers launch credible skill tests for nontraditional pathways (entry barriers drop)
- (+) [Learning to learn] → adult learners assemble personalized stacks of micro-tools across careers (learning becomes modular)
- (+) [Contextuality] → assessments are generated around local tools and real tasks rather than generic exams (proof becomes situated)
- (-) [Quality assurance] → many weakly validated skill tests flood the market (credential noise rises)
- (-) [Market structure] → a few foundation model or cloud providers capture most AutoML-dependent education services (dependence concentrates)
- (-) [Overemphasis on technology] → institutions substitute rapidly generated assessments for genuine pedagogy redesign (form overtakes substance)
- (+) [Authorized evaluation of formal learning] → exam and accreditation bodies approve tool-generated assessment templates with review layers (production capacity scales)

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART enables teams of AI agents to act as tutors, assessors, coaches, and workflow simulators that cover more contexts than a single static model; its strongest pathway is not one super-agent but a stack of specialist agents that coach, observe, and document performance across contexts. Around the GVN, that can shift scarce human mentoring time toward edge cases while routine support and evidence collection become continuous. In feedback-loop terms, as multi-agent support gets embedded into work, proof of proficiency may increasingly come from coordinated task performance and audit trails rather than single exams. The main downsides are opaque delegation, brittle coordination, and workers being judged by agent-mediated metrics they do not control. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Direct feedback and motivation] → learners interact with persistent tutor teams rather than single chatbots (support becomes continuous)
- (+) [Procedural and systemic skills] → assessment systems grade collaboration with simulated colleagues or agents (teamwork proof expands)
- (+) [Private sector and on-the-job learning] → workplaces deploy agent swarms for coaching, checklists, and evidence capture (mentoring scales)
- (+) [Recognizability of proficiency] → employers value task-completion audit trails produced by human-AI teams (proof becomes process-rich)
- (+) [Learning to learn] → career transitions are mediated by agent teams that map prior evidence into new competency graphs (reskilling shortens)
- (-) [Accountability] → disputes arise over whether failures belong to the learner, the agent team, or the platform (responsibility blurs)
- (-) [Equality in access] → top-performing agent teams remain tied to premium ecosystems (assistance stratifies)
- (-) [Security and dual-use] → compromised agents manipulate assessments or coaching records (multi-agent attack surface grows)
- (+) [Authorized evaluation of formal learning] → institutions approve bounded multi-agent support in tutoring or assessment workflows (governance catches up)

**ART 03.020 - Quantum-Accelerated AI Systems****Score: 1 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART mostly matters through cheaper compute for AI, simulation, and rich digital content rather than through any learning-specific mechanism. Around the GVN, its main institutional effect would be to lower costs for platforms that deliver tutoring, assessment, or credential services. In feedback-loop terms, unless those downstream systems change hiring and accreditation practices, the GVN impact stays indirect. The main downside is concentration of capability in firms controlling specialized hardware stacks. The impact is concrete and worth

monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced compute stacks practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced compute stacks experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 03.021 - AI-Driven Autonomous Scientific Discovery**

### **Score: 3 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART changes what counts as scientific proficiency by automating parts of hypothesis generation, experimental design, and data interpretation. Around the GVN, that raises demand for proof of skills in problem framing, validation, oversight, and tool orchestration rather than routine bench or analytics work alone. In feedback-loop terms, if challenge-based and lab-automation-centered science spreads, portfolios and reproducibility logs gain value relative to traditional credential markers. The downside is concentration of discovery capacity and devaluation of early-career skill formation through manual practice. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

#### **Weak signals (6):**

- (+) [Recognizability of proficiency] → hiring committees ask for reproducibility and orchestration logs alongside publications (proof changes in research)
- (+) [Learning to learn] → early-career scientists train on AI-managed discovery workflows (skill mix shifts upward)
- (+) [Authorized evaluation of formal learning] → doctoral programs add validated AI-lab workflow modules (curricula adjust)
- (+) [Private sector and on-the-job learning] → automated labs create continuous performance traces for staff development (workplace proof deepens)

- (-) [Quality assurance] → concerns grow that junior researchers lose hands-on method intuition (formation gap appears)
- (-) [Market structure] → elite institutions with automated infrastructure dominate recognized proof pathways (capability concentrates)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 10 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART gives learners situated, repeatable practice for procedural, systemic, and contextual skills that are poorly transmitted through text or lectures; this directly advances the GVN's emphasis on contextuality and procedural/systemic skill, especially where mistakes are expensive or dangerous. Around the GVN, that supports competence-based assessment, faster content updates, and stronger integration between formal education and workplace learning. In feedback-loop terms, if employers and regulators accept simulation performance as evidence, immersive practice can become a mainstream route to both learning and proof. The main negatives are unequal access to high-fidelity setups, new cheating/provenance problems, and overreliance on simulated rather than real contexts. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

**Weak signals (10):**

- (+) [Procedural and systemic skills] → regulators accept simulator hours or XR drills for partial licensure (practice scales)
- (+) [Contextuality] → employers request XR performance logs or digital rehearsal records in hiring (proof becomes in-context)
- (+) [Understanding of meanings] → complex systems courses replace lecture time with scenario walkthroughs (systems intuition deepens)
- (+) [Private sector and on-the-job learning] → factories, hospitals, and utilities expose training twins to schools and apprentices (workplace learning integrates)
- (+) [Learning to learn] → adult learners subscribe to short, repeatable rehearsal environments for new tools and roles (reskilling accelerates)
- (+) [Modernization and relevance] → rare or dangerous scenarios are practiced routinely in shared environments (high-value practice democratizes)
- (-) [Quality assurance] → disputes emerge over simulator-to-real-world transfer performance (validity gets contested)

- (-) [Equality in access] → high-fidelity setups cluster in elite institutions and large firms (hardware access stratifies)
- (-) [Authority of educational institutions] → some institutions refuse to grant credit for externally logged immersive practice (regime defense persists)
- (-) [Security and dual-use] → spoofed performance logs or synthetic practice artifacts appear in credential disputes (provenance becomes critical)

## ART 04.023 - Brain-Computer Interfaces (BCI)

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART expands who can participate in learning and skilled work, and in some cases improves the ability to retain, execute, or demonstrate competence. Around the GVN, that changes accommodation norms, fairness debates, and the boundary between assistance and enhancement in assessment. In feedback-loop terms, if augmented participation becomes normal, lifelong learning and recredentialing can include groups previously excluded from some roles. The central risks are stratification between enhanced and non-enhanced users and contested legitimacy of augmented performance. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

### **Weak signals (6):**

- (+) [Accessibility] → accommodations shift from extra time to adaptive interfaces or assistive augmentation (participation broadens)
- (+) [Recognizability of proficiency] → assessment rules start distinguishing assistance from prohibited enhancement (fairness boundary gets formalized)
- (+) [Individual advancement] → insurers or employers reimburse augmentation tied to learning or work capability (inclusion pathway opens)
- (+) [Private sector and on-the-job learning] → training programs are redesigned for augmented users rather than exception handling (mainstreaming begins)
- (-) [Equality] → premium augmentation tools cluster in elite schools, firms, or clinics (capability gap widens)
- (-) [Authority and legitimacy] → disputes emerge over what counts as authentic performance under augmentation (proof norms destabilize)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART expands who can participate in learning and skilled work, and in some cases improves the ability to retain, execute, or demonstrate competence. Around the GVN, that changes accommodation norms, fairness debates, and the boundary between assistance and enhancement in

assessment. In feedback-loop terms, if augmented participation becomes normal, lifelong learning and recredentialing can include groups previously excluded from some roles. The central risks are stratification between enhanced and non-enhanced users and contested legitimacy of augmented performance. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

#### **Weak signals (6):**

- (+) [Accessibility] → accommodations shift from extra time to adaptive interfaces or assistive augmentation (participation broadens)
- (+) [Recognizability of proficiency] → assessment rules start distinguishing assistance from prohibited enhancement (fairness boundary gets formalized)
- (+) [Individual advancement] → insurers or employers reimburse augmentation tied to learning or work capability (inclusion pathway opens)
- (+) [Private sector and on-the-job learning] → training programs are redesigned for augmented users rather than exception handling (mainstreaming begins)
- (-) [Equality] → premium augmentation tools cluster in elite schools, firms, or clinics (capability gap widens)
- (-) [Authority and legitimacy] → disputes emerge over what counts as authentic performance under augmentation (proof norms destabilize)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 04.025 - Haptic and Multi-Sensory Feedback Systems**

### **Score: 5 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART gives learners situated, repeatable practice for procedural, systemic, and contextual skills that are poorly transmitted through text or lectures; its main relevance is turning remote and simulated practice into something closer to embodied skill formation rather than screen-based approximation. Around the GVN, that supports competence-based assessment, faster content updates, and stronger integration between formal education and workplace learning. In feedback-loop terms, if employers and regulators accept simulation performance as evidence, immersive practice can become a mainstream route to both learning and proof. The main negatives are unequal access to high-fidelity setups, new cheating/provenance problems, and overreliance on simulated rather than real contexts. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

#### **Weak signals (10):**

- (+) [Procedural and systemic skills] → regulators accept simulator hours or XR drills for partial licensure (practice scales)
- (+) [Contextuality] → employers request XR performance logs or digital rehearsal records in hiring (proof becomes in-context)



- (+) [Understanding of meanings] → complex systems courses replace lecture time with scenario walkthroughs (systems intuition deepens)
- (+) [Private sector and on-the-job learning] → factories, hospitals, and utilities expose training twins to schools and apprentices (workplace learning integrates)
- (+) [Learning to learn] → adult learners subscribe to short, repeatable rehearsal environments for new tools and roles (reskilling accelerates)
- (+) [Modernization and relevance] → rare or dangerous scenarios are practiced routinely in shared environments (high-value practice democratizes)
- (-) [Quality assurance] → disputes emerge over simulator-to-real-world transfer performance (validity gets contested)
- (-) [Equality in access] → high-fidelity setups cluster in elite institutions and large firms (hardware access stratifies)
- (-) [Authority of educational institutions] → some institutions refuse to grant credit for externally logged immersive practice (regime defense persists)
- (-) [Security and dual-use] → spoofed performance logs or synthetic practice artifacts appear in credential disputes (provenance becomes critical)

## ART 04.026 - AI Understanding of Human Intent & Context

**Score: 10 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART lets interfaces infer confusion, overload, intent, and social context so support, feedback, and assessment can adapt in real time; the most important shift is from one-size-fits-all interfaces to systems that adapt to confusion, overload, intent, and social setting in real time. Around the GVN, that changes who can participate effectively, how accommodations are delivered, and how far assessment can move from standardized one-size-fits-all formats. In feedback-loop terms, if context-aware support becomes normal, people will expect tools and credential pathways to adapt continuously rather than asking learners to fit fixed interfaces. The main downsides are behavioral surveillance, biased interpretation of signals, and pressure to surrender intimate data to remain competitive. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

### **Weak signals (10):**

- (+) [Individual advancement] → tutoring systems adapt timing, modality, and difficulty from gaze, tone, and workflow cues (support feels personalized)
- (+) [Learning to learn] → users carry persistent preference and overload profiles across tools and jobs (adaptation compounds)
- (+) [Accessibility] → assessments shift from one rigid interface to context-aware accommodations (proof broadens participation)

- (+) [Private sector and on-the-job learning] → tools detect confusion and escalate help during real work tasks (embedded coaching normalizes)
- (+) [Recognizability of proficiency] → collaboration skills and situational judgment become easier to observe and document (soft-skill proof improves)
- (+) [Modernization and relevance] → interfaces choose the right mix of text, speech, visuals, and haptics automatically (tool friction falls)
- (-) [Privacy and power] → learners or workers are pressured to share more behavioral data to access premium pathways (consent erodes)
- (-) [Fairness] → bias audits show systematic misreading of culture, disability, or emotion signals (context inference skews outcomes)
- (-) [Authority of educational institutions] → formal assessment bodies ban certain context-sensing modes in exams (legitimacy boundary appears)
- (-) [Security and dual-use] → spoofing of attention, emotion, or identity signals appears in high-stakes settings (behavioral signals become attack surface)

## ART 04.027 - Brain-to-Brain Interfaces

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART would alter communication and collaboration for a relatively small set of users rather than redesign mainstream learning systems. Around the GVN, the main institutional effect would be around niche accommodations, elite coordination, and new ethics rules for what counts as authentic performance. In feedback-loop terms, broader GVN effects appear only if the interface escapes specialist use and becomes a common way to capture or transmit tacit skill. Privacy, coercion, and fairness concerns would likely slow any wider legitimacy. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for brain-to-brain interfaces practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention brain-to-brain interfaces experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART expands who can participate in learning and skilled work, and in some cases improves the ability to retain, execute, or demonstrate competence. Around the GVN, that changes accommodation norms, fairness debates, and the boundary between assistance and enhancement in assessment. In feedback-loop terms, if augmented participation becomes normal, lifelong learning and recredentialing can include groups previously excluded from some roles. The central risks are stratification between enhanced and non-enhanced users and contested legitimacy of augmented performance. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Accessibility] → accommodations shift from extra time to adaptive interfaces or assistive augmentation (participation broadens)
- (+) [Recognizability of proficiency] → assessment rules start distinguishing assistance from prohibited enhancement (fairness boundary gets formalized)
- (+) [Individual advancement] → insurers or employers reimburse augmentation tied to learning or work capability (inclusion pathway opens)
- (+) [Private sector and on-the-job learning] → training programs are redesigned for augmented users rather than exception handling (mainstreaming begins)
- (-) [Equality] → premium augmentation tools cluster in elite schools, firms, or clinics (capability gap widens)
- (-) [Authority and legitimacy] → disputes emerge over what counts as authentic performance under augmentation (proof norms destabilize)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART redefines many jobs from manual execution toward supervision, exception handling, system understanding, and human-machine coordination; the largest effect is indirect but large: whole credential systems built around driving itself start shifting toward oversight, exception

handling, and fleet coordination. Around the GVN, that changes hiring filters, creates new micro-credentials, and puts pressure on incumbent degree and license structures that describe the old task mix. In feedback-loop terms, the more automation spreads, the more valuable rapid reskilling and continuous proof become, which can accelerate the move away from one-off early-life credentials. The downside is large transition pain: job loss, credential lag, and vendor-defined certificates that fragment labor markets. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

### Weak signals (9):

- (+) [Learning to learn] → adult retraining demand jumps in occupations exposed to automation (skill churn becomes visible)
- (+) [Recognizability of proficiency] → new supervisor, exception-handler, and human-robot coordination certificates appear (task mix gets recoded)
- (+) [Procedural and systemic skills] → hiring tests shift from manual execution to system oversight and troubleshooting (proof follows new work)
- (+) [Private sector and on-the-job learning] → firms use simulator logs and fleet telemetry in progression decisions (work evidence gains weight)
- (+) [Contextuality] → apprenticeship programs add modules on intervention, recovery, and escalation around automated systems (new practice norms)
- (-) [Dependence on established structures] → legacy degrees or licenses remain hiring gates after tasks have changed (credential lag persists)
- (-) [Equality and bargaining power] → workers without reskilling support see wage dispersion widen (transition costs concentrate)
- (-) [Market structure] → vendor-specific certificates become quasi-mandatory for employment (training lock-in expands)
- (-) [Security and dual-use] → failures or hacks trigger renewed demands for human-only oversight credentials (trust swings back)

## ART 05.030 - Drone Swarms & Aerial Robots

### Score: 3 (Impact in GVN 15)

#### Justification (3–5 sentences):

Directly, this ART redefines many jobs from manual execution toward supervision, exception handling, system understanding, and human-machine coordination. Around the GVN, that changes hiring filters, creates new micro-credentials, and puts pressure on incumbent degree and license structures that describe the old task mix. In feedback-loop terms, the more automation spreads, the more valuable rapid reskilling and continuous proof become, which can accelerate the move away from one-off early-life credentials. The downside is large transition pain: job loss, credential lag, and vendor-defined certificates that fragment labor markets. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (9):**

- (+) [Learning to learn] → adult retraining demand jumps in occupations exposed to automation (skill churn becomes visible)
- (+) [Recognizability of proficiency] → new supervisor, exception-handler, and human-robot coordination certificates appear (task mix gets recoded)
- (+) [Procedural and systemic skills] → hiring tests shift from manual execution to system oversight and troubleshooting (proof follows new work)
- (+) [Private sector and on-the-job learning] → firms use simulator logs and fleet telemetry in progression decisions (work evidence gains weight)
- (+) [Contextuality] → apprenticeship programs add modules on intervention, recovery, and escalation around automated systems (new practice norms)
- (-) [Dependence on established structures] → legacy degrees or licenses remain hiring gates after tasks have changed (credential lag persists)
- (-) [Equality and bargaining power] → workers without reskilling support see wage dispersion widen (transition costs concentrate)
- (-) [Market structure] → vendor-specific certificates become quasi-mandatory for employment (training lock-in expands)
- (-) [Security and dual-use] → failures or hacks trigger renewed demands for human-only oversight credentials (trust swings back)

**ART 05.031 - Humanoid and General-Purpose Robots****Score: 5 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART redefines many jobs from manual execution toward supervision, exception handling, system understanding, and human-machine coordination; if this diffuses broadly, many entry-level and mid-skill jobs become supervision-and-integration roles, forcing much more continuous proof of current capability. Around the GVN, that changes hiring filters, creates new micro-credentials, and puts pressure on incumbent degree and license structures that describe the old task mix. In feedback-loop terms, the more automation spreads, the more valuable rapid reskilling and continuous proof become, which can accelerate the move away from one-off early-life credentials. The downside is large transition pain: job loss, credential lag, and vendor-defined certificates that fragment labor markets. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Learning to learn] → adult retraining demand jumps in occupations exposed to automation (skill churn becomes visible)
- (+) [Recognizability of proficiency] → new supervisor, exception-handler, and human-robot coordination certificates appear (task mix gets recoded)

- (+) [Procedural and systemic skills] → hiring tests shift from manual execution to system oversight and troubleshooting (proof follows new work)
- (+) [Private sector and on-the-job learning] → firms use simulator logs and fleet telemetry in progression decisions (work evidence gains weight)
- (+) [Contextuality] → apprenticeship programs add modules on intervention, recovery, and escalation around automated systems (new practice norms)
- (-) [Dependence on established structures] → legacy degrees or licenses remain hiring gates after tasks have changed (credential lag persists)
- (-) [Equality and bargaining power] → workers without reskilling support see wage dispersion widen (transition costs concentrate)
- (-) [Market structure] → vendor-specific certificates become quasi-mandatory for employment (training lock-in expands)
- (-) [Security and dual-use] → failures or hacks trigger renewed demands for human-only oversight credentials (trust swings back)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART creates new tasks and training needs in selected sectors but does not by itself reshape the wider learning-and-proof regime. Around the GVN, the institutional effects are mainly vendor training pipelines and updated safety certifications. In feedback-loop terms, broader GVN relevance depends on whether the machines diffuse beyond niche settings into everyday service or industrial work. The main negative is proprietary lock-in of training and assessment. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for robotic systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention robotic systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART redefines many jobs from manual execution toward supervision, exception handling, system understanding, and human-machine coordination. Around the GVN, that changes hiring filters, creates new micro-credentials, and puts pressure on incumbent degree and license structures that describe the old task mix. In feedback-loop terms, the more automation spreads, the more valuable rapid reskilling and continuous proof become, which can accelerate the move away from one-off early-life credentials. The downside is large transition pain: job loss, credential lag, and vendor-defined certificates that fragment labor markets. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

### **Weak signals (9):**

- (+) [Learning to learn] → adult retraining demand jumps in occupations exposed to automation (skill churn becomes visible)
- (+) [Recognizability of proficiency] → new supervisor, exception-handler, and human-robot coordination certificates appear (task mix gets recoded)
- (+) [Procedural and systemic skills] → hiring tests shift from manual execution to system oversight and troubleshooting (proof follows new work)
- (+) [Private sector and on-the-job learning] → firms use simulator logs and fleet telemetry in progression decisions (work evidence gains weight)
- (+) [Contextuality] → apprenticeship programs add modules on intervention, recovery, and escalation around automated systems (new practice norms)
- (-) [Dependence on established structures] → legacy degrees or licenses remain hiring gates after tasks have changed (credential lag persists)
- (-) [Equality and bargaining power] → workers without reskilling support see wage dispersion widen (transition costs concentrate)
- (-) [Market structure] → vendor-specific certificates become quasi-mandatory for employment (training lock-in expands)
- (-) [Security and dual-use] → failures or hacks trigger renewed demands for human-only oversight credentials (trust swings back)

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART moves some skill requirements from individual robot operation to supervision of autonomy-ready environments and shared control systems. Around the GVN, that influences how



competence is certified in facilities adopting autonomy at scale, but only where such infrastructure is installed. In feedback-loop terms, if environments become autonomy-native, simpler workers and simpler robots alike may be judged by compliance with infrastructure rules rather than by rich local skill. The downside is concentration of power in facility owners and platform vendors who define the standards. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for autonomy-ready facilities practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention autonomy-ready facilities experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics**

### **Score: 0 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

#### **Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for optical/microwave power beaming for persistent robotics roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on optical/microwave power beaming for persistent robotics use (training base widens)

- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to optical/microwave power beaming for persistent robotics (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 0 (Impact in GVN 15)**

### Justification (3–5 sentences):

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

### Weak signals (4):

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for gecko-inspired dry-adhesion mobility & manipulation roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on gecko-inspired dry-adhesion mobility & manipulation use (training base widens)
- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to gecko-inspired dry-adhesion mobility & manipulation (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score: 3 (Impact in GVN 15)**

### Justification (3–5 sentences):

Directly, this ART changes industrial skill profiles toward faster reconfiguration, digital design, process integration, and evidence-rich quality control. Around the GVN, that supports more competence-based hiring and certification because live outputs, machine logs, and simulated runs become easier to inspect than static credentials alone. In feedback-loop terms, as production changes more often, learning-to-learn becomes more valuable and modular industrial credentials

can proliferate. The main negatives are vendor-specific skill silos and unequal access to expensive equipment for proof-building. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

#### **Weak signals (6):**

- (+) [Learning to learn] → vocational programs shorten around modular re-skilling cycles rather than fixed machine careers (adaptation accelerates)
- (+) [Recognizability of proficiency] → employers accept machine logs, simulation records, or validated outputs as skill evidence (proof becomes operational)
- (+) [Private sector and on-the-job learning] → manufacturers co-design credentials with schools and equipment vendors (education-work boundary softens)
- (+) [Contextuality] → workers are assessed on changeover, troubleshooting, and integration tasks, not just steady-state operation (real task mix appears)
- (-) [Market structure] → vendor certificates become more important than portable occupational standards (lock-in risk rises)
- (-) [Equality] → smaller regions and schools struggle to access current equipment for proof-building (training access polarizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.038 - Digital Twin & Simulation-Driven Production**

### **Score: 5 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART creates reusable digital environments where learners and workers can rehearse complex tasks, see system interactions, and generate auditable evidence of performance; this is close to the GVN core because it makes systems understanding and rehearsed competence observable rather than inferred from course completion. Around the GVN, that strongly supports the GVN's emphasis on procedural and systemic skills, contextuality, and private-sector/on-the-job learning. In feedback-loop terms, if simulation logs become accepted in hiring, training, and regulation, digital practice can displace part of course-completion logic. The main negatives are model drift, false confidence, and dependence on proprietary twin ecosystems. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

#### **Weak signals (9):**

- (+) [Procedural and systemic skills] → sector regulators accept validated simulation logs in training and recertification (evidence moves beyond hours)
- (+) [Understanding of meanings] → learners routinely inspect cause-effect maps inside digital twins (big-picture reasoning strengthens)
- (+) [Private sector and on-the-job learning] → employers expose operational twins to schools, apprentices, and new hires (workplace learning deepens)

- (+) [Recognizability of proficiency] → hiring and progression decisions include replayable scenario performance records (proof becomes auditable)
- (+) [Modernization and relevance] → course content updates when real systems, software, or regulations change (curriculum lag narrows)
- (+) [Learning to learn] → adults rehearse role changes in safe virtual settings before doing them live (transition costs fall)
- (-) [Quality assurance] → model error or stale parameters are shown to mis-train workers (simulation validity becomes central)
- (-) [Market structure] → one vendor's twin model becomes the de facto gatekeeper for recognized competence (ecosystem lock-in appears)
- (-) [Equality in access] → smaller institutions rely on low-fidelity twins and weaker evidence (proof quality stratifies)

## ART 06.039 - Reconfigurable & Agile Factories

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART changes industrial skill profiles toward faster reconfiguration, digital design, process integration, and evidence-rich quality control. Around the GVN, that supports more competence-based hiring and certification because live outputs, machine logs, and simulated runs become easier to inspect than static credentials alone. In feedback-loop terms, as production changes more often, learning-to-learn becomes more valuable and modular industrial credentials can proliferate. The main negatives are vendor-specific skill silos and unequal access to expensive equipment for proof-building. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

### **Weak signals (6):**

- (+) [Learning to learn] → vocational programs shorten around modular re-skilling cycles rather than fixed machine careers (adaptation accelerates)
- (+) [Recognizability of proficiency] → employers accept machine logs, simulation records, or validated outputs as skill evidence (proof becomes operational)
- (+) [Private sector and on-the-job learning] → manufacturers co-design credentials with schools and equipment vendors (education-work boundary softens)
- (+) [Contextuality] → workers are assessed on changeover, troubleshooting, and integration tasks, not just steady-state operation (real task mix appears)
- (-) [Market structure] → vendor certificates become more important than portable occupational standards (lock-in risk rises)
- (-) [Equality] → smaller regions and schools struggle to access current equipment for proof-building (training access polarizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.040 - Circular & Sustainable Manufacturing

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART changes industrial skill profiles toward faster reconfiguration, digital design, process integration, and evidence-rich quality control. Around the GVN, that supports more competence-based hiring and certification because live outputs, machine logs, and simulated runs become easier to inspect than static credentials alone. In feedback-loop terms, as production changes more often, learning-to-learn becomes more valuable and modular industrial credentials can proliferate. The main negatives are vendor-specific skill silos and unequal access to expensive equipment for proof-building. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Learning to learn] → vocational programs shorten around modular re-skilling cycles rather than fixed machine careers (adaptation accelerates)
- (+) [Recognizability of proficiency] → employers accept machine logs, simulation records, or validated outputs as skill evidence (proof becomes operational)
- (+) [Private sector and on-the-job learning] → manufacturers co-design credentials with schools and equipment vendors (education-work boundary softens)
- (+) [Contextuality] → workers are assessed on changeover, troubleshooting, and integration tasks, not just steady-state operation (real task mix appears)
- (-) [Market structure] → vendor certificates become more important than portable occupational standards (lock-in risk rises)
- (-) [Equality] → smaller regions and schools struggle to access current equipment for proof-building (training access polarizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.041 - Bio-fabrication technologies

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART primarily creates new specialist domains that require updated curricula, licenses, and professional standards. Around the GVN, the GVN effect comes through niche credential markets and the need to prove competence in new technical tasks, not through mass learning-system redesign. In feedback-loop terms, spillovers rise only if the technology becomes a widely deployed platform that many occupations must understand or supervise. Fragmented vendor certificates and unequal access to expensive training are the main negatives. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new specialist platforms practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new specialist platforms experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART primarily creates new specialist domains that require updated curricula, licenses, and professional standards. Around the GVN, the GVN effect comes through niche credential markets and the need to prove competence in new technical tasks, not through mass learning-system redesign. In feedback-loop terms, spillovers rise only if the technology becomes a widely deployed platform that many occupations must understand or supervise. Fragmented vendor certificates and unequal access to expensive training are the main negatives. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new specialist platforms practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new specialist platforms experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly shortens prototyping and custom-production cycles, which modestly changes how makers and engineers learn by doing and prove capability through outputs. Around the GVN, its institutional effect is mainly more portfolio-based evidence in certain design and fabrication communities. In feedback-loop terms, larger GVN effects depend on whether compact fabrication becomes common in schools, labs, and local production networks. The main downside is widening gaps between institutions with and without access to advanced fabrication tools. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for compact fabrication systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention compact fabrication systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid



proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.045 - Room-Temperature Superconductors**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)

- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and

certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.048 - High-Entropy Alloys & Advanced Metals**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)

- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation**

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)

- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination**

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors**

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is



fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART mostly affects the GVN through new specialist training, safety rules, and certification needs in the sectors adopting the material. Around the GVN, it does not directly change how most people learn, but it can expand vendor and regulator influence over what counts as valid proof in affected trades. In feedback-loop terms, the impact grows only if the material becomes part of a large installed base that forces widespread upskilling or relicensing. The main negative is fragmented, proprietary credentialing rather than portable proof of transferable skill. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for advanced-material systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention advanced-material systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)

- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.058 - Thin-film solar cells****Score: 1 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)

- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.059 - Bionic Leaf Technology

**Score: 0 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

**Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for bionic leaf technology roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on bionic leaf technology use (training base widens)
- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to bionic leaf technology (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In

feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 08.061 - Solid-State Batteries**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)

- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates substantial new safety-critical and systems-integration skills in the energy transition; the GVN effect comes through the speed with which whole adjacent workforces can or cannot re-skill into a new safety-critical energy domain. Around the GVN, that pushes vocational providers, employers, and regulators to define faster, more modular proof pathways than traditional multi-year programs alone. In feedback-loop terms, as deployment scales, labor shortages can make alternative credentials and workplace-based proof more legitimate. The main negatives are uneven regional access to training and vendor-dominated certification ecosystems. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Recognizability of proficiency] → sector bodies launch short-cycle certificates for hydrogen, storage, or microgrid operators (new proof pathways form)
- (+) [Private sector and on-the-job learning] → utilities and installers use live system data in training and recertification (work evidence expands)
- (+) [Learning to learn] → adult reskilling programs target adjacent trades rather than only new entrants (transition pipeline broadens)
- (+) [Regulatory barriers] → safety authorities publish competency requirements for new energy roles (governance catches up)
- (-) [Quality assurance] → cross-vendor certificates prove hard to compare (portability remains weak)
- (-) [Equality] → training capacity clusters around first-mover firms and regions (transition benefits concentrate)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 08.064 - Wireless & Space-Based Power Transfer**

**Score: 0 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

**Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for wireless & space-based power transfer roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on wireless & space-based power transfer use (training base widens)



- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to wireless & space-based power transfer (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

**Score: 1 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART mainly creates new sector-specific operating, safety, maintenance, and regulatory skills. Around the GVN, the GVN effect comes from updated professional standards and the need to prove competence in new energy systems rather than from a general redesign of education. In feedback-loop terms, if adoption becomes broad, recurrent recertification and simulation-heavy training could become more important across energy trades. The key downside is credential lag, where old qualifications remain gatekeepers even after task profiles change. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for new-energy systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention new-energy systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

**Score: 3 (Impact in GVN 15)**

### **Justification (3–5 sentences):**

Directly, this ART creates substantial new safety-critical and systems-integration skills in the energy transition; its strongest GVN link is community and workplace capability: local operators need provable competence to keep critical systems running during wider disruption. Around the GVN,

that pushes vocational providers, employers, and regulators to define faster, more modular proof pathways than traditional multi-year programs alone. In feedback-loop terms, as deployment scales, labor shortages can make alternative credentials and workplace-based proof more legitimate. The main negatives are uneven regional access to training and vendor-dominated certification ecosystems. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

#### **Weak signals (6):**

- (+) [Recognizability of proficiency] → sector bodies launch short-cycle certificates for hydrogen, storage, or microgrid operators (new proof pathways form)
- (+) [Private sector and on-the-job learning] → utilities and installers use live system data in training and recertification (work evidence expands)
- (+) [Learning to learn] → adult reskilling programs target adjacent trades rather than only new entrants (transition pipeline broadens)
- (+) [Regulatory barriers] → safety authorities publish competency requirements for new energy roles (governance catches up)
- (-) [Quality assurance] → cross-vendor certificates prove hard to compare (portability remains weak)
- (-) [Equality] → training capacity clusters around first-mover firms and regions (transition benefits concentrate)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **9. Bio-engineering & Life-Science Technologies**

### **ART 09.067 - Next-Generation Gene Editing**

**Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)

- (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

### Score: 1 (Impact in GVN 15)

#### Justification (3–5 sentences):

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### Weak signals (6):

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART opens new bioindustrial production and process-control roles that blend lab, software, and operations skills; the main pathway is new bioindustrial work that blends process control, data literacy, and regulated protocol execution rather than traditional agrifood skill alone. Around the GVN, that can favor competence-based proof because monitored process outcomes and validated protocols are easier to inspect than generic degrees alone. In feedback-loop terms, if bio-production scales, sector bodies may normalize modular credentials that link directly to plant and platform tasks. The downside is concentration of recognized training around large firms and regulated incumbents. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Recognizability of proficiency] → employers post roles requiring validated process-control and protocol-execution badges (bioindustry proof emerges)
  - (+) [Private sector and on-the-job learning] → bio-production facilities expose live process data for trainee assessment (workplace evidence grows)
  - (+) [Learning to learn] → adjacent chemical, food, and lab workers enter conversion programs into bio-platform roles (reskilling pipeline opens)
  - (+) [Authorized evaluation of formal learning] → technical colleges add modular bio-process credentials with industry sign-off (curricula realign)
  - (-) [Equality] → recognized training remains concentrated around large regulated firms (entry gates harden)
  - (-) [Quality assurance] → contamination or protocol-drift incidents trigger tighter credential controls (trust tightens after failures)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)

- (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART opens new bioindustrial production and process-control roles that blend lab, software, and operations skills; this creates a large need for modular proof in hybrid wet-lab/software/manufacturing roles that do not map neatly to legacy degrees. Around the GVN, that can favor competence-based proof because monitored process outcomes and validated protocols are easier to inspect than generic degrees alone. In feedback-loop terms, if bio-production scales, sector bodies may normalize modular credentials that link directly to plant and platform tasks. The downside is concentration of recognized training around large firms and regulated incumbents. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Recognizability of proficiency] → employers post roles requiring validated process-control and protocol-execution badges (bioindustry proof emerges)
  - (+) [Private sector and on-the-job learning] → bio-production facilities expose live process data for trainee assessment (workplace evidence grows)
  - (+) [Learning to learn] → adjacent chemical, food, and lab workers enter conversion programs into bio-platform roles (reskilling pipeline opens)
  - (+) [Authorized evaluation of formal learning] → technical colleges add modular bio-process credentials with industry sign-off (curricula realign)
  - (-) [Equality] → recognized training remains concentrated around large regulated firms (entry gates harden)
  - (-) [Quality assurance] → contamination or protocol-drift incidents trigger tighter credential controls (trust tightens after failures)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 - Microbiome Engineering

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART could personalize accommodations, pacing, and risk management for learners and workers, while also changing how capabilities are classified; the upside for this GVN is more tailored support and accommodation; the danger is a new biological gatekeeping layer around opportunity. Around the GVN, that creates new governance questions about whether biological profiles should inform support, selection, or certification. In feedback-loop terms, if personalized diagnostics become routine, they can drive more individualized learning pathways but also intensify stratification and screening. The main negative is turning health or genomic data into a new gatekeeping layer around opportunity and proof. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Individual advancement] → support plans in education and work start referencing individualized biomarker or genomic findings (accommodation becomes tailored)
- (+) [Learning to learn] → people receive personalized pacing, fatigue, or risk management guidance tied to biological profiles (support becomes more specific)
- (+) [Recognizability of proficiency] → some assessments separate current performance from diagnosed biological constraints (proof gets contextualized)
- (-) [Equality] → better diagnostic access produces better-tailored learning pathways for higher-income groups (support stratifies)
- (-) [Bargaining power] → employers or insurers begin requesting predictive biological data in capability decisions (new screening pressure appears)
- (-) [Authority and ethics] → public backlash targets using biological propensities in education or hiring decisions (legitimacy boundary tested)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 09.075 - Biological Aging & Longevity Barriers

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART extends the period over which people can productively learn, work, and be recertified, making lifelong proficiency maintenance more central; a longer healthy working life makes recurrent upskilling and recertifying much more central to everyday life rather than a niche adult-learning activity. Around the GVN, that weakens the old assumption that one early-life degree can anchor a whole career and strengthens demand for periodic proof of current capability. In feedback-loop terms, if healthy working lives lengthen, employers and public systems will invest more in continuous upskilling and age-inclusive assessment. The main negatives are unequal access to enhancement and pressure for older workers to remain continuously certified and productive. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Learning to learn] → employers and public agencies extend reskilling budgets deeper into later life (continuous updating becomes normal)
- (+) [Recognizability of proficiency] → recertification windows lengthen in some domains but become more regular in others (current capability matters more)
- (+) [Individual advancement] → mid- and late-career learners return to credential pathways in large numbers (career arcs lengthen)
- (+) [Contextuality] → mixed-age teams and retraining programs become standard in skill-short sectors (age barriers soften)
- (+) [Private sector and on-the-job learning] → insurers or employers cover maintenance-of-capability programs, not only acute treatment (health and skill merge)
- (-) [Equality] → enhancement access tracks income and employer quality (capability gap widens)
- (-) [Authority and pressure] → older workers face new expectations to remain continuously measurable and productive (support becomes coercive)
- (-) [Quality assurance] → disputes emerge over whether augmentation or treatment changes what counts as fair assessment (legitimacy strains)
- (+) [Authorized evaluation of formal learning] → colleges and regulators redesign late-career return pathways around current capability rather than past credentials (re-entry becomes easier)

## ART 09.076 - Engineered Living Materials

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility

records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

#### **Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 09.077 - Gene Drive Pest Control**

**Score: 0 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

#### **Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for gene drive pest control roles (linkage could broaden)
  - (+) [Learning to learn] → universities and vocational programs create recurring modules on gene drive pest control use (training base widens)
  - (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to gene drive pest control (workplace demand appears)
  - (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates new bio-literacy, lab, data, ethics, and regulatory skills, mostly in specialist domains. Around the GVN, the GVN effect is strongest where new therapies or bio-platforms require fresh standards for who is allowed to do what and how competence is evidenced. In feedback-loop terms, if these fields industrialize, challenge-based portfolios and reproducibility records can grow in importance relative to static titles. The main negatives are exclusion through expensive training pipelines and strong dependence on regulatory gatekeepers. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for bio-platforms practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention bio-platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART expands reliable access to online learning, remote practice, rich simulations, and portable assessment beyond specific campuses or urban centers; relative to the current baseline, the major effect is resilience, reach, and richer media for learning and proof rather than first-time connectivity alone. Around the GVN, it weakens location-based institutional advantage and makes employer-recognized remote proof more plausible. In feedback-loop terms, once remote study, work trials, and assessments become routine, more providers can compete on pedagogy and skill proof rather than campus presence. The main downsides are infrastructure dependence, platform concentration, and new forms of exclusion for learners lacking premium devices or service quality. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Flexibility and accessibility] → public procurement bundles ubiquitous connectivity with national learning platforms (access barrier falls)
- (+) [Location-based limitations] → remote schools and apprenticeship sites stop maintaining offline-only teaching schedules (place constraint weakens)
- (+) [Recognizability of proficiency] → employers accept remotely supervised skills tests from rural and mobile learners (proof travels farther)
- (+) [Private sector and on-the-job learning] → firms open live remote observation of workplace tasks for trainees (work-based learning scales)
- (+) [Modernization and relevance] → course providers shift from low-bandwidth video to interactive simulation and labs (richer pedagogy normalizes)
- (+) [Learning to learn] → adult learners study during commuting and distributed work intervals (learning time expands)
- (-) [Equality in access] → high-value credential pathways begin to require premium terminals or service tiers (device gap widens)
- (-) [Institutional resistance] → universities keep physical-attendance rules after network reliability improves (campus gatekeeping persists)
- (-) [Quality assurance and trust] → credential disputes are traced to outages, latency spikes, or routing failures (infrastructure trust matters)

**ART 10.080 - Space Resource Utilization (SRU)****Score: 0 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

**Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for space resource utilization (sru) roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on space resource utilization (sru) use (training base widens)
- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to space resource utilization (sru) (workplace demand appears)

- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

**Score: 0 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART has no strong society-scale pathway into how most people acquire or prove proficiency. In institutional terms, any effect would stay confined to small expert communities unless employers, regulators, or schools start treating it as a mainstream competency domain. The main thing to watch is whether adjacent sectors unexpectedly turn it into a broad training or certification issue. For now there is no clear pathway to a meaningful society-scale impact on this GVN, so 0 is the disciplined score.

**Weak signals (4):**

- (+) [Recognizability of proficiency] → regulators or sector bodies draft competency rules for closed-loop life support system roles (linkage could broaden)
- (+) [Learning to learn] → universities and vocational programs create recurring modules on closed-loop life support system use (training base widens)
- (+) [Private sector and on-the-job learning] → employers start paying for recurring specialist certificates tied to closed-loop life support system (workplace demand appears)
- (-) [Quality assurance] → early incidents trigger calls for licensed specialists only (proof may become gatekept)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART expands reliable access to online learning, remote practice, rich simulations, and portable assessment beyond specific campuses or urban centers; its relevance is strongest where terrestrial infrastructure is fragile, overloaded, or slow to upgrade but educational and work coordination must continue. Around the GVN, it weakens location-based institutional advantage and makes employer-recognized remote proof more plausible. In feedback-loop terms, once remote study, work trials, and assessments become routine, more providers can compete on pedagogy and skill proof rather than campus presence. The main downsides are infrastructure dependence, platform concentration, and new forms of exclusion for learners lacking premium devices or service quality. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (9):**

- (+) [Flexibility and accessibility] → public procurement bundles ubiquitous connectivity with national learning platforms (access barrier falls)

- (+) [Location-based limitations] → remote schools and apprenticeship sites stop maintaining offline-only teaching schedules (place constraint weakens)
- (+) [Recognizability of proficiency] → employers accept remotely supervised skills tests from rural and mobile learners (proof travels farther)
- (+) [Private sector and on-the-job learning] → firms open live remote observation of workplace tasks for trainees (work-based learning scales)
- (+) [Modernization and relevance] → course providers shift from low-bandwidth video to interactive simulation and labs (richer pedagogy normalizes)
- (+) [Learning to learn] → adult learners study during commuting and distributed work intervals (learning time expands)
- (-) [Equality in access] → high-value credential pathways begin to require premium terminals or service tiers (device gap widens)
- (-) [Institutional resistance] → universities keep physical-attendance rules after network reliability improves (campus gatekeeping persists)
- (-) [Quality assurance and trust] → credential disputes are traced to outages, latency spikes, or routing failures (infrastructure trust matters)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART makes skills, projects, assessments, and identity attributes portable and verifiable outside a single institution; the most relevant slice here is verifiable credentials, learner-owned records, and tamper-evident proof rather than speculative asset trading. Around the GVN, that directly challenges degree-centric gatekeeping and can redistribute authority toward learners, employers, and networked trust infrastructures. In feedback-loop terms, once portable proof starts to matter in hiring and credit transfer, more learning shifts into modular, evidence-rich pathways, which further raises demand for portable proof. The main downsides are new intermediaries, standards battles, fraud, and unequal influence over the trust layer. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (10):**

- (+) [Recognizability of proficiency] → major employers accept wallet-based skills, project proofs, or verified work records in job ads (proof unbundles from degrees)
- (+) [Learning outside formal education] → public employment services ingest portable skill wallets and external evidence (informal learning becomes legible)

- (+) [Authorized evaluation of formal learning] → universities and regulators grant credit for externally verified competencies (institutional permeability increases)
- (+) [Individual advancement] → learners aggregate project, work, volunteer, and assessment evidence in one profile (proof diversifies)
- (+) [Contextuality] → task-specific credentials linked to real outputs spread in technical and service roles (situated proof grows)
- (+) [Resistance to change] → some prestige employers drop degree-only filters for selected roles (gatekeeping weakens visibly)
- (-) [Quality assurance] → low-trust issuers or forged records trigger blacklist and accreditation battles (trust market hardens)
- (-) [Market structure] → a few wallet, identity, or trust providers become de facto gatekeepers (new intermediaries dominate)
- (-) [Equality and bargaining power] → workers are pressured to expose more granular history than is fair or necessary (proof becomes extractive)
- (-) [Security and dual-use] → stolen credentials, compromised keys, or provenance breaks affect hiring outcomes (trust layer becomes attack surface)

## ART 11.084 - Platform Cooperatives & Fair Work

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART changes how work platforms recognize, reward, and document competence, especially for people whose skills are built outside formal degrees. Around the GVN, because governance and data rights sit closer to workers, it can make ranking and reputation systems more contestable than in investor-owned platforms. In feedback-loop terms, if successful, fairer platform proof systems can spill back into mainstream hiring and adult learning markets. The main negative is fragmentation and undercapitalization, which could limit reach despite better alignment. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Recognition of diverse proficiencies] → worker-owned platforms publish transparent ranking and payout rules (skill proof becomes contestable)
- (+) [Private sector and on-the-job learning] → members pool training, insurance, and credentialing services inside the platform (learning and work align)
- (+) [Bargaining power] → workers can export ratings and verified task histories when leaving a platform (reputation portability improves)
- (+) [Authority of educational institutions] → platform-earned records are accepted for selected hiring or procurement decisions (informal proof gains legitimacy)
- (-) [Scale and market structure] → cooperative platforms struggle to match incumbents' visibility and capital (reach stays limited)



- (-) [Governance] → internal voting blocs or disputes weaken trust in platform-issued proof (collective legitimacy gets tested)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART reduces friction in accessing the datasets needed to build better tutors, benchmarks, labor-market signals, and skill analytics. Around the GVN, that can broaden participation in learning innovation, but also creates new bargaining power around who controls valuable educational and work-performance data. In feedback-loop terms, if standardized data access improves model quality and comparability, more actors can build alternative assessment and guidance tools. The downside is commodification of learner and worker traces without equal negotiating power. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Modernization and relevance] → more providers gain access to benchmark and labor-market data for updating curriculum (content improves faster)
- (+) [Quality assurance] → standardized data-quality signals appear next to training or assessment datasets (evidence becomes more comparable)
- (+) [Recognizability of proficiency] → employers and educators buy structured outcome datasets to refine skill requirements (signals become more market-linked)
- (+) [Private sector and on-the-job learning] → firms monetize anonymized training or performance data under explicit rules (new evidence market forms)
- (-) [Bargaining power] → learners and workers receive little leverage over resale of traces derived from their activity (data extraction persists)
- (-) [Market structure] → a few exchanges dominate pricing and metadata standards (data gatekeeping emerges)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART supports durable peer communities, reputation systems, and collaborative learning spaces outside any single fragile or extractive platform. Around the GVN, that can strengthen informal learning and peer proof, especially where public trust in centralized platforms is low. In feedback-loop terms, if communities can persist across outages and provider shifts, portfolio and reputation-building become more resilient and cumulative. The main negatives are moderation burdens, enclave formation, and difficulty aligning trust across nodes. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Learning outside formal education] → peer communities preserve course materials, mentorship, and reputation across platform failures (informal learning stabilizes)
  - (+) [Recognizability of proficiency] → community-issued endorsements or contribution histories are referenced in hiring or admissions (peer proof strengthens)
  - (+) [Flexibility and accessibility] → resilient networks keep study groups and support available during outages or political disruption (continuity improves)
  - (+) [Individual advancement] → users move social graphs and learning histories between services without starting over (reputation becomes portable)
  - (-) [Quality assurance] → fragmented moderation standards make cross-community trust hard to maintain (proof stays local)
  - (-) [Safety and governance] → harassment, manipulation, or enclave behavior drive skepticism toward community-based credentials (social legitimacy strains)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 11.087 - Collective Open Innovation Networks****Score: 5 (Impact in GVN 15)****Justification (3–5 sentences):**

Directly, this ART creates challenge-based environments where people can learn by contributing and prove proficiency through visible outputs, version history, and validation; this matters because it creates visible, challenge-based evidence of skill that employers can compare without relying only on institutional brand. Around the GVN, that offers a strong alternative to degree-first proof in technical and problem-solving domains. In feedback-loop terms, as employers start valuing demonstrated contribution records, more learners will choose open project pathways, which further enriches the evidence base. The downsides are uneven rewards, public-failure pressure, and concentration of visibility on already advantaged contributors. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Recognition of diverse proficiencies] → employers cite open challenge results and merge histories in recruitment (contribution becomes visible proof)
- (+) [Learning to learn] → learners join challenge networks to pivot careers without full degree programs (project pathways grow)
- (+) [Private sector and on-the-job learning] → firms sponsor public problem challenges tied to real hiring needs (learning and labor connect)
- (+) [Understanding of meanings] → problem framing and validation become explicit scored skills, not hidden work (systems thinking becomes legible)
- (+) [Authorized evaluation of formal learning] → universities award credit for externally validated challenge contributions (boundary softens)

- (-) [Equality] → visibility and ranking effects favor already networked contributors (reputation compounds advantage)
- (-) [Quality assurance] → disputes appear over plagiarism, benchmark gaming, or unverifiable contributions (credibility gets tested)
- (-) [Market structure] → a few challenge platforms monopolize attention and reputational value (new prestige bottlenecks emerge)
- (+) [Learning outside formal education] → public challenge records are imported into mainstream credential and hiring systems (open work becomes legible)

## ART 11.088 - Scalable Decentralized Governance

**Score: 3 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART builds new civic and organizational skills around proposing, debating, and verifying decisions in digital systems. Around the GVN, it also changes who gets to define credential rules, standards, and access rights in networked learning ecosystems. In feedback-loop terms, if governance itself becomes participatory and machine-supported, communities may update skill frameworks faster than legacy institutions. The main negatives are manipulation, voter fatigue, and software rulebooks that do not map cleanly to real accountability. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

**Weak signals (6):**

- (+) [Authority of educational institutions] → communities start voting on competency frameworks, badge criteria, or funding priorities (rule-making becomes participatory)
  - (+) [Recognizability of proficiency] → auditable governance histories become part of proving leadership or stewardship skills (civic proof emerges)
  - (+) [Learning to learn] → learners practice proposal-writing, evidence review, and delegated decision-making inside platforms (governance literacy grows)
  - (+) [Private sector and on-the-job learning] → organizations use governed rule updates instead of static HR policy for skill frameworks (adaptation speeds up)
  - (-) [Manipulation and accountability] → sybil attacks, capture attempts, or voter fatigue erode trust in outcomes (governance remains fragile)
  - (-) [Equality] → highly active or technically fluent groups dominate rule-setting (voice becomes uneven)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 20 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART is the clearest direct embodiment of the challenger regime: modular online learning, AI support, evidence-based assessment, and portable credentials; it is the clearest

candidate for a keystone score because it directly operationalizes the challenger regime described in the GVN. Around the GVN, it shifts authority away from teacher-time and campus-bound credentials toward networked assessment, employer recognition, and learner-owned evidence. In feedback-loop terms, the more employers, regulators, and public services accept these records, the more people invest in them, making the model self-reinforcing and weakening title-only gatekeeping. The biggest risks are low-quality credential mills, platform concentration, cheating at scale, and unequal access to premium guidance and reputation signals. At 5.5M-society scale it plausibly becomes a linchpin touching the weekly routines of hundreds of thousands to millions of learners and workers, so 20 is warranted.

### **Weak signals (11):**

- (+) [Flexibility and accessibility] → public systems fund modular online learning and portable credentials on equal footing with seat-time programs (operating model shifts)
- (+) [Direct feedback and motivation] → AI tutors become default support for adult reskilling and mainstream schooling (feedback abundance normalizes)
- (+) [Recognizability of proficiency] → major employers list verified microcredentials and performance portfolios as valid entry routes (labor market recognition broadens)
- (+) [Learning outside formal education] → community, workplace, and self-directed evidence is accepted into public qualification pathways (informal learning counts)
- (+) [Authorized evaluation of formal learning] → universities sign credit-transfer agreements for external competency records (institutional boundaries soften)
- (+) [Modernization and relevance] → course and assessment content updates track tool and regulation changes monthly (curriculum lag collapses)
- (+) [Private sector and on-the-job learning] → firms integrate internal task evidence into externally shareable credentials (work and learning merge)
- (+) [Learning to learn] → individuals maintain persistent skill graphs across multiple career changes (lifelong navigation becomes normal)
- (-) [Quality assurance] → credential mills, shallow badges, or manipulated AI assessments trigger public crackdowns (trust becomes selective)
- (-) [Equality and bargaining power] → premium reputation layers and coaching services become decisive for top opportunities (platform stratification intensifies)
- (-) [Authority of educational institutions] → incumbent institutions preserve prestige by refusing recognition or building closed credential ecosystems (dual regime persists)

## **ART 11.090 - Prediction-Market Forecasting Platforms**

### **Score: 1 (Impact in GVN 15)**

#### **Justification (3–5 sentences):**

Directly, this ART creates a measurable way to teach and prove judgment, calibration, and system-level anticipation rather than only static knowledge. Around the GVN, that can be useful in selected domains, but it is unlikely to replace mainstream proof systems outside decision-intensive roles. In feedback-loop terms, broader impact depends on employers and public bodies treating forecast records as a legitimate competency signal. The main negatives are gaming, thin participation, and

overvaluing one narrow style of reasoning. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for prediction-market forecasting platforms practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention prediction-market forecasting platforms experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 1 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART mostly reduces integration and troubleshooting friction in the systems that later support learning, assessment, or proof. Around the GVN, its institutional value is to make ecosystems less vendor-fragmented, but it does not itself transform pedagogy or recognition. In feedback-loop terms, if the downstream market becomes large, standards can quietly enable scale and portability that users later take for granted. The main negative is slow standard-setting that freezes incumbent assumptions. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

**Weak signals (6):**

- (+) [Learning to learn] → professional bodies launch short-course badges for interoperability-dependent systems practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention interoperability-dependent systems experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)

- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.092 - Interoperable Digital Twin Ecosystems

**Score: 5 (Impact in GVN 15)**

**Justification (3–5 sentences):**

Directly, this ART creates reusable digital environments where learners and workers can rehearse complex tasks, see system interactions, and generate auditable evidence of performance; its importance lies in portability: once twins and performance traces move across vendors, simulation-based proof becomes much easier to institutionalize. Around the GVN, that strongly supports the GVN's emphasis on procedural and systemic skills, contextuality, and private-sector/on-the-job learning. In feedback-loop terms, if simulation logs become accepted in hiring, training, and regulation, digital practice can displace part of course-completion logic. The main negatives are model drift, false confidence, and dependence on proprietary twin ecosystems. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

**Weak signals (9):**

- (+) [Procedural and systemic skills] → sector regulators accept validated simulation logs in training and recertification (evidence moves beyond hours)
- (+) [Understanding of meanings] → learners routinely inspect cause-effect maps inside digital twins (big-picture reasoning strengthens)
- (+) [Private sector and on-the-job learning] → employers expose operational twins to schools, apprentices, and new hires (workplace learning deepens)
- (+) [Recognizability of proficiency] → hiring and progression decisions include replayable scenario performance records (proof becomes auditable)
- (+) [Modernization and relevance] → course content updates when real systems, software, or regulations change (curriculum lag narrows)
- (+) [Learning to learn] → adults rehearse role changes in safe virtual settings before doing them live (transition costs fall)
- (-) [Quality assurance] → model error or stale parameters are shown to mis-train workers (simulation validity becomes central)
- (-) [Market structure] → one vendor's twin model becomes the de facto gatekeeper for recognized competence (ecosystem lock-in appears)
- (-) [Equality in access] → smaller institutions rely on low-fidelity twins and weaker evidence (proof quality stratifies)



## ART 12.093 — Global Supply Chain Traceability Networks

### Score: 1 (Impact in GVN 15)

Justification (3–5 sentences):

Directly, this ART mostly reduces integration and troubleshooting friction in the systems that later support learning, assessment, or proof. Around the GVN, its institutional value is to make ecosystems less vendor-fragmented, but it does not itself transform pedagogy or recognition. In feedback-loop terms, if the downstream market becomes large, standards can quietly enable scale and portability that users later take for granted. The main negative is slow standard-setting that freezes incumbent assumptions. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

Weak signals (6):

- (+) [Learning to learn] → professional bodies launch short-course badges for interoperability-dependent systems practitioners (new skill market forms)
  - (+) [Recognizability of proficiency] → employers mention interoperability-dependent systems experience or certificates in job ads (proof demand becomes visible)
  - (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
  - (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)
  - (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
  - (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.094 — Personal Data Portability & Trust Frameworks

### Score: 10 (Impact in GVN 15)

Justification (3–5 sentences):

Directly, this ART lets individuals carry learning records, assessment history, accommodations, and permissions across institutions and platforms under their own control; this shifts control over records and sharing logic toward the individual, which is central to weakening dependence on single institutions. Around the GVN, that shifts power away from siloed institutions and reduces the friction of proving prior learning, sharing support needs, or changing providers. In feedback-loop terms, if employers, schools, and public services all consume portable records, people gain more reason to maintain rich lifelong evidence, which further weakens single-institution lock-in. The main downsides are coercive over-sharing, security failures around wallets or recovery, and new inequalities in data literacy. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

Weak signals (9):



- (+) [Recognizability of proficiency] → schools, employers, and public employment services accept learner-controlled records through common APIs (records become portable in practice)
- (+) [Learning outside formal education] → self-study, workplace, and community evidence is imported into one permissions-managed profile (proof sources diversify)
- (+) [Flexibility and accessibility] → switching learning providers no longer requires manual transcript and accommodation transfer (friction drops sharply)
- (+) [Individual advancement] → users issue time-limited consent receipts instead of resubmitting the same records repeatedly (control becomes visible)
- (+) [Quality assurance] → standardized schemas for skills, accommodations, and outcomes appear across major platforms (comparison gets easier)
- (-) [Bargaining power] → employers or lenders pressure applicants to reveal more detailed histories than necessary (portability becomes coercive)
- (-) [Equality] → people with weak data literacy or poor recovery options lose access to important records (control is unevenly usable)
- (-) [Security] → wallet compromise or failed recovery produces high-profile loss-of-proof cases (trust depends on safety and recovery)
- (-) [Market structure] → a few wallet or identity providers dominate the consent layer (portability recentralizes through infrastructure)

## ART 12.095 — Interoperable Digital Currency Payment Networks

Score: 1 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART mainly reduces transaction friction around paying for learning, credential verification, or cross-border work rather than changing skill formation itself. Around the GVN, that can help modular learning markets function, but it remains an enabling layer below the main GVN bottlenecks. In feedback-loop terms, the impact rises only if micro-payments and cross-system settlement become essential to how skill markets operate. The downside is adding another infrastructure dependency without solving trust in the credentials themselves. The impact is concrete and worth monitoring, but the total plausible magnitude stays limited relative to the higher anchors, which fits 1.

Weak signals (6):

- (+) [Learning to learn] → professional bodies launch short-course badges for cross-platform learning transactions practitioners (new skill market forms)
- (+) [Recognizability of proficiency] → employers mention cross-platform learning transactions experience or certificates in job ads (proof demand becomes visible)
- (+) [Private sector and on-the-job learning] → equipment or platform vendors bundle simulation or training logs with deployments (work-based proof emerges)
- (-) [Dependence on established structures] → legacy degrees or old licenses remain hiring gates despite task changes (credential lag persists)

- (-) [Equality in access] → training capacity concentrates in large firms or a few labs (access bottleneck forms)
- (-) [Quality assurance] → disputes arise over whether certificates transfer across vendors and sites (portability stays weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

Score: 5 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART turns parts of accreditation, licensure, and compliance into machine-readable logic that can update faster than manual policy translation; the key leverage is speeding recognition of new proof pathways in regulated occupations that currently lag behind real skill change. Around the GVN, that could significantly reduce one of the GVN's key inhibitors: regulatory preference for old educational pathways and slow recognition of new proof methods. In feedback-loop terms, if rules can be updated and tested quickly, competency frameworks can evolve more often and alternative providers can enter more easily. The main negatives are over-formalization, loss of discretion, and regulatory capture through encoded rules. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

Weak signals (9):

- (+) [Regulatory barriers] → ministries or professional bodies publish machine-readable competency and licensure rules (recognition updates accelerate)
- (+) [Authorized evaluation of formal learning] → providers run sandbox checks against regulation before launching new credentials (entry friction falls)
- (+) [Modernization and relevance] → changes in safety, labor, or sector rules propagate into courseware and assessment logic quickly (content sync improves)
- (+) [Recognizability of proficiency] → employers automate validation of whether a credential meets current regulatory requirements (proof becomes more legible)
- (+) [Learning outside formal education] → alternative providers align portfolios to code-based compliance checks (nontraditional routes gain clarity)
- (-) [Authority and discretion] → edge cases expose where human judgment cannot be cleanly coded (formalization hits limits)
- (-) [Market structure] → a few rule-engine vendors become essential intermediaries for compliance-grade learning systems (governance centralizes)
- (-) [Regulatory capture] → encoded rules preserve legacy assumptions and exclude novel competence proofs (old pathways get hardened digitally)
- (+) [Resistance to change] → incumbent institutions lose some advantage from interpreting complex rules manually (translation monopoly weakens)

## ART 12.097 — Open Metaverse Interoperability Protocols

Score: 5 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART makes immersive learning spaces, identities, assets, and performance records portable across platforms instead of trapping them inside single vendors; the value here is less the 3D worlds themselves and more the fact that learning assets, identities, and evidence can persist across them. Around the GVN, that matters because the educational value of XR rises sharply when schools, employers, and learners can carry evidence and content across ecosystems. In feedback-loop terms, if portability becomes normal, more organizations will invest in serious immersive practice and proof because assets and records retain value beyond one platform. The main downsides are standards wars, new moderation and safety burdens, and dominant gateways reappearing at the protocol layer. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

Weak signals (9):

- (+) [Flexibility and accessibility] → learning assets and accessibility settings move between major immersive platforms (switching costs fall)
- (+) [Recognizability of proficiency] → employers and schools accept performance records generated in different virtual environments (proof becomes portable)
- (+) [Private sector and on-the-job learning] → firms reuse training worlds and credentials across vendors rather than rebuilding them (investment risk drops)
- (+) [Learning to learn] → users maintain persistent skill histories across multiple immersive contexts (lifelong record deepens)
- (+) [Modernization and relevance] → open content pipelines make XR course updates faster and less vendor-dependent (content portability improves)
- (-) [Quality assurance] → inconsistent physics, moderation, or identity semantics undermine trust in cross-platform evidence (standards quality matters)
- (-) [Market structure] → a few large gateways dominate discovery and identity despite open protocols (interoperability recentralizes)
- (-) [Safety and governance] → harassment, spoofing, or asset theft in shared virtual spaces trigger tighter proof controls (social trust becomes decisive)
- (+) [Authorized evaluation of formal learning] → cross-platform assessment rules for immersive evidence are published by sector bodies (legitimacy standardizes)

## ART 12.098 — Content Authenticity Infrastructure

Score: 10 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART attaches auditable provenance to assessments, portfolios, project artifacts, and AI-assisted work so others can verify what a person actually did; in an AI-heavy environment, portfolio and assessment integrity becomes a first-order issue for whether proficiency can be believed at all. Around the GVN, that directly stabilizes the 'proof' side of the GVN as synthetic media and AI generation make unauthenticated evidence less trustworthy. In feedback-loop terms, if

employers, schools, and platforms start preferring credentialed provenance, more learning activity will be captured with authenticity metadata from the start. The main downsides are unequal access to capture tools, false confidence in provenance as truth, and pressure for pervasive traceability. If adopted across major education, hiring, and workplace-learning settings, the effect plausibly reaches hundreds of thousands of people weekly or exceeds €1B-equivalent in labor and learning time, which fits 10.

Weak signals (9):

- (+) [Recognizability of proficiency] → employers or admissions teams require provenance-bearing portfolios for selected roles (artifact trust becomes decisive)
- (+) [Authorized evaluation of formal learning] → exam and coursework systems attach verifiable creation histories by default (assessment integrity hardens)
- (+) [Learning outside formal education] → community and workplace projects gain legitimacy because contribution history is machine-checkable (informal proof strengthens)
- (+) [Resistance to change] → institutions move from blanket AI bans to provenance-based acceptance rules (governance matures)
- (+) [Quality assurance] → browsers, LMSs, and hiring platforms expose simple provenance summaries to non-experts (verification becomes routine)
- (-) [Equality in access] → people without authenticity-enabled devices or workflows face weaker trust in their outputs (proof quality stratifies)
- (-) [Bargaining power] → platforms demand excessive traceability over every draft and interaction (evidence becomes extractive)
- (-) [Quality assurance] → forged or broken provenance chains still slip through and trigger public trust crises (metadata is not truth)
- (-) [Security and dual-use] → capture-device keys or signing workflows are compromised in high-stakes credential disputes (trust infrastructure becomes attack surface)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

Score: 5 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART lets institutions jointly analyze performance, benchmark assessments, and improve models without pooling sensitive raw data; its biggest contribution is letting institutions collaborate on better proof systems without defaulting to risky raw-data pooling. Around the GVN, that can lower the compliance and trust burden blocking cross-organizational learning innovation and skill proof. In feedback-loop terms, if trusted collaboration becomes cheaper, more actors participate, models improve, and common proof standards become easier to maintain. The main downside is complexity that favors large incumbents unless tooling becomes very usable. In a 5.5M-person society the largest plausible pathway is big enough to land in the €100M–1B or 50–500M person-hour range, fitting 5.

Weak signals (9):

- (+) [Quality assurance] → institutions jointly benchmark assessments without exchanging raw learner records (shared improvement becomes feasible)
- (+) [Private sector and on-the-job learning] → employers and educators run joint analytics on transition outcomes under cryptographic controls (cross-boundary learning improves)
- (+) [Recognizability of proficiency] → sector bodies compare competence evidence across providers without central data pooling (standard-setting becomes easier)
- (+) [Regulatory barriers] → privacy authorities accept secure collaboration protocols for sensitive education or workforce data (compliance route opens)
- (+) [Learning to learn] → users authorize portable analytics on their own history across providers (lifelong guidance strengthens)
- (-) [Equality] → only large actors can afford the secure-computation stack at first (small providers are left out)
- (-) [Quality assurance] → slow or opaque protocols reduce trust in outputs despite stronger privacy claims (usability becomes a blocker)
- (-) [Market structure] → protocol operators or compute brokers gain disproportionate influence over who can collaborate (new gatekeepers emerge)
- (+) [Authorized evaluation of formal learning] → cross-provider quality reviews run on encrypted evidence rather than sampled raw files (audit burden falls)

## **ART 12.100 — Manufacturing-specific standards + conformance testing + certification infrastructure**

Score: 3 (**Impact in GVN 15**)

Justification (3–5 sentences):

Directly, this ART makes skills and process claims in advanced manufacturing more testable through standardized conformance evidence. Around the GVN, that supports competence-based hiring and certification in a large industrial domain, but not across the whole GVN. In feedback-loop terms, if adopted broadly, auditable machine/job evidence can reduce reliance on tacit local reputation and static credentials in manufacturing work. The main negatives are compliance overhead and the risk that standards ossify vendor assumptions. The largest plausible pathway is sectoral rather than society-wide, but still material enough to reach roughly €10–100M or 5–50M person-hours annually, which fits 3.

Weak signals (6):

- (+) [Recognizability of proficiency] → buyers and employers require standardized conformance evidence alongside worker certificates (proof becomes more testable)
- (+) [Authorized evaluation of formal learning] → technical schools align assessments to accredited benchmark jobs and test artifacts (education links to certification)
- (+) [Private sector and on-the-job learning] → machine-generated quality data feeds directly into recertification and progression (work evidence formalizes)

- (+) [Quality assurance] → shared benchmark jobs make cross-site skill claims easier to compare (trust improves)
- (-) [Compliance burden] → smaller firms struggle with audit and metrology costs (access to recognized proof narrows)
- (-) [Market structure] → standards or test suites embed incumbent vendor assumptions (innovation and portability suffer)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## GVN 16: Producing Experiences ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score: 20 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Mature global broadband removes a core bottleneck to the challenger regime: time- and location-independent shared experiences become ordinary across entertainment, gaming, fandom, political mobilization, and remote participation. Second-order effects are large because access bundles, recommendation markets, and identity layers become new gatekeepers for who can create, join, and monetize experiences; harms scale too, especially manipulation, addictive engagement, and unequal platform power. If 400k–800k people in a 5.5M society participate weekly in connected immersive formats, the affected spend and person-hours clearly clear the 10-point anchor; because this is a linchpin of the shift, it reaches 20.

**Weak signals (9):**

- [Time/location independence] → national festivals sell remote-presence tickets with near-parity perks (distance stops mattering)
- [Shared experiences] → co-watch, co-play, and co-create modes become default in mass-market subscriptions (co-presence normalized)
- [Creator economy] → rural and independent creators reach national audiences without local intermediaries (distribution barrier collapses)
- [Education/work/leisure boundary] → immersive access reimbursements appear outside leisure budgets (usage spills outward)
- [Authenticity norm] → critics and public funders rank networked performances beside physical ones (status hierarchy erodes)
- [Access equality] → telecom policy frames immersive access as inclusion infrastructure (democratization politicized)
- – [Manipulation risk] → campaign groups buy broadband-native live influence formats (targeting scales fast)

- – [Market power] → connectivity bundles lock users into a few experience platforms (gatekeepers consolidate)
- – [Social alienation] → youth services track conflict tied to online-only peer groups (offline ties weaken)

## ART 01.002 - Ultra-Low Latency Networks

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Ultra-low latency makes synchronized co-presence, cloud-rendered immersion, responsive telepresence, and high-stakes live participation feel immediate enough to rival physical attendance. It changes not only user experience but venue design, labor allocation, and platform competition, while also increasing dependence on tightly controlled infrastructure and making manipulative real-time nudging more effective. Once shared games, concerts, training, political events, and creator tools rely on millisecond responsiveness, hundreds of thousands of weekly users can be affected, which clears the 10-point anchor.

### **Weak signals (9):**

- [Shared experiences] → remote participants appear in live events without visible lag penalties (remote feels live)
- [Interactive media] → esports and social worlds market latency guarantees, not just bandwidth (timing becomes product)
- [Venues] → arenas and museums procure edge-linked rendering and interaction stacks (infrastructure hardens)
- [Skill development] → simulation and rehearsal systems shift from niche to routine use (practice gets embodied)
- [Producer-consumer divide] → audiences vote, steer, or perform inside live formats in real time (participation deepens)
- [Travel substitution] → premium remote attendance products sell against physical trip costs (presence detaches physically)
- – [Market structure] → only platforms with edge-node access can host top-tier formats (advantage concentrates)
- – [Manipulation risk] → instant behavioral adaptation is used in political or commercial persuasion (nudging tightens)
- – [Resilience] → outages during synchronized mass events trigger liability claims (latency becomes mission-critical)

## ART 01.003 - Edge AI for Sensor Data

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Mature edge AI lets venues, devices, and media systems interpret gesture, gaze, motion, voice, crowd mood, and environmental context locally and in real time. That changes how experiences are staged and monetized: installations adapt moment by moment, creators can personalize without



central delay, and operators can reduce staff while expanding surveillance and behavioral influence. If adaptive retail, tourism, entertainment, education, and campaign environments become routine, the weekly lives of hundreds of thousands are plausibly touched, which clears the 10-point anchor.

#### **Weak signals (9):**

- [Experience venues] → museums, arenas, and retail spaces procure on-device multimodal perception kits (adaptation localizes)
- [Creativity] → game engines and event software expose edge-personalization by default (design logic shifts)
- [Shared experiences] → installations visibly change pacing or content from group behavior (collective feedback loops)
- [Accessibility] → overload, fatigue, and mobility cues trigger automatic interface adjustments (participation widens)
- [Cost structure] → venues reduce live technical staffing after local automation upgrades (labor reallocates)
- [Privacy acceptance] → operators market “local-only processing” as a customer feature (trust becomes differentiator)
- – [Manipulation risk] → scandals emerge around emotion-responsive pricing or persuasion (influence gets granular)
- – [Governance] → unions and watchdogs demand disclosure when affect inference is active (oversight formalizes)
- – [Security] → spoofing or adversarial input disrupts adaptive shows and spaces (experience integrity weakens)

## **ART 01.004 - Quantum & High-Precision Sensing**

### **Score: 1 (Impact in GVN 16)**

#### **Justification (3–5 sentences):**

The most plausible route here is niche: premium affective measurement, ultra-precise tracking, or new scientific spectacle formats. Most producing-experiences impacts stay indirect unless biosignal-rich immersion or location-tracking becomes routine consumer input. That keeps it worth watching, but below material societal anchors; it would rise to 3 only if precision sensing becomes a standard experience interface.

#### **Weak signals (5):**

- [Premium experiences] → high-end installations market “lab-grade” biosensing as immersion feature (niche demand appears)
- [Performance art] → creators use precision magnetics or gravimetry as artistic medium (new sensory grammar)
- [Gaming/VR] → headset suppliers test precision physiological tracking modules (consumer bridge forms)
- – [Ethics] → watchdogs question covert biometric measurement in experience settings (consent becomes salient)

- – [Procurement] → venue buyers still avoid precision-sensing requirements in mainstream tenders (pathway stays narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Dense micro/nano sensor networks make physical environments more measurable, which helps create responsive architecture, crowd-aware venues, and condition-aware props and wearables. The larger effect is on operating economics and design freedom rather than on experience formats alone, while privacy and data ownership conflicts scale with invisibility. That is material but not transformative, which fits a 3.

**Weak signals (5):**

- [Experience venues] → new builds embed sensor meshes into walls, floors, and seating (spaces become instrumented)
- [Shared experiences] → crowd-flow and interaction heatmaps are used to redesign live events (collective behavior measured)
- [Safety/comfort] → venues tune temperature, sound, and vibration from dense local feedback (experience gets optimized)
- – [Privacy] → audience groups challenge invisible tracking in public leisure spaces (social license weakens)
- – [Market power] → dominant venue platforms hoard sensor-derived behavioral datasets (data advantage widens)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART matters less because sensing becomes richer and more because richer sensing becomes socially deployable at scale. It can unlock adaptive venues, context-aware media, and personalized participation while reducing some legal and reputational barriers, but it also normalizes continuous measurement as long as it is packaged as “safe.” That combination can materially reshape access, trust, and business models across experience markets, fitting a 5.

**Weak signals (5):**

- [Shared spaces] → malls, museums, and stadiums advertise privacy-preserving analytics badges (trust barrier lowers)
- [Venue procurement] → tenders require on-device inference and bounded retention by default (compliance shapes design)
- [Users] → consent dashboards show granular sharing choices for live experiences (agency becomes visible)

- – [Audience data ownership] → disputes emerge over whether aggregate emotion data is exploitative (new rights conflict)
- – [Regulators] → certification schemes appear for privacy-preserving experience sensing stacks (deployment standardizes)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Secure communication matters for premium virtual goods, creator rights, political experiences, and remote control of live environments, but it is mostly an enabling trust layer rather than a new experience form. The bigger effect is second-order: fewer integrity failures, more confidence in remote participation and high-value digital events, and stronger platform control over secure identity infrastructure. That is material enough for a 3, but not central to the GVN's main transition.

### **Weak signals (5):**

- [Premium digital experiences] → major event platforms upgrade long-lived identity and ticket channels (trust becomes selling point)
- [Political/ideological experiences] → secure livestream and coordination products target campaigns and movements (high-stakes use grows)
- [Creator rights] → virtual asset platforms market quantum-resilient provenance and ownership (IP protection tightens)
- – [Market structure] → only large operators can afford certified secure event stacks (scale advantages deepen)
- – [Governance] → insurance or licensing starts requiring upgraded secure networks for flagship events (assurance becomes mandatory)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 - Integrated Sensing and Communication (ISAC)

**Score: 5 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

ISAC makes communication infrastructure double as spatial sensing infrastructure, which is valuable for responsive venues, AR layers, crowd management, and context-aware public experiences. Its largest impact is systemic: it lowers deployment cost for ambient experience systems while expanding the reach of invisible monitoring, safety controls, and behavioral analytics. That can materially shift how commercial and civic experiences are staged and governed, fitting a 5.

### **Weak signals (5):**

- [Venue infrastructure] → arena and campus networks advertise combined connectivity and spatial awareness (dual-use turns commercial)

- [AR experiences] → location-based content uses network sensing instead of separate tracking rigs (deployment gets cheaper)
- [Safety/flow] → venues manage queues and crowd density from radio-sensing overlays (operations become adaptive)
- – [Privacy] → pushback rises against sensing-by-network in “just connectivity” environments (trust boundary blurs)
- – [Regulation] → spectrum and venue rules begin addressing communication-linked sensing explicitly (governance catches up)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART matters by bringing always-on multimodal inference into headsets, wearables, props, robots, and venue hardware without prohibitive heat or battery penalties. Its second-order impact is large enough to reshape who can build adaptive experiences, because more intelligence moves to cheaper edge devices rather than centralized specialist infrastructure; manipulation and covert sensing also get easier. That broad enabling role fits a 5.

**Weak signals (5):**

- [Wearable experiences] → headset and earbud roadmaps emphasize always-on local adaptation (edge intelligence cheapens)
- [Creator tools] → consumer-grade devices run multimodal interaction locally, not in cloud (entry barrier drops)
- [Experience venues] → robotic props and kiosks gain low-power event-recognition modules (ambient interactivity widens)
- – [Privacy/manipulation] → watchdogs flag covert inference in “offline” devices (hidden processing matters)
- – [Supply chain power] → a few chip platforms dominate experience-device ecosystems (hardware gatekeeping grows)  
Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This is a broad compute enabler whose experiential effect comes through lighter, cooler, and longer-

lasting immersive devices and infrastructure. The bigger change is economic: lower power and heat relax design constraints for headsets, wearables, sensors, and venue equipment, but they do not define the experience logic themselves. That is material enough for a 3.

#### **Weak signals (5):**

- [Device form factor] → premium AR/VR hardware gets visibly lighter and cooler without capability loss (wearability improves)
  - [Always-on experiences] → consumer devices keep context features active all day (ambient use expands)
  - [Venue infrastructure] → rendering and interaction nodes shrink in size and cooling needs (deployment gets easier)
  - – [Market structure] → component dependence shifts toward a few new materials ecosystems (supplier power reorders)
  - – [Authenticity debate] → critics note mediated experiences feel less “tech-heavy” and more natural (friction softens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 02.011 - Quantum Computing Platforms**

**Score: 1 (Impact in GVN 16)**

#### **Justification (3–5 sentences):**

The most plausible route is through niche optimization, simulation, or premium generative tools for content and scheduling rather than through direct experiential change. Most experience producers will encounter the effects indirectly, if at all, through cloud services embedded elsewhere. That makes it worth monitoring but below material anchors for this GVN.

#### **Weak signals (5):**

- [Premium content pipelines] → flagship studios market quantum-assisted optimization or rendering workflows (niche creative use)
  - [Event operations] → large venues test quantum-assisted scheduling or pricing tools (back-end experimentation starts)
  - [Prestige experiences] → quantum-branded exhibitions or games appear as novelty draws (symbolic linkage forms)
  - – [Cost barrier] → mainstream creator tools still avoid quantum-dependent features (diffusion remains narrow)
  - – [Governance] → no sector-specific rules yet treat quantum use in experience markets as distinctive (institutional pull absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 02.012 - Photonic and Optical Computing**

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Photonic computing mainly affects producing experiences by lowering the cost and thermal burden of heavy rendering, simulation, and interconnect loads. That helps dense immersive worlds and venue infrastructure scale, but the main effect is through backend economics and performance ceilings rather than through new formats alone. It is therefore material but not transformative, fitting a 3.

**Weak signals (5):**

- [Cloud experiences] → immersive platforms advertise lower-latency optical compute backends (performance ceiling rises)
  - [Venue infrastructure] → large experience sites replace bulky render clusters with optical modules (space and heat ease)
  - [Creator tools] → real-time volumetric or generative workflows become affordable to smaller teams (production widens)
  - – [Market power] → only hyperscale providers initially control optical compute capacity (dependency deepens)
  - – [Resilience] → outages in centralized optical backends disrupt many linked experience services (concentration risk visible)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 02.013 - Next-Gen Memory & Storage****Score: 5 (Impact in GVN 16)****Justification (3–5 sentences):**

Persistent virtual worlds, rich audience histories, volumetric media libraries, and creator-side asset reuse all depend on cheaper and denser memory/storage. The second-order effect is important: switching costs rise when social graphs, personalized memory trails, and persistent identities become part of the product, while archives and replay markets expand. That is a meaningful part of the GVN shift, fitting a 5.

**Weak signals (5):**

- [Persistent experiences] → virtual worlds keep years of user state and world history live by default (persistence becomes norm)
  - [Shared memories] → consumer platforms sell searchable life-archive and replay services (memory becomes product)
  - [Creator economy] → volumetric asset libraries expand without premium pricing (production scales faster)
  - – [Switching costs] → users lose major value when leaving a platform-bound archive (lock-in strengthens)
  - – [Governance] → disputes rise over retention rights for experiential traces and audience histories (data ownership sharpens)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

No strong mature-state route from molecular computing to the core operating model of producing experiences is visible beyond speculative bio-art or niche interface concepts. Meaningful impact would require adjacent sectors to create a usable consumer or venue format first. For now that keeps it below the threshold for non-trivial GVN impact.

**Weak signals (5):**

- [Bio-art] → mainstream festivals commission molecular-compute installations, not just lab demos (linkage begins)
  - [Creator tools] → experience-sector suppliers mention molecular logic in product roadmaps (commercial bridge forms)
  - [Wellness/therapy experiences] → controlled environments use molecular computing as interactive substrate (first real use)
  - – [Regulation] → cultural-use guidance appears for reactive molecular systems in public spaces (public deployment gated)
  - – [Investment] → entertainment and tourism funds start backing molecular-experience ventures (market meaning shifts)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 - Causal Learning & Reasoning

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Causal AI matters because experience producers increasingly want to know what actually changes engagement, bonding, persuasion, learning, or addictive behavior, not just what correlates with clicks. That improves experience design and governance, but it also sharpens behavioral optimization for political, commercial, and ideological influence. The combination is material across media, venues, gaming, and social platforms, fitting a 5.

**Weak signals (5):**

- [Creator strategy] → platforms move from A/B dashboards to intervention-effect dashboards (optimization gets deeper)
- [Mission experiences] → advocacy campaigns model which experiences change behavior, not just attention (mobilization refines)
- [Skill development] → simulations explain why a design choice changed participant outcomes (feedback improves)



- – [Manipulation] → firms sell causal persuasion stacks to advertisers or political actors (influence becomes engineered)
- – [Governance] → regulators ask for causal evidence in harm and addiction claims (scrutiny gets sharper)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART allows personalization and adaptation to draw on sensitive behavior, emotion, health, or social data without pooling all raw traces in one place. That can widen socially acceptable use of AI in intimate and public experiences, while also strengthening the actors that control update protocols and model governance. Because it unlocks adoption more than it creates formats, 5 is appropriate.

**Weak signals (5):**

- [Personalization] → major experience platforms advertise device-local model learning as a feature (trust unlocks tailoring)
- [Shared experiences] → group recommendations adapt from private device histories without central upload (coordination improves privately)
- [Access equality] → smaller venues join shared model pools without sharing raw data (capability diffuses)
- – [Governance] → disputes emerge over who benefits from locally generated learning signals (value capture contested)
- – [Compliance] → certification appears for federated audience-learning systems (deployment formalizes)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.017 - Trustworthy AI Systems

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

For this GVN, trustworthy AI is mainly an adoption gate: without it, personalized and immersive experiences are easier to reject in schools, workplaces, public institutions, and high-visibility civic settings. Its largest impact is second-order, through certification, auditing, liability, and public trust, while also creating stronger control points for large platforms and regulators. That is materially important but not itself the core experience shift, so 5 fits.

**Weak signals (5):**

- [Public-sector experiences] → schools, museums, and civic platforms require audited AI stacks (trust becomes entry ticket)
- [Platform competition] → providers market explainability and safe-mode features to parents and institutions (assurance monetizes)

- [Creator tools] → generative assistants include visible guardrail and provenance controls (workflow norms harden)
- – [Market power] → compliance costs push smaller experience creators onto giant audited platforms (consolidation risk)
- – [Governance] → insurers price premiums differently for certified vs non-certified AI experiences (trust gets financialized)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.018 - Automated Machine Learning (AutoML)

**Score: 5 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

AutoML lowers the skill barrier for building recommendation systems, adaptive storylines, audience models, and creator-side optimization tools. That widens the producer base and speeds experimentation, but it also makes manipulative and homogenized design easier to industrialize at lower cost. The net magnitude is clearly material across experience markets, fitting a 5.

### **Weak signals (5):**

- [Creativity] → non-technical creators launch personalized experience features without specialist teams (production democratizes)
- [Platform competition] → smaller firms rapidly clone recommendation and targeting capabilities (capability diffuses)
- [Participatory media] → local communities spin up adaptive worlds or events from templates (entry friction drops)
- – [Homogenization] → experience formats converge around machine-optimized engagement patterns (novelty narrows)
- – [Manipulation] → cheap optimization stacks show up in political and ideological experiences (influence industrializes)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 5 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Collaborative multi-agent AI can run dynamic worlds, coordinated NPC ecologies, live service operations, moderation, and mixed physical-digital event orchestration. Its bigger effect is systemic: fewer humans are needed to monitor many small interactions, while creators gain capacity to stage richer shared experiences at scale and platforms gain new control levers. That is a substantial but not singular shift, fitting a 5.

### **Weak signals (5):**

- [Shared experiences] → online worlds use persistent AI factions or hosts that coordinate live events (worlds feel inhabited)

- [Venue operations] → concerts, parks, and exhibitions deploy multi-agent backstage automation (complexity becomes manageable)
- [Sociability] → AI agents broker introductions, team formation, or mission coordination in communities (participation scaffolds)
- – [Labor] → live moderation and event-support roles shrink after agent orchestration adoption (human oversight thins)
- – [Safety] → failures in agent coordination create visible crowd or platform incidents (complex systems misfire)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.020 - Quantum-Accelerated AI Systems

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This is mostly a high-end backend accelerator for selected optimization or search tasks, not a direct experiential technology. Any impact on producing experiences would arrive through premium cloud services embedded in existing AI systems. That is worth monitoring, but it remains below material societal anchors for this GVN.

**Weak signals (5):**

- [Premium creator tools] → top-end media platforms advertise quantum-assisted planning or generation (niche capability enters)
- [Large venues] → enterprise orchestration tools test quantum-assisted optimization modules (back-end experimentation appears)
- [Prestige branding] → experiences market quantum AI as exclusivity signal (symbolic use emerges)
- – [Cost barrier] → mainstream creative tools still avoid quantum-dependent features (diffusion remains elite)
- – [Governance] → experience-sector policy does not yet single out quantum AI as distinctive (institutional pull weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The strongest route here is indirect: faster discovery may feed new materials, interface methods, or content-generation tools later. It does not itself alter the experience-production operating model except through long-lag spillovers and occasional “science as spectacle” use. That keeps it in the watchlist rather than the material-impact tier.

**Weak signals (5):**

- [Science-as-experience] → museums and media brands build public formats around autonomous discovery systems (symbolic linkage appears)
  - [Creator technology] → experience-sector suppliers cite AI-discovery-derived materials or devices (spillover becomes concrete)
  - [Public imagination] → autonomous science becomes recurring narrative content in entertainment and politics (cultural salience grows)
  - – [Procurement] → no large creator or venue stack yet depends directly on autonomous discovery (operating linkage weak)
  - – [Governance] → cultural institutions treat it as research infrastructure, not experience infrastructure (boundary persists)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 20 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This is the clearest keystone ART for the challenger regime because it directly turns experiences into portable, participatory, manipulable, and globally shared environments. It reconfigures the producer-consumer divide, shifts value from physical attendance to hybrid presence, and expands both creativity and addiction/manipulation risks at scale. If several hundred thousand people use spatial entertainment, education, tourism, work-leisure blends, and social spaces weekly, the impact is clearly above the 10-point anchor; because it is central rather than supportive, it earns 20.

**Weak signals (9):**

- [Escapism] → persistent virtual hangouts compete with mainstream physical nightlife (virtual sociality mainstreams)
- [Shared experiences] → remote attendance products deliver parity status with in-person participation (presence detaches location)
- [Creativity] → creators release spatial-first works before flat-screen versions (format hierarchy flips)
- [Skill development] → simulation-rich cultural and leisure formats move into mass consumer bundles (practice becomes experience)
- [Travel substitution] → tourism boards market immersive visits as paid products, not previews (distance loses primacy)
- [Authenticity norm] → critics, schools, and funders stop treating VR/AR as secondary media (legitimacy rises)
- – [Addiction] → treatment and insurance protocols start naming immersive overuse explicitly (harm becomes visible)

- – [Manipulation] → regulation targets biometric adaptation and subliminal spatial nudging (influence concern escalates)
- – [Inequality] → premium hardware and exclusive worlds create new cultural class markers (access stratifies)

## ART 04.023 - Brain-Computer Interfaces (BCI)

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

BCIs can change how experiences are entered, controlled, and felt by bypassing some of the limits of hands, screens, and speech. The direct upside is accessibility and deeper immersion; the second-order downside is extreme intimacy of data, new coercion risks, and stronger platform control over attention and internal states. If BCI-based control and feedback become routine in premium entertainment, therapy, learning, and community participation, the 10-point anchor is plausible.

### **Weak signals (9):**

- [Accessibility] → immersive platforms ship BCI modes as standard accessibility options (participation widens sharply)
- [Escapism] → premium leisure products market hands-free deep immersion sessions (friction to entry falls)
- [Self-exceeding] → competitive gaming and training use neural control benchmarks publicly (new skill status forms)
- [Shared experiences] → social platforms add attention- or affect-linked interaction channels (communication gets internalized)
- [Device ecosystem] → major headset vendors expose neural input APIs to creators (toolchain opens)
- [Healthcare-leisure crossover] → therapeutic BCI products are repurposed for mainstream experience markets (adjacent validation spills)
- – [Neural privacy] → lawsuits or scandals arise over retention of inferred neural-state data (inner life commodified)
- – [Coercion] → employers or schools restrict or mandate BCI-linked participation modes (power boundary moves)
- – [Security] → spoofing or hijack incidents trigger high-profile trust shocks (neural interfaces feel unsafe)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

These technologies mainly affect the GVN by widening who can participate in physical, performative, and social experiences and by enabling new embodied performance formats. The second-order effect is cultural and economic: accessibility becomes a design norm, some labor roles broaden, and some performance standards shift. That is meaningful and material, but not a core restructuring of the experience economy.

**Weak signals (5):**

- [Participation] → festivals, sports, and arts venues add exoskeleton-compatible access services (embodied inclusion rises)
  - [Creativity] → performers and creators build exoskeleton-native acts or choreography (new aesthetics emerge)
  - [Self-exceeding] → consumer experiences market assisted climbing, dance, or endurance formats (augmentation becomes leisure)
  - – [Equality] → disputes appear over enhancement advantages in participatory experiences (fairness boundary shifts)
  - – [Insurance] → venue liability policies start naming assistive robotics use (institutionalization begins)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 04.025 - Haptic and Multi-Sensory Feedback Systems****Score: 10 (Impact in GVN 16)****Justification (3–5 sentences):**

Richer haptics make mediated experiences feel physically consequential rather than mainly visual and auditory, which materially changes gaming, intimacy, performance, training, tourism, and remote sociality. They also alter labor and platform control because whoever defines haptic standards controls part of the user's embodied reality, and misuse can intensify addiction, coercion, or injury. With widespread integration into immersive entertainment and remote participation, the 10-point anchor is credible.

**Weak signals (9):**

- [Shared experiences] → remote concerts, sports, and social apps add synchronized haptic layers (co-presence becomes bodily)
- [Escapism] → review culture starts treating “feel quality” as a mainstream criterion (sensory depth normalizes)
- [Creativity] → creators release haptic-first works, not just optional add-ons (new expressive layer forms)
- [Skill development] → simulation products use force and texture feedback in mass-market training (practice becomes tactile)
- [Accessibility] → multisensory substitution tools reduce dependence on sight and hearing alone (participation diversifies)
- [Intimacy markets] → touch-mediated social and care experiences grow outside niche products (social bandwidth expands)
- – [Safety] → injury, overstimulation, or harassment complaints target haptic features (body-risk becomes visible)
- – [Standards power] → a few platforms lock creators into proprietary sensory profiles (embodiment gets gated)
- – [Manipulation] → persuasive design starts using bodily cues, not only visual nudges (influence deepens)

## ART 04.026 - AI Understanding of Human Intent & Context

**Score: 20 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART directly matches one of the challenger regime’s named mechanisms: AI that reads emotions, preferences, roles, and context to tailor experiences continuously. It can dramatically deepen sociability, personalization, participation, and accessibility, but also intensifies manipulation, covert influence, and unequal bargaining power around intimate behavioral data. If adaptive media, venues, devices, and communities become routine across hundreds of thousands of weekly users, the 10-point anchor is easily passed; because this capability drastically increases the core shift toward personalized immersive experiences, it merits 20.

**Weak signals (9):**

- [Emotional experiences] → consumer platforms openly market mood- and context-adaptive content streams (affect targeting normalizes)
- [Shared experiences] → group events change pacing or narrative based on live social dynamics (collective adaptation emerges)
- [Accessibility] → systems infer overload, confusion, or exclusion and adjust automatically (participation widens in practice)
- [Producer-consumer divide] → audiences stop “choosing menus” and start being continuously interpreted (interface logic shifts)
- [Creativity] → creators author intent-responsive story branches as standard workflow (content becomes contingent)
- [Institutional use] → schools, employers, and civic platforms pilot context-aware participation layers (use escapes entertainment)
- – [Manipulation] → outrage follows covert emotion-adaptive pricing, persuasion, or ideology formats (power asymmetry sharpens)
- – [Privacy] → class-action disputes target opaque inference of mood, intent, and social role (data boundary hardens)
- – [Social alienation] → users report stronger attachment to adaptive systems than local groups (machine bonding deepens)

## ART 04.027 - Brain-to-Brain Interfaces

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

BBIs could create entirely new shared experiences around tacit coordination, empathy transfer, and collective performance, which matters to this GVN’s emphasis on shared experiences and influence. The impact remains below the top tier because adoption is likely narrower and more specialized than mass AR/VR or context AI, yet the social and ethical ripple effects could still be large where it does take hold. That combination supports a 5.

**Weak signals (5):**



- [Shared experiences] → premium social or therapeutic products test direct neural cue exchange (new social bandwidth appears)
  - [Creativity] → artists and performers build BBI-mediated collective acts (novel co-presence emerges)
  - [Influence] → training or coordination markets sell tacit-state transfer as advantage (coordination becomes intimate)
  - – [Consent] → public backlash focuses on unclear boundaries of mental sharing (ethics becomes central)
  - – [Governance] → specialized licensing or venue rules appear for BBI-enabled experiences (deployment gets bounded)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Memory prostheses affect this GVN through recall, replay, and continuity of experience rather than through new shared environments alone. Their largest second-order effects are in therapeutic participation, life-logging, and the market for curated personal memory services, alongside new privacy and authenticity conflicts. That is material enough for a 3, but not a dominant operating-model shift.

**Weak signals (5):**

- [Emotional experiences] → memory-support features are sold as premium life-archive or remembrance services (memory becomes commodity)
  - [Participation] → people with memory impairments re-enter richer leisure and social formats (inclusion improves)
  - [Creativity] → creators use prosthetic recall for long-form worldbuilding or performance continuity (production changes subtly)
  - – [Authenticity] → debates grow over edited or replay-biased memories in relationships and culture (genuine experience contested)
  - – [Privacy] → stored memory traces become target of legal and commercial claims (inner archive commodified)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Autonomous road transport changes producing experiences mainly by turning travel time into experience time and by making mobile venues, commuting media, nightlife logistics, and

destination access more flexible. Second-order effects include new spatial patterns of attendance, changed venue catchments, and altered labor in transport-linked experience sectors. That is significant enough to fit a 5.

#### **Weak signals (5):**

- [Time/location independence] → ride cabins are sold as media, work-leisure, or social pods (travel becomes experience)
  - [Access] → remote venues market attendance without parking or sober-driver constraints (friction to go falls)
  - [Shared experiences] → autonomous shuttle fleets bundle synchronized en-route entertainment (journey becomes collective)
  - – [Labor] → nightlife and tourism logistics jobs shift as vehicle autonomy spreads (support roles reconfigure)
  - – [Governance] → cities zone pickup/loiter rules around autonomous experience traffic (space politics changes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 05.030 - Drone Swarms & Aerial Robots**

**Score: 5 (Impact in GVN 16)**

#### **Justification (3–5 sentences):**

Drone swarms are directly relevant to spectacle, broadcasting, surveillance-linked public experiences, and rapid production of location-based media. Their larger systemic effect is on who can stage large-scale visual events and how public space is monitored, policed, and monetized. That is a meaningful shift in experience production and control, fitting a 5.

#### **Weak signals (5):**

- [Creativity] → drone choreography displaces fireworks and static light shows in major events (spectacle format shifts)
  - [Political/ideological experiences] → rallies and campaigns deploy swarm-based displays and live imaging (symbolic power scales)
  - [Shared experiences] → tourism products bundle aerial robot accompaniment or guided visuals (experience layer thickens)
  - – [Security] → anti-drone infrastructure becomes standard at mass gatherings (risk becomes structural)
  - – [Public-space governance] → municipalities limit or license swarm spectacle corridors (airspace becomes contested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 05.031 - Humanoid and General-Purpose Robots**

**Score: 10 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART directly enters the challenger regime's physical branch: robots can cook, perform, guide, host, build sets, maintain venues, and extend human creators into many places at once. The second-order impact is major because labor structure, creator identity, service expectations, and authenticity norms all shift, while gig-like teleoperation and synthetic social bonding can deepen inequality and manipulation. If hospitality, arts, care-like experiences, retail, tourism, and events normalize robotic performers and hosts, the 10-point anchor is plausible.

**Weak signals (9):**

- [Physical experiences] → restaurants, hotels, and venues market robot-hosted premium formats (robot service becomes draw)
- [Creativity] → artists and labels release performances designed for robotic embodiment (new performance grammar forms)
- [Access] → remote experts supervise many local robots in tourism or cultural venues (skills scale geographically)
- [Shared experiences] → families and communities treat robot guides or companions as recurring participants (social role thickens)
- [Cost structure] → venues expand operating hours because robots handle low-demand time slots (supply broadens)
- [Customization] → patrons choose robot persona, style, or sensory profile as part of purchase (experience personalizes)
- – [Authenticity] → backlash frames robot-made art, food, or care as emotionally hollow (status conflict sharpens)
- – [Labor] → hospitality, event, and backstage workers organize against robotic substitution (labor politics intensifies)
- – [Manipulation] → emotionally tuned robot companions are used for upselling or ideological nudging (trust gets exploited)

## ART 05.032 – Soft Robotics & Bio-Inspired Machines

**Score: 3 (Impact in GVN 16)****Justification (3–5 sentences):**

Soft robotics matters where safe touch, variable objects, intimate contact, or fragile environments are part of the experience. Its main GVN role is to widen the range of physical interaction design in installations, therapy, hospitality, and play, while lowering some injury barriers. That is material but not a central systemic shift.

**Weak signals (5):**

- [Touch-rich experiences] → museums, therapy spaces, and family venues adopt soft interactive robots (safe contact matters)
- [Creativity] → creators use compliant robots as performative partners, not backstage tools (aesthetics diversify)
- [Accessibility] → assistive leisure and play products use soft actuation for mixed-ability participation (gentle interaction widens)

- – [Liability] → insurers create separate categories for close-contact soft robotic experiences (risk model matures)
- – [Authenticity] → user reviews split on whether soft robotic contact feels comforting or uncanny (acceptance remains unsettled)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

This ART mostly expands where experiences can be produced or accessed: remote tourism, live mapping, dangerous-site storytelling, underwater spectacle, and autonomous media capture. The biggest effects are on access and operating cost rather than on mainstream everyday experience formats. That makes it material but not transformative.

### **Weak signals (5):**

- [Exploration experiences] → tourism and media packages offer autonomous remote dives, flights, or site visits (access widens remotely)
- [Shared experiences] → live autonomous capture from dangerous environments becomes a recurring content genre (risk becomes consumable)
- [Creativity] → creators rent autonomous fleets instead of specialist crews for immersive capture (production democratizes somewhat)
- – [Security] → public backlash follows autonomous filming in sensitive or protected spaces (surveillance concerns rise)
- – [Regulation] → permits and insurance begin treating autonomous experiential capture separately (use gets bounded)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Autonomy-support infrastructure matters when venues, public spaces, parks, campuses, or retail districts are redesigned for robot-readable experiences. Its main impact is second-order: simpler robots become usable, choreographed machine activity becomes denser, and venue owners gain new control over traffic and interaction rules. That is material but mainly infrastructural, fitting a 3.

### **Weak signals (5):**

- [Venues] → new entertainment districts install robot lanes, docking points, and machine-readable surfaces (space adapts to robots)
- [Experience operations] → venue design briefs assume mixed human-robot flows from the start (autonomy becomes baseline)

- [Cost structure] → smaller robots enter experience work because infrastructure carries complexity (deployment gets cheaper)
- – [Access/power] → only high-capex operators can build autonomy-ready sites (spatial inequality grows)
- – [Governance] → public debate emerges over who sets machine behavior rules in semi-public venues (control becomes political)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The main experiential route is niche: longer-running aerial shows, persistent robotic guides, or untethered sensing in large sites. Most impacts remain support-function improvements rather than a shift in the experience economy's core logic. That keeps the score at 1.

**Weak signals (5):**

- [Large venues] → persistent aerial or mobile robots run full event durations without charging breaks (uptime becomes visible)
- [Spectacle] → long-endurance drone shows outcompete battery-limited formats (duration expands)
- [Remote experiences] → robot coverage in remote parks or campuses lasts continuously (service continuity improves)
- – [Safety] → beam-exposure rules become a visible constraint in public leisure settings (deployment is gated)
- – [Procurement] → most mainstream venues still avoid power-beaming infrastructure (pathway stays narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This could matter in niche stagecraft, vertical venue maintenance, climbing robots for spectacle, or delicate set manipulation. Those uses are real but narrow, and most of the GVN would only see indirect spillovers through production efficiency. That makes it worth watching but not materially impactful overall.

**Weak signals (5):**

- [Stagecraft] → climbing robots begin servicing facades or overhead sets in live venues (vertical access improves)

- [Spectacle] → performances use wall-climbing robotic actors as a draw (novel format appears)
  - [Production efficiency] → delicate set handling shifts from rigging crews to dry-adhesion tools (backstage use grows)
  - – [Safety] → adhesion failures in public performance contexts gain visibility (trust remains fragile)
  - – [Procurement] → adoption stays limited to specialty venues and production houses (diffusion remains narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART shortens the path from idea to physical experience by letting creators print props, wearables, interactive objects, scenography, and customized sensory artifacts in one workflow. The larger effect is on creator structure and local production: smaller teams can prototype and personalize faster, while IP leakage and quality variance become more important. That fits a 5.

**Weak signals (5):**

- [Creativity] → experience studios print finished multi-material props, not just prototypes (production localizes)
  - [Desire to stand out] → customized event wearables and merch become economically routine (uniqueness gets cheaper)
  - [Participation] → communities fabricate localized mission or fan artifacts on demand (co-creation expands)
  - – [IP] → rights disputes rise around downloadable experiential object files (physical piracy changes form)
  - – [Quality/safety] → certification or insurance rules appear for printed interactive consumer objects (trust needs formalization)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 06.038 - Digital Twin & Simulation-Driven Production

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Digital twins matter by making venues, attractions, sets, and productized experiences easier to test before building or reconfiguring. The main impact is on design speed, reliability, and coordination

between creators, operators, and suppliers rather than on audience-facing experience forms alone. That is materially useful but not transformative.

**Weak signals (5):**

- [Experience venues] → major attractions and exhibition sites keep live digital twins through operations (rehearsal becomes routine)
  - [Creativity] → event designers simulate audience flow and emotional pacing before launch (design gets data-rich)
  - [Cost structure] → fewer costly rebuilds or cancellations follow twin-based planning (risk falls visibly)
  - – [Market power] → only larger operators can maintain high-fidelity twin ecosystems (capability gap widens)
  - – [Governance] → contracts start requiring twin-access rights between venue owners and creators (data control matters)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.039 - Reconfigurable & Agile Factories**

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART affects the GVN through faster churn of physical experience goods, themed merchandise, modular installations, and limited-run products. Its systemic value is in flexibility and lower changeover costs, not in a direct change to how audiences experience content. That keeps it at a material but not transformative 3.

**Weak signals (5):**

- [Experience goods] → merch and exhibit hardware turn over in shorter cycles without stock blowouts (variant speed rises)
  - [Local production] → regional factories win work for small-batch experiential products (distance shrinks in supply)
  - [Creator economy] → niche communities order short-run physical products profitably (micro-audiences monetize better)
  - – [Labor] → manufacturing work shifts toward setup, orchestration, and platform dependence (skills profile changes)
  - – [Market structure] → platform-linked factories dominate creator fulfillment contracts (coordination power concentrates)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.040 - Circular & Sustainable Manufacturing**

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The strongest route is reputational and mission-oriented: experience producers increasingly sell



low-waste, traceable, or regenerative physical formats as part of the experience itself. The main impact is second-order through legitimacy, procurement standards, and cost structures for events, venues, and merchandise. That is material enough for 3.

#### **Weak signals (5):**

- [Mission experiences] → festivals and cultural brands market closed-loop production as a core narrative (ethics becomes experience)
  - [Merchandise] → recycled and bio-derived experiential goods become standard, not premium niche (norms shift)
  - [Public procurement] → funding criteria reward circular event and venue supply chains (institutional demand grows)
  - – [Greenwashing] → authenticity disputes target unverifiable sustainability claims in experience markets (trust becomes contested)
  - – [Cost structure] → smaller creators struggle with circular compliance and reporting demands (burden redistributes unevenly)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.041 - Bio-fabrication technologies**

### **Score: 1 (Impact in GVN 16)**

#### **Justification (3–5 sentences):**

The main experiential pathways are niche: cultivated sensory materials, bio-art, biomedical tourism, or specialized gastronomy and wellness. Those could become visible but would not broadly reconfigure the operating model of producing experiences without strong complementary shifts. So this stays at 1.

#### **Weak signals (5):**

- [Bio-art] → major exhibitions and festivals use fabricated tissues or bio-materials as headline features (symbolic linkage appears)
  - [Food/wellness] → premium experience venues trial bio-fabricated textures or materials (niche demand forms)
  - [Medical tourism] → therapeutic and experiential packages begin bundling bio-fabrication narratives (adjacent market crossover)
  - – [Ethics] → public controversy limits deployment in mainstream leisure contexts (acceptance remains fragile)
  - – [Procurement] → broad venue and media supply chains still avoid bio-fabricated inputs (linkage stays niche)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.042 - 4D Printed & Programmable Materials**

### **Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Programmable materials matter because they let physical experiences change form over time without heavy mechanics, which is powerful for sets, wearables, toys, themed spaces, and participatory artifacts. The bigger effect is on creator freedom and maintenance economics, while also creating new safety and reliability expectations for adaptive objects. That makes them a significant enabling layer, fitting a 5.

**Weak signals (5):**

- [Creativity] → stage, retail, and exhibition elements visibly reconfigure without motors or staff (matter becomes performance)
  - [Desire to stand out] → adaptive wearables and props become mainstream premium products (novelty gets embodied)
  - [Experience operations] → venues use self-deploying or self-calibrating fixtures to cut setup time (labor needs shrink)
  - – [Safety] → failure of transforming consumer objects triggers new liability rules (adaptation needs assurance)
  - – [Authenticity] → audiences debate whether programmable matter feels magical or gimmicky (acceptance still negotiated)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 06.043 - Volumetric Additive Manufacturing****Score: 3 (Impact in GVN 16)****Justification (3–5 sentences):**

Faster additive production helps experience markets that value customization, rapid iteration, and compact localized fabrication. Its main effect is to reduce delays and coordination costs for physical artifacts in events, retail, fandom, and experiential design rather than to create a new dominant format. That fits a 3.

**Weak signals (5):**

- [Experience goods] → same-day fabrication becomes normal for props, merch, and exhibit components (latency collapses)
  - [Local production] → venues or malls host on-site object fabrication for personalized purchases (production meets audience)
  - [Creativity] → designers test many physical variants inside one event cycle (experimentation accelerates)
  - – [Quality] → reliability problems in fast-made consumer artifacts trigger trust questions (speed tests assurance)
  - – [IP] → event-branded product files circulate outside authorized channels (piracy becomes physical)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART can materially improve AR optics, spatial displays, sensing, and wireless quality in crowded venues, all of which matter to richer and lighter immersive experiences. The main GVN effect is enabling: better comfort, lower device bulk, and more controllable environments, while also making surveillance and exposure management more subtle. That significant enabling role fits a 5.

**Weak signals (5):**

- [Immersive devices] → AR glasses shed visible bulk through flat-optic designs (wearability jumps)
  - [Venue infrastructure] → stadiums and public spaces install wave-shaping panels for better AR/connectivity (environment becomes tuned)
  - [Shared experiences] → spatial overlays stay stable in dense crowds without heavy hardware (mass adoption barrier falls)
  - – [Privacy] → venue owners gain finer control over who can sense or connect where (information asymmetry sharpens)
  - – [Market structure] → proprietary optical/connectivity layers lock creators into specific device ecosystems (platform dependence grows)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 07.045 - Room-Temperature Superconductors

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Its most plausible experiential effect is indirect: cheaper power handling, denser compute, improved magnetic/audio/sensing hardware, and lower operating costs for large venues or data infrastructure. Those could be material at system scale but do not directly define how experiences are produced. Hence 3, not higher.

**Weak signals (5):**

- [Venue infrastructure] → flagship arenas or data-rich attractions adopt superconducting power systems first (infrastructure economics shift)
- [Immersive hardware] → premium sensing or audio systems advertise superconducting performance gains (quality ceiling rises)
- [Cost structure] → continuous-operation immersive sites report major energy savings from upgraded electrical backbones (uptime gets cheaper)

- – [Access inequality] → only large operators can afford first-wave deployment (benefits concentrate)
- – [Hype risk] → experiential claims outpace verifiable user benefits in mainstream markets (signal remains noisy)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

These materials mainly matter by making wearables, props, seating, haptics, and adaptive interiors more durable and sometimes more responsive. That changes maintenance economics and reliability in experience-heavy environments, with some upside for safety and sustainability. It is useful and material, but not a core shift.

**Weak signals (5):**

- [Experience venues] → high-traffic surfaces market self-healing durability as lower downtime feature (maintenance burden drops)
- [Wearables] → adaptive costumes and accessories survive repeated event cycles with less replacement (lifecycle lengthens)
- [Interactive objects] → consumer devices adjust feel or stiffness by use mode (objects become context-aware)
- – [Trust] → users report hidden degradation despite “self-healing” claims (assurance matters)
- – [Recycling] → waste rules start addressing smart-polymer separation in event and merch streams (material complexity grows)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The linkage is mostly indirect: better coatings can improve screens, stage surfaces, anti-fouling, touch feel, hygiene, and maintenance. Those matter operationally but do not strongly change the core experience economy unless paired with larger interface shifts. That keeps the score at 1.

**Weak signals (5):**

- [Venues] → premium attractions market anti-fog, self-cleaning, or high-durability surfaces (operational use appears)
- [Displays] → improved optical coatings become visible in immersive hardware reviews (user benefit becomes legible)
- [Hospitality experiences] → hygienic or low-friction coatings are sold as comfort and trust features (maintenance becomes marketing)

- – [Safety] → coating wear or chemical concerns trigger product scrutiny in consumer experience devices (risk pathway appears)
- – [Procurement] → mainstream buyers still treat coatings as backstage detail, not experience differentiator (impact remains narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score: 1 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

HEAs mainly affect producing experiences through more durable rides, robotics, structures, and hardware in harsh use conditions. That is operationally helpful but far from a primary driver of how experiences are created and shared. So it stays at 1.

### **Weak signals (5):**

- [Experience infrastructure] → premium rides, robots, or stage hardware adopt HEA components for durability (backbone improves)
- [Remote/harsh venues] → tourism assets in corrosive or high-stress environments shift to HEA parts (reliability expands access)
- [Safety] → longer inspection intervals become feasible for critical moving experience hardware (uptime improves)
- – [Cost] → use stays limited to flagship assets with extreme duty cycles (diffusion remains narrow)
- – [Branding] → audiences rarely perceive material choice as part of the experience value (consumer salience stays low)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

**Score: 1 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

The main route into this GVN is legitimacy: low-carbon operations can matter to mission experiences, public trust, and regulation around travel- and venue-intensive formats. But the effect is mostly contextual, not a direct shift in experience production methods. That makes it worth monitoring at 1.

### **Weak signals (5):**

- [Mission experiences] → venues and festivals market on-site carbon capture as part of identity (ethics becomes visible)
- [Public legitimacy] → licensing or sponsorship favors lower-carbon experience operations (indirect pressure grows)
- [Tourism] → premium destinations use capture systems as educational or symbolic attractions (narrative linkage appears)

- – [Greenwashing] → scrutiny rises over overstated capture claims in experience branding (trust can backfire)
- – [Cost] → smaller creators avoid the technology despite reputational incentives (impact remains uneven)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Lighter, tougher composites can materially improve wearables, drones, haptics, mobile stages, sports and adventure equipment, and immersive hardware. The effect is enabling and spread across many products rather than concentrated in one format, but it can still shift cost/performance in meaningful ways. That supports a 3.

**Weak signals (5):**

- [Wearable experiences] → headsets, exosuits, and haptic gear drop weight without losing robustness (comfort threshold improves)
- [Spectacle] → drone and mobile-scenography products gain longer runtimes or larger payloads (show capabilities widen)
- [Adventure experiences] → premium gear markets higher strength-to-weight as access enabler (range and safety rise)
- – [Health/safety] → nanoparticle handling and disposal become visible issues in consumer-facing products (regulation catches up)
- – [Cost] → benefits remain concentrated in premium tiers for several cycles (mass access lags)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Comfort is central to many experiences, and these materials can materially improve wearability, venue usability, and device runtime while cutting energy overhead. The main effect is operational and infrastructural rather than narrative, but it can widen where immersive and outdoor experiences are viable. That is material enough for a 3.

**Weak signals (5):**

- [Wearability] → immersive devices and costumes become comfortable for much longer sessions (session length rises)

- [Venue comfort] → pop-up and outdoor experiences rely on passive thermal regulation instead of heavy HVAC (site options widen)
- [Energy costs] → venues use thermal materials to flatten peaks during high-sensory events (operations stabilize)
- – [Equity] → premium comfort remains locked to higher-priced devices and venues first (benefits stratify)
- – [Safety] → failures of thermal management in consumer gear draw liability attention (trust depends on reliability)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This mainly reduces supply risk in motors, speakers, haptics, robotics, and transport systems used by the experience economy. The effect is real but indirect, showing up through availability and cost stability rather than a visible change in experience formats. So 1 is sufficient.

**Weak signals (5):**

- [Device supply] → audio, haptic, and robotic experience hardware advertises rare-earth-light designs (sourcing pressure shows)
- [Cost stability] → experience-device pricing becomes less sensitive to magnet material shocks (supply risk eases)
- [Mission branding] → sustainable device lines use magnet sourcing as part of their identity (ethics enters product story)
- – [Performance] → premium segments delay adoption if feel or power quality drops (trade-off remains visible)
- – [Consumer salience] → most users still do not select experiences based on motor magnet chemistry (linkage remains backstage)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

**Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

There is no strong direct route from low-energy desalination membranes to the core operating model of producing experiences, except in limited resort or remote-site infrastructure contexts. Those spillovers are too indirect to count as meaningful GVN impact on their own. So this remains a watchpoint at 0.

**Weak signals (5):**



- [Remote tourism] → water-constrained destinations market membrane-enabled expansion of visitor experiences (linkage begins locally)
- [Festival infrastructure] → large temporary sites adopt desalination as part of onsite service systems (operational bridge forms)
- [Mission experiences] → sustainability branding explicitly features water-autonomy infrastructure (narrative linkage appears)
- – [Procurement] → mainstream cultural and leisure operators do not mention desalination capability (commercial bridge absent)
- – [Public meaning] → the technology remains framed as utilities infrastructure, not experience infrastructure (boundary stays firm)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Better power electronics matter to smaller, quieter, cooler devices and mobile systems across headsets, lighting, drones, robotics, and venues. The impact is spread across many enabling subsystems rather than concentrated in one visible format, but it can still materially improve feasibility and runtime. That fits a 3.

**Weak signals (5):**

- [Immersive hardware] → smaller power modules extend headset, haptic, or drone runtime without bulk (mobility improves)
- [Venue infrastructure] → lighting, audio, and motion systems shrink cooling and noise needs (experience quality improves quietly)
- [Pop-up experiences] → compact high-power kits enable temporary installations in harder locations (deployment widens)
- – [Supply power] → a few semiconductor ecosystems dominate upgraded experience hardware stacks (dependency increases)
- – [Safety] → reliability and heat-cycling standards tighten around new power modules in public-use devices (assurance becomes crucial)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This could help remote venues, long-duration robotics, or mobile events where batteries are constraining, but those are support-function benefits. The core operating model of producing experiences changes little unless hydrogen-backed autonomy becomes a common experiential backbone. That keeps the score at 1.

**Weak signals (5):**

- [Remote experiences] → long-duration event support robots or vehicles shift to solid-hydrogen cartridges (niche operational use)
  - [Pop-up venues] → off-grid experiences market silent long-endurance hydrogen support systems (range constraint eases)
  - [Adventure tourism] → endurance platforms use safer hydrogen storage as service differentiator (logistics improve)
  - – [Safety] → public-use rules for hydrogen cartridges in leisure contexts become visible constraint (risk still central)
  - – [Diffusion] → mainstream experience sites still favor batteries and grids for simplicity (pathway stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Fusion's route into this GVN is extremely indirect: abundant clean power could cheapen data centers, venues, and travel-intensive experience formats. But it does not by itself alter how experiences are designed, shared, or governed. So it remains a low-score background factor.

**Weak signals (5):**

- [Large-scale digital experiences] → hyperscale immersive providers cite fusion-backed clean power procurement (indirect cost floor shifts)
  - [Mission branding] → cultural and civic venues use fusion-linked power sourcing in identity narratives (symbolic linkage appears)
  - [Remote venues] → energy-intensive attractions explore fusion-powered districts or grids (site economics change slowly)
  - – [Distance from GVN] → no experience format depends specifically on fusion capability (linkage remains background)
  - – [Public meaning] → fusion is discussed as energy infrastructure, not experience infrastructure (operating bridge weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

SMRs mostly matter via energy reliability for data-rich campuses, districts, or remote tourism/entertainment sites. That can matter to operations and legitimacy, but it is still an infrastructure spillover rather than a meaningful reshaping of the GVN. So 1 is appropriate.

**Weak signals (5):**

- [Remote destinations] → resorts, parks, or cultural districts explore SMR-backed energy autonomy (site feasibility changes)
  - [Reliability] → always-on digital experience campuses pair branding with SMR power resilience (uptime becomes narrative)
  - [Mission experiences] → public education or controversy around SMRs enters experience programming (symbolic use appears)
  - – [Public acceptance] → safety concerns make leisure-sector association politically costly (adoption remains limited)
  - – [Procurement] → mainstream experience operators do not treat SMRs as a direct strategic lever (linkage stays indirect)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.058 - Thin-film solar cells****Score: 3 (Impact in GVN 16)****Justification (3–5 sentences):**

Thin-film solar matters where energy generation can be embedded into surfaces, wearables, pop-up venues, or low-power ambient devices used in experience settings. The main effect is to widen autonomy and lower setup friction rather than to redefine experiences by itself. That supports a material but not transformative 3.

**Weak signals (5):**

- [Wearable experiences] → costumes, accessories, and lightweight devices integrate visible solar skins (autonomy enters design)
  - [Pop-up venues] → temporary installations rely on surface-integrated power rather than heavy cabling (deployment gets easier)
  - [Outdoor experiences] → tourism and festival equipment markets solar-enabled resilience as user benefit (service continuity improves)
  - – [Aesthetics] → visual integration quality becomes a deciding adoption factor in consumer-facing formats (form still matters)
  - – [Durability] → weathering and repair complaints slow mainstream use in experience-heavy products (reliability remains gate)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.059 - Bionic Leaf Technology****Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

No strong direct route from artificial-photosynthesis panels to the core operating model of producing experiences is visible today. Any effect would likely be symbolic, infrastructural, or confined to highly themed sustainability venues. That keeps it below the threshold for non-trivial impact.

**Weak signals (5):**

- [Mission experiences] → sustainability-focused venues showcase bionic-leaf panels as part of the visitor experience (symbolic linkage begins)
  - [Remote sites] → off-grid attractions test the panels to support niche energy autonomy (operational bridge forms)
  - [Education/culture] → museums and science parks feature working systems as participatory exhibits (public meaning shifts slightly)
  - – [Commercial pull] → mainstream event and leisure procurement does not request the technology (bridge stays weak)
  - – [Narrative status] → the technology remains framed as climate-tech, not experience-tech (sector boundary holds)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.060 - Grid-Scale Energy Storage****Score: 3 (Impact in GVN 16)****Justification (3–5 sentences):**

Reliable storage matters to experience production because data-rich and venue-rich systems are increasingly continuous, energy-sensitive, and outage-intolerant. The main impact is systemic: fewer interruptions, more flexible siting, and lower need for diesel or overbuilt backup in events and districts. That is materially useful, which fits a 3.

**Weak signals (5):**

- [Experience districts] → venues and campuses market storage-backed uninterrupted operation (reliability becomes visible)
  - [Live events] → fewer backup generators are used at major temporary events (operational model shifts)
  - [Remote participation] → storage smooths service quality for always-on immersive platforms and local nodes (outage risk falls)
  - – [Capex inequality] → resilient energy remains concentrated in larger venues and districts first (access differs by scale)
  - – [Safety] → storage fire or failure rules reshape event and venue permitting (infrastructure risk becomes explicit)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.061 - Solid-State Batteries

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Safer, denser batteries directly improve the wearability, comfort, and untethered duration of headsets, haptics, robots, wearables, and mobile experience devices. The wider effect is commercial: more acceptable all-day form factors, fewer safety frictions, and more mobile physical-digital experiences, while dependence on specific supply chains and health data from devices can deepen. That is a significant enabling shift, fitting a 5.

**Weak signals (5):**

- [Immersive devices] → all-day AR/VR products become commercially credible without heavy battery packs (wearability barrier drops)
  - [Mobile experiences] → untethered haptic, robotic, and multisensory systems run full sessions reliably (mobility expands)
  - [Safety] → insurers and venues relax restrictions on dense wearable power packs (trust improves)
  - – [Market structure] → battery-rich incumbents gain new advantage in device ecosystems (supply power grows)
  - – [Data/control] → longer-lived devices collect much deeper behavior trails over time (intimacy of data expands)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Its link to the GVN is mainly infrastructural and reputational: low-carbon fuels can support remote venues, mobility, and public legitimacy of energy-intensive experiences. Those are real but indirect effects, not direct changes to content, participation, or experience design. So 1 is appropriate.

**Weak signals (5):**

- [Remote venues] → hard-to-grid attractions market low-carbon fuel autonomy (logistics improve at edges)
  - [Mission branding] → festivals or tourism operators certify hydrogen-backed operations visibly (ethics enters operations)
  - [Mobility-linked experiences] → transport-heavy event circuits pilot green-fuel fleets (support systems decarbonize)
  - – [Safety/permitting] → hydrogen handling rules constrain use in public-facing settings (deployment remains bounded)
  - – [Consumer salience] → audiences rarely choose an experience primarily for its Power-to-X backbone (linkage stays indirect)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Like other generation technologies, this mainly matters through general energy price and reliability effects. There may be symbolic uses in mission-driven destinations or remote infrastructure, but it does not strongly alter how experiences are created or shared. That keeps it at 1.

**Weak signals (5):**

- [Remote destinations] → wind-backed autonomy is marketed by off-grid leisure and tourism sites (symbolic operational linkage)
  - [Mission experiences] → cultural brands tie identity to direct wind-powered operation (ethics becomes visible)
  - [Public spectacle] → turbine-rich landscapes become part of educational or scenic experience design (cultural meaning broadens)
  - – [Aesthetics/conflict] → opposition to visual or sound impacts affects nearby experience sites (energy-experience tension appears)
  - – [Direct leverage] → no major experience format depends specifically on wind efficiency gains (linkage remains background)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The strongest route into this GVN is niche: powering drones, remote installations, temporary venues, or mobility-rich experiences where wires are constraining. Those uses are real but unlikely to reshape the core operating model broadly. So the score stays at 1.

**Weak signals (5):**

- [Remote experiences] → temporary events test beam-powered sensors or small robots in hard-to-wire areas (niche feasibility appears)
  - [Spectacle] → endurance aerial or kinetic installations depend on wireless power links (format extension emerges)
  - [Mobility] → public demos show mobile devices receiving useful experience-grade power untethered (consumer imagination stirs)
  - – [Safety] → beam intensity and exclusion-zone rules limit public deployment (regulation remains central)
  - – [Cost] → mainstream venues still prefer wired or battery solutions (commercial crossover stays weak)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Advanced geothermal affects the GVN through steady low-carbon power and heat, particularly for districts, data-rich venues, or remote tourism. That is useful background infrastructure but not a direct lever on how experiences are produced or shared. So it remains a 1.

**Weak signals (5):**

- [Destination infrastructure] → geothermal-backed districts market resilient experience operations (site economics improve)
  - [Mission branding] → venues use geothermal sourcing in public identity and education (symbolic linkage appears)
  - [Thermal experiences] → spa, wellness, or attraction clusters combine geothermal utility with consumer narrative (adjacent fit emerges)
  - – [Public salience] → most consumers still do not perceive geothermal as part of the experience offer (linkage stays indirect)
  - – [Direct adoption] → mainstream experience operators treat geothermal as landlord-level infrastructure (boundary remains upstream)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Microgrids matter because live events, immersive venues, and platform-linked physical spaces are increasingly intolerant of outages and poor power quality. Their main effect is infrastructural resilience, flexible siting, and reduced disruption rather than new experience logic. That is materially relevant and fits a 3.

**Weak signals (5):**

- [Live experiences] → venues market blackout-resistant operation and faster recovery as part of service promise (uptime becomes differentiator)
  - [Remote destinations] → microgrids enable premium experiences in weak-grid locations (site options widen)
  - [Temporary events] → modular microgrids replace diesel-heavy backup norms (operations become cleaner and steadier)
  - – [Capex inequality] → only high-volume operators can afford resilient local grids (quality gap widens)
  - – [Governance] → event permits start expecting islanding and recovery plans (resilience becomes institutionalized)
- Signal density: LOW (linkage weak; additional signals would be speculative).



## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Its main routes into this GVN are cultural, political, and niche experiential: wellness, bodily enhancement narratives, bio-art, or altered food and companion-animal experiences. Those could become visible, but they do not yet imply a broad shift in the operating model of producing experiences. So it stays at 1.

**Weak signals (5):**

- [Body/identity experiences] → enhancement-adjacent leisure or wellness offerings invoke gene-editing narratives (cultural bridge appears)
  - [Bio-art] → mainstream exhibitions feature editable biology as participatory medium (symbolic linkage grows)
  - [Food/companions] → experience markets experiment with edited novelty organisms or ingredients (niche consumer pull)
  - – [Ethics/politics] → controversy makes public-facing experiential use difficult (social license remains fragile)
  - – [Mainstream adoption] → broad leisure and cultural markets avoid direct gene-editing use (pathway stays narrow)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 09.068 - mRNA Therapies & Vaccines

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The primary impact is indirect: healthier populations, faster epidemic control, and perhaps more confidence in dense gatherings or travel. That is important societally, but it does not directly change how experiences are designed, distributed, or monetized beyond resilience effects. So it remains a 1 here.

**Weak signals (5):**

- [Mass gatherings] → event sectors explicitly rely on rapid-response vaccine infrastructure in continuity plans (resilience linkage forms)
- [Travel experiences] → destinations market health-security responsiveness as part of visitor trust (indirect experience value)
- [Wellness markets] → personalized mRNA narratives spill into consumer identity and prevention offerings (adjacent symbolism grows)

- – [Public trust] → controversy around platform medicines spills into event and tourism legitimacy debates (confidence can polarize)
- – [Direct leverage] → experience producers rarely treat mRNA capability as a primary creative input (operating linkage weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 5 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Food is explicitly named in the GVN as a source of emotional and sensory experience, so mature cultured meat and fermentation can directly change hospitality, gastronomy, tourism, and ethical mission experiences. The second-order effects are also significant: provenance, identity politics, creator-chef roles, and notions of authenticity all shift. That is a clear 5.

### **Weak signals (5):**

- [Food experiences] → flagship restaurants and festivals treat cultured products as creative medium, not novelty (culinary grammar shifts)
- [Mission experiences] → ethical dining and climate-linked food events scale into mainstream hospitality (values become sensory)
- [Authenticity debate] → critics and diners split over whether “realness” still requires animal origin (status hierarchy moves)
- [Shared experiences] → communal tasting formats use provenance storytelling as core social content (food becomes narrative)
- – [Market structure] → ingredient platforms rather than chefs capture growing value share (creative power may relocate)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

**Score: 1 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

The direct experience routes are niche: bio-art, educational spectacle, biomedical tourism, and advanced therapeutic participation. Those are real but unlikely to reshape the experience economy broadly without major adjacent changes. So the score remains 1.

### **Weak signals (5):**

- [Bio-art/education] → organoid-based installations appear in mainstream cultural institutions (symbolic linkage forms)
- [Therapeutic experiences] → high-end medical or wellness centers use tissue-engineering narratives in service design (adjacent crossover)
- [Public imagination] → tissue engineering becomes recurring theme in popular interactive media (cultural salience grows)

- – [Ethics] → controversy constrains mainstream leisure adoption of living tissue artifacts (license remains fragile)
- – [Commercial demand] → few experience operators procure organoid-based inputs directly (operating bridge stays weak)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Designer microbes can affect producing experiences through novel scents, materials, foods, responsive environments, and mission-oriented sustainable production narratives. The main impact is not only sensory novelty but also cheaper local reconfiguration of experiential materials, with governance concerns around containment and authenticity. That is material enough for a 3.

### **Weak signals (5):**

- [Sensory experiences] → venues deploy bio-derived scent, color, or texture systems as core design elements (new media emerges)
- [Mission experiences] → brands use microbial production visibly in ethical or educational formats (process becomes part of story)
- [Food/wellness] → fermentation-led experiential products diversify quickly around local microbe recipes (creator flexibility rises)
- – [Containment] → biosecurity rules start governing public-facing use of engineered microbes (institutional friction appears)
- – [Authenticity] → users debate whether bio-made sensory goods feel crafted or artificial (meaning remains contested)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 - Microbiome Engineering

**Score: 1 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

The main links are wellness, personalized bodily comfort, environmental quality in shared spaces, and some niche therapeutic or hospitality formats. Those may matter at the margins, but they do not broadly reorganize how experiences are produced. So 1 is appropriate.

### **Weak signals (5):**

- [Wellness experiences] → personalized microbiome adjustment becomes part of premium retreats or care packages (adjacent service grows)
- [Shared spaces] → venues market engineered microbial balance for smell, comfort, or hygiene (environmental experience changes)
- [Identity markets] → microbiome profiles become part of self-optimization and lifestyle branding (symbolic linkage appears)

- – [Ethics/safety] → unintended ecosystem concerns limit public-facing deployment (trust remains fragile)
- – [Mainstream adoption] → most entertainment and culture producers see microbiome engineering as outside their core stack (bridge stays narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score: 1 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Its strongest experience-sector effects are indirect: people may participate longer, tailor wellness experiences differently, or carry genomic identity into personalized services. But that is not a direct shift in the GVN's operating model; it is mainly a support layer for adjacent health and lifestyle markets. So 1 fits.

### **Weak signals (5):**

- [Wellness/identity experiences] → leisure and care services start integrating genomic risk or trait data (adjacent personalization expands)
- [Participation] → tailored physical or cognitive experiences are marketed from genomic profiles (identity enters service logic)
- [Data politics] → genomic results become a status or segmentation signal in premium experiences (sorting risk appears)
- – [Privacy] → pushback rises against genotype-linked pricing or access in leisure markets (boundary hardens)
- – [Core linkage] → most mainstream experience producers do not rely on genomic diagnostics directly (operating impact remains narrow)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 0 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

No strong mature-state route from organs-on-chips to the core operating model of producing experiences is visible beyond bio-art, education, or long-lag tool spillovers. Meaningful impact would require a new public-facing interface or service model to emerge around them. For now, that keeps the linkage below the threshold for non-trivial impact.

### **Weak signals (5):**

- [Bio-art/education] → public institutions exhibit organs-on-chips as participatory media (symbolic bridge begins)
- [Creator tools] → experience-sector suppliers reference chip-based biological testing in sensory product design (spillover becomes concrete)

- [Therapeutic experiences] → premium wellness or rehab services use chip-derived personalization claims (adjacent crossover appears)
- – [Public comfort] → ethical unease limits mainstream entertainment use of living-chip narratives (license remains weak)
- – [Commercial demand] → venue and media procurement rarely mention the technology (bridge remains missing)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 — Biological Aging & Longevity Barriers

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

If healthy longevity expands, the experience economy changes through longer active participation, different demand patterns, and less age-linked exclusion from physical, creative, or social formats. The second-order effects are substantial but diffuse: labor in performance and care shifts, and experience design targets older but more active cohorts. That is material enough for a 3.

### **Weak signals (5):**

- [Participation] → older cohorts stay active in physically demanding leisure and cultural formats for longer (demand profile shifts)
- [Creativity/labor] → performers, guides, and creators extend careers with less functional decline (career timelines stretch)
- [Wellness experiences] → longevity-linked services merge with mainstream leisure and self-transformation markets (adjacent sector fuses)
- – [Inequality] → premium access to healthy longevity becomes a status divider in experience markets (participation stratifies)
- – [Authenticity/social norms] → age markers lose clarity in status and identity cultures (social scripts change)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 - Engineered Living Materials

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Engineered living materials can directly affect architecture, scenography, educational environments, and mission-driven venues by making materials responsive, self-healing, or visibly alive. The strongest effects are in place-based experiences and sustainability narratives rather than mass media formats. That supports a material 3.

### **Weak signals (5):**

- [Experience architecture] → venues use living walls or self-healing surfaces as core attraction elements (material becomes medium)

- [Mission experiences] → regenerative-material storytelling becomes part of visitor engagement (ethics becomes embodied)
- [Maintenance] → living materials reduce downtime in high-touch experiential spaces (operations improve visibly)
- – [Trust/safety] → contamination or failure incidents create public hesitation (living matter feels risky)
- – [Authenticity] → users split on whether living materials feel wondrous or unsettling (acceptance remains negotiated)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

The route into this GVN is indirect but real: outdoor leisure, tourism, festivals, and shared social experiences can be materially improved or politically contested if pest burdens change. Even so, the operating model of producing experiences is only weakly affected. So it remains at 1.

**Weak signals (5):**

- [Outdoor experiences] → tourism and event operators lobby for localized pest-suppression zones (quality-of-experience case appears)
- [Public perception] → destinations market pest-light outdoor participation as a safety and comfort advantage (user benefit becomes visible)
- [Mission politics] → environmental protest or support links the technology to leisure access debates (GVN enters governance)
- – [Ecological trust] → backlash makes outdoor experience brands avoid association with gene drives (risk spills into reputation)
- – [Deployment rules] → tightly bounded approval regimes keep experiential uses highly local (scale remains constrained)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART may have huge societal and political significance, but its direct route into the operating model of producing experiences is weak. It would matter to this GVN mainly through cultural narratives, ethical conflict, or niche reproductive and educational services, not through broad experience production. That keeps it below the non-trivial-impact threshold here.

**Weak signals (5):**

- [Cultural narratives] → mainstream media and exhibits reframe artificial gestation as a public experience topic (symbolic linkage begins)

- [Ethical politics] → movements use the technology in identity and relationship-centered campaigns (GVN enters ideology)
  - [Niche services] → reproductive, educational, or conservation centers package public-facing experiences around it (commercial bridge forms)
  - – [Public acceptance] → controversy blocks most leisure and cultural institutions from direct use (license stays fragile)
  - – [Core markets] → mainstream entertainment, tourism, and social platforms do not reorganize around the technology (operating bridge absent)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 10 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART expands the connectivity side of the challenger regime into remote, mobile, and disrupted contexts where terrestrial infrastructure is weak, while also creating new sensing and monitoring layers for location-based experiences. Second-order effects include stronger dependence on a small number of orbital platform operators, new power in geo-targeted media and tourism, and resilience gains for distributed participation. Given how often shared experiences depend on being online everywhere, a 10 is justified.

**Weak signals (9):**

- [Time/location independence] → remote tourism, festivals, and field events offer fully connected premium participation (connectivity follows the user)
- [Shared experiences] → mobile and rural communities join high-fidelity co-presence formats without terrestrial upgrades (access gap narrows)
- [Creator economy] → field creators stream rich interactive formats from previously weak-signal locations (production geography widens)
- [Travel substitution] → live orbital or remote-place feeds become routine paid experience products (distance becomes less binding)
- [Experience security] → venues use constellation resilience as continuity guarantee in contracts (network reliability monetizes)
- [Location-based services] → AR and tourism layers depend on space-linked positioning and sensing (context becomes richer)
- – [Market power] → a few constellation operators gain leverage over cultural and civic access (orbital gatekeeping grows)
- – [Surveillance] → space-sensed audience or site data enters monetized experience ecosystems (observation expands)



- – [Geopolitics] → cross-border service restrictions disrupt experience access and rights (cultural reach becomes contested)

## ART 10.080 - Space Resource Utilization (SRU)

**Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Returning space-mined materials to Earth could matter to many sectors, but the direct route into producing experiences is extremely weak. Any effect would be indirect through long-run material markets or symbolic prestige narratives. That keeps it below the threshold for meaningful GVN impact.

**Weak signals (5):**

- [Cultural prestige] → entertainment and tourism brands market “space-sourced” materials as premium symbolism (narrative linkage begins)
  - [Luxury experiences] → limited products or venues use space-origin materials as status artifacts (niche bridge forms)
  - [Public imagination] → space-mining missions become recurring participatory media events (symbolic salience grows)
  - – [Core operations] → no mainstream experience format depends on SRU supply (operating linkage absent)
  - – [Commercial bridge] → venue and creator procurement never mentions space-derived inputs beyond novelty (market impact stays trivial)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

**Score: 0 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Outside extreme-environment tourism or habitats, closed-loop life support does not strongly connect to the operating model of producing experiences. It is primarily a space-habitation utility layer, not an experience-production technology for this GVN. So it remains at 0.

**Weak signals (5):**

- [Extreme tourism] → sealed habitat experiences advertise true closed-loop life-support participation (linkage begins in niche tourism)
- [Education/culture] → public installations turn life-support loops into interactive exhibits (symbolic bridge appears)
- [Remote habitats] → very isolated experience sites adopt closed-loop living systems as attraction and utility (adjacent use emerges)
- – [Mainstream venues] → urban entertainment and social platforms do not depend on life-support loops (operating bridge absent)

- – [Public meaning] → the technology stays framed as habitat engineering, not experience infrastructure (sector boundary holds)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

HAPs mainly affect the GVN by extending connectivity, sensing, and media coverage to remote or disrupted areas faster than terrestrial buildout. That can materially widen location-based and event-based experiences, but it remains an enabling infrastructure rather than a core experience format. Hence 3.

**Weak signals (5):**

- [Remote experiences] → temporary coverage from HAPs supports festivals, tourism, or crisis-time cultural access (connectivity becomes deployable)
- [Shared experiences] → high-altitude observation feeds become recurring live products or layers (vantage becomes content)
- [Event operations] → organizers rent HAP-based network and sensing packages instead of fixed infrastructure (capex shifts operationally)
- – [Airspace governance] → permits and public acceptance constrain experience-sector use (regulatory ceiling remains strong)
- – [Market structure] → only large operators can bundle HAP services at first (benefits concentrate)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

In mature form, decentralized trust networks can materially change tickets, fan communities, creator monetization, virtual goods, and portable ownership claims across experience markets. Their largest effect is systemic: they redistribute value capture, automate some rules, and create new intermediaries around wallets, identity, and compliance while also enabling fraud and speculative extraction in new forms. That magnitude fits a 5.

**Weak signals (5):**

- [Creator economy] → major fan and event ecosystems use portable ownership or membership tokens routinely (monetization structure shifts)
- [Shared experiences] → ticketing and access rights become transferable across multiple platforms or venues (interoperability gains value)

- [Community governance] → fan communities vote on releases, events, or budgets through embedded rules (participation formalizes)
- – [Speculation] → membership and access markets become volatile financialized status goods (experience turns asset-like)
- – [Compliance] → consumer protection and tax rules reshape wallet-based experience markets (governance hardens)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.084 - Platform Cooperatives & Fair Work

**Score: 5 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

This ART directly affects who captures value in experience production, especially where creators, guides, performers, couriers, moderators, or hosts rely on platforms. The direct user experience may change modestly, but second-order effects on bargaining power, transparency, income stability, and rule legitimacy can materially reshape the GVN's institutions. That justifies a 5.

### **Weak signals (5):**

- [Creator labor] → worker- or user-owned marketplaces win visible share in events, culture, or tourism (ownership model diversifies)
- [Transparency] → members can inspect ranking, fee, and payout logic directly (rules become legible)
- [Shared experiences] → community-run platforms retain local cultural formats that investor platforms ignore (diversity persists)
- – [Capital access] → co-op platforms struggle to scale infrastructure relative to venture-backed rivals (growth constraint appears)
- – [Governance burden] → factional voting or capture disputes slow service quality and trust (coordination costs surface)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Open data marketplaces mainly affect producing experiences through audience insight, cross-organization personalization, and better matching of content, space, and behavior. The major effects are second-order: better coordination and sharper targeting, alongside stronger disputes over consent, re-identification, and who owns audience-derived value. That is material enough for 3.

### **Weak signals (5):**

- [Audience insight] → venues, platforms, and brands buy/sell standardized experience datasets (coordination gets easier)

- [Smaller actors] → local creators access high-quality planning data once reserved for large firms (capability diffuses)
- [Personalization] → cross-platform data deals improve recommendation or attendance prediction visibly (matching gets tighter)
- – [Privacy] → backlash targets repackaged behavioral data from leisure and social contexts (consent boundary hardens)
- – [Market power] → a few brokers dominate valuable audience and mobility datasets (data gatekeeping grows)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Shared experiences, community identity, ideological mobilization, and social coordination are central to this GVN, so platforms that remain usable under outage, blocking, harassment, or data extraction pressures can materially shift how these experiences happen. The second-order impact is large: moderation norms, identity portability, collective action, and the balance between privacy and public accountability all change. Because everyday social and cultural participation for hundreds of thousands can be affected weekly, 10 is warranted.

### **Weak signals (9):**

- [Shared experiences] → communities keep functioning during outages or blocks with minimal loss of continuity (coordination gets resilient)
- [Sociability] → users carry contacts, groups, and reputation between compatible services (social lock-in weakens)
- [Political/ideological experiences] → civic and movement groups adopt resilient-by-default platforms as primary channels (collective action hardens)
- [Creator communities] → fan groups self-host or federate without losing audience reach (control redistributes)
- [Trust] → private-by-default settings become a mainstream expectation, not a niche preference (privacy normalizes)
- [Access] → low-connectivity or contested regions maintain participation in national cultural life (inclusion improves materially)
- – [Moderation] → abusive communities exploit resilience and portability to evade intervention (harm gets harder to suppress)
- – [Governance] → conflicts intensify over who can lawfully force content or identity changes (accountability reopens)
- – [Market structure] → infrastructure providers and federation hubs become new choke points (centralization reappears differently)

## ART 11.087 - Collective Open Innovation Networks

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

For producing experiences, these networks lower the coordination cost of bringing many creators, niche experts, and communities into shared experimentation. The biggest effect is systemic: faster idea recombination, more parallel attempts, and less dependence on a few firms or cities, though platform governance and IP disputes can intensify. That is a clear 5.

**Weak signals (5):**

- [Creativity] → experience challenges attract distributed teams that deliver usable outputs quickly (idea sourcing broadens)
  - [Producer-consumer divide] → audiences co-develop features, narratives, or formats inside structured networks (participation becomes productive)
  - [Skill scarcity] → small creators solve specialist problems through open challenge calls (capability diffuses)
  - – [IP conflict] → disputes grow over ownership of merged or crowd-sourced experience ideas (rights become contested)
  - – [Platform power] → a few innovation hosts mediate access to talent and validation (new bottlenecks form)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 11.088 - Scalable Decentralized Governance****Score: 5 (Impact in GVN 16)****Justification (3–5 sentences):**

This ART matters where communities, fan groups, virtual worlds, festivals, or creator cooperatives want rule-setting power embedded in the platform itself. The direct effect is on participation and legitimacy; the second-order effect is a new politics of delegation, identity, and automated enforcement that can either widen agency or harden factional control. That is materially important, fitting a 5.

**Weak signals (5):**

- [Shared experiences] → large fan or world communities make binding decisions through embedded governance tools (collective agency formalizes)
  - [Creator economy] → pooled budgets for events or media are released automatically after community votes (rules gain execution)
  - [Legitimacy] → users prefer platforms where ranking, fees, or moderation can be contested procedurally (governance becomes product)
  - – [Manipulation] → identity farming, bloc voting, or governance capture incidents rise (power can still be gamed)
  - – [Fatigue] → participation drops if too many decisions are pushed onto users (coordination burden rebounds)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART expands the creator and facilitator base by lowering barriers to learning and proving experience-design, performance, moderation, production, and technical skills. Its larger effect is labor-market and institutional: skills become more portable and verifiable, while platform-defined credentials can also become new gatekeepers. That supports a 5.

**Weak signals (5):**

- [Creator workforce] → experience-sector hiring accepts portable digital credentials in place of legacy pedigree (entry barriers fall)
  - [Participation] → communities learn specialized production skills through AI-guided practice networks (capability spreads quickly)
  - [Quality control] → venues and platforms verify facilitator skills in real time from portable records (matching improves)
  - – [Platform power] → a few credentialing ecosystems become dominant gatekeepers to paid participation (new bottleneck forms)
  - – [Trust] → fraud or over-credentialing scandals force heavier audits and human review (legitimacy gets tested)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.090 - Prediction-Market Forecasting Platforms

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Prediction markets mainly affect the GVN through commissioning, scheduling, pricing, risk assessment, and expectation management around experience projects. They can improve coordination and reduce blind spots, but they do not directly define the experience format, and they can also incentivize perverse attention dynamics. That is material enough for a 3.

**Weak signals (5):**

- [Experience planning] → studios, venues, and festivals use live probability markets in greenlighting or scheduling (decision quality formalizes)
  - [Shared uncertainty] → communities consult market forecasts about releases, attendance, or outcomes (expectations become measurable)
  - [Coordination] → public forecast signals reduce internal debate time in complex event planning (alignment gets faster)
  - – [Manipulation] → actors attempt to sway or trade against narrative outcomes for strategic gain (incentives distort discourse)
  - – [Legitimacy] → creators reject forecast-led decisions as hostile to originality or minority taste (cultural resistance persists)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

These standards matter because ambient experience systems only scale cleanly when devices, venues, wearables, sensors, and services can interoperate without bespoke integration. The second-order effect is substantial: smaller creators can compose richer systems, while standards-setting bodies and dominant platforms gain leverage over permissible behaviors and data flows. That is a significant enabling shift, fitting a 5.

**Weak signals (5):**

- [Experience venues] → procurement specs demand plug-and-play interoperability across sensors, props, lighting, and wearables (integration friction falls)
  - [Creator economy] → small teams combine off-the-shelf ambient devices into polished experiences (capability democratizes)
  - [Shared experiences] → users carry personal devices across venues with stable functionality (experience continuity improves)
  - – [Standards power] → certification and compliance costs advantage big vendors (openness can still centralize)
  - – [Privacy/governance] → common APIs make cross-device tracking easier unless tightly governed (interoperability widens surveillance too)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 12.092 - Interoperable Digital Twin Ecosystems

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART mainly reduces coordination friction around venues, attractions, installations, and live operations by making virtual representations portable across tools and partners. The result is better rehearsal, diagnostics, and continuity across ownership or contractor changes, not a direct transformation of experience formats. That is material but not central, fitting a 3.

**Weak signals (5):**

- [Experience operations] → venue twins move between design, operations, and contractor tools without rebuilds (coordination improves)
- [Creativity] → creators test interventions on operator-owned twins under shared permissions (rehearsal becomes collaborative)



- [Downtime] → remote troubleshooting of experience assets becomes routine from shared twins (response gets faster)
- – [Data control] → disputes rise over who owns the twin of a venue or installation (model rights matter)
- – [Access inequality] → smaller operators remain outside high-fidelity twin ecosystems (capability gap persists)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.093 - Global Supply Chain Traceability Networks

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Traceability networks matter where authenticity, ethics, provenance, and anti-counterfeit assurance shape experiential goods, tickets, branded objects, and mission-oriented narratives. The biggest effect is institutional: faster trust-building and dispute resolution, but also new compliance burdens and data asymmetries. That is materially relevant, fitting a 3.

### **Weak signals (5):**

- [Authenticity] → premium experiences and merch offer queryable provenance histories to users (trust becomes visible)
- [Mission experiences] → ethical sourcing claims are backed by portable traceability records (values become auditable)
- [Counterfeit control] → fake tickets, goods, or memorabilia are traced and blocked faster (fraud costs fall)
- – [Compliance burden] → small creators struggle to meet traceability expectations of large buyers (power redistributes)
- – [Selective disclosure politics] → disputes grow over how much sourcing detail must be revealed publicly (trust vs secrecy tension)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.094 - Personal Data Portability & Trust Frameworks

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Portable personal data and consent frameworks can materially change this GVN because taste profiles, accessibility settings, social graphs, purchase histories, and preference signals are core inputs to personalized experiences. The direct gain is continuity across platforms and stronger user agency; the second-order effect is a redistribution of bargaining power away from single-platform lock-in, though new identity intermediaries can still emerge. If hundreds of thousands of people carry their experiential identity across services weekly, the 10-point anchor is plausible.

### **Weak signals (9):**

- [Personalization] → users bring tastes, accessibility settings, and history into new services with one consent flow (switching friction falls)
- [Shared experiences] → social graphs and group preferences move across worlds and platforms (community continuity improves)
- [Access equality] → smaller services compete by importing user context instead of rebuilding data monopolies (entry barrier lowers)
- [Privacy] → dashboards show time-bound, purpose-bound sharing for experience data as default (agency becomes legible)
- [Producer-consumer divide] → users negotiate terms of data use rather than silently surrendering them (bargaining power shifts)
- [Mission trust] → institutions and parents accept personalization more readily under portable consent receipts (adoption broadens)
- – [Identity power] → wallet or trust-framework providers become new gatekeepers over experiential identity (intermediation reappears)
- – [Manipulation] → richer portable context lets bad actors tune persuasion across services (profiling follows the user)
- – [Governance] → disputes intensify over revocation, deletion, and derived-model rights (control becomes contested)

## ART 12.095 - Interoperable Digital Currency Payment Networks

**Score: 5 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART can materially change experience markets by lowering cross-platform, cross-border, and microtransaction friction for tickets, tips, subscriptions, fan memberships, and digital goods. Its second-order importance is high for creator monetization and platform competition, though compliance layers and routing intermediaries can recreate concentration. That supports a 5.

**Weak signals (5):**

- [Creator economy] → tips, access fees, and micro-payments flow across platforms and borders with little friction (monetization broadens)
  - [Shared experiences] → group purchases and split payments work seamlessly across services (coordination gets easier)
  - [Access] → low-connectivity and offline payment modes support participation in harder contexts (inclusion improves materially)
  - – [Compliance] → identity and anti-fraud layers create new chokepoints despite interoperability (gatekeeping reappears)
  - – [Volatility/trust] → users resist if settlement feels opaque or reversible rules differ by rail (adoption depends on clarity)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score: 3 (Impact in GVN 16)**

**Justification (3–5 sentences):**

Rules-as-code mainly affects this GVN by speeding compliance for AI content, events, safety, identity, payments, accessibility, and data use. The main effect is second-order: faster adaptation to rule changes, clearer audit trails, and lower overhead for large players, though smaller actors may still struggle with implementation. That is material enough for a 3.

**Weak signals (5):**

- [Compliance] → platforms and venues plug official rule packages directly into workflows (interpretation costs fall)
  - [Creator access] → smaller firms launch regulated experiences faster using reusable compliance modules (entry friction drops somewhat)
  - [Governance transparency] → users can see which rule triggered a moderation or access decision (legibility improves)
  - – [Power imbalance] → larger actors implement rules faster and capture market openings first (compliance speed becomes advantage)
  - – [Edge cases] → public disputes show where coded rules mismatch social nuance (human judgment remains necessary)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 12.097 - Open Metaverse Interoperability Protocols****Score: 10 (Impact in GVN 16)****Justification (3–5 sentences):**

These protocols matter because persistent cross-world identity, asset portability, and shared interaction rules are what make digital experiences cumulative rather than siloed. Their direct effect is on continuity and creator reuse; their systemic effect is on platform power, royalties, moderation, and the viability of user-owned social and economic histories. That can touch hundreds of thousands of weekly users once immersive spaces are mainstream, so 10 is justified.

**Weak signals (9):**

- [Shared experiences] → users carry avatars, inventories, and accessibility settings across multiple worlds (continuity becomes expected)
- [Creativity] → creators publish once and sell or stage across many engines (reusability changes economics)
- [Sociability] → communities persist across platforms instead of rebuilding from scratch (social lock-in weakens)
- [Producer-consumer divide] → users bring their own assets and identity into brand-owned spaces (control redistributes)
- [Access equality] → smaller worlds gain relevance by interoperating instead of building full stacks (entry barrier lowers)
- [Mission experiences] → civic, educational, and cultural spaces adopt the same identity and rights layer (immersion generalizes)
- – [Moderation] → harmful actors move seamlessly across worlds with portable reputational ambiguity (governance gets harder)

- – [Royalties/power] → protocol owners and dominant marketplaces fight over fee capture (infrastructure politics intensifies)
- – [Security/trust] → compromised assets or identities propagate across many worlds at once (failure cascades widen)

## ART 12.098 - Content Authenticity Infrastructure

**Score: 10 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

Authenticity is a named value conflict in this GVN, and once synthetic media and adaptive AI become normal, provenance infrastructure becomes central to what counts as trustworthy experience, art, testimony, and presence. The direct effect is on media verification and creator credit; the second-order effect is on platform rules, political influence, cultural legitimacy, and the economics of traceable versus untraceable content. Because these dynamics can shape the weekly media lives of hundreds of thousands, 10 is appropriate.

### **Weak signals (9):**

- [Authenticity] → browsers, apps, and platforms expose provenance summaries by default (verification becomes ordinary)
- [Creator rights] → audiences prefer credentialed media for payments, trust, or status (traceability gets monetized)
- [Political/ideological experiences] → campaigns and civic platforms require authenticity metadata for key content (governance hardens)
- [Shared experiences] → live and recorded media are filtered by provenance confidence in social feeds (attention reallocates)
- [Institutional use] → schools, museums, and broadcasters treat credentials as baseline media literacy infrastructure (norms stabilize)
- [Producer-consumer divide] → creators can prove authorship and edit history without relying on one platform (credit becomes portable)
- – [Exclusion] → uncredentialed grassroots content is deprioritized or distrusted regardless of truth (gatekeeping risk rises)
- – [Spoofing] → credential theft or fake-provenance scandals trigger broad trust shocks (infrastructure can fail)
- – [Surveillance] → creators fear overly revealing provenance links identity to all output (credibility can reduce privacy)

## ART 12.099 - Privacy-Preserving Collaboration Protocols

**Score: 3 (Impact in GVN 16)**

### **Justification (3–5 sentences):**

These protocols mainly help experience operators, platforms, brands, and institutions collaborate on audience insight or personalization without pooling raw data. The direct gains are coordination and trust; the indirect risk is that more collaboration becomes politically acceptable, expanding behavior

optimization without fully resolving fairness or accountability issues. That is material enough for a 3.

**Weak signals (5):**

- [Coordination] → competing venues or platforms run joint analytics without sharing raw audience data (cooperation barrier drops)
  - [Smaller actors] → niche creators access pooled insight through safe-query services (capability diffuses)
  - [Mission trust] → institutions approve collaboration that would previously fail privacy review (use cases broaden)
  - – [Opacity] → users struggle to understand who is still influencing experiences behind privacy-preserving layers (accountability blurs)
  - – [Performance/cost] → only larger operators can afford complex secure collaboration initially (benefits concentrate)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure**

**Score: 1 (Impact in GVN 16)**

**Justification (3–5 sentences):**

This ART matters indirectly by making advanced experience hardware, robotics, scenography, and physical product supply chains easier to trust and scale. It improves qualification and procurement more than it changes audience-facing experience logic. That makes it relevant but narrow, so 1 fits.

**Weak signals (5):**

- [Experience hardware] → buyers start requiring certified conformance data for immersive and robotic systems (trust formalizes procurement)
  - [Creator access] → smaller firms adopt certified modules instead of custom proving everything (entry cost softens)
  - [Safety] → faster qualification shortens rollout of new public-facing devices and installations (time-to-market improves)
  - – [Compliance burden] → certification costs disadvantage experimental or artisanal creators (standardization can narrow diversity)
  - – [Market structure] → large certified suppliers become preferred defaults for venues and platforms (purchasing power centralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## GVN 17: Safety and Security ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, mature near-ubiquitous broadband extends warnings, tele-assistance, citizen reporting, and remote supervision into rural, mobile, and disrupted settings, shrinking safety blind spots. Institutionally, it shifts part of situational awareness from centralized agencies to households, communities, and private operators, while also enlarging cyber-surveillance and misinformation pathways. If safety coordination and incident handling for hundreds of thousands of people becomes dependent on continuous connectivity, the operating model is clearly transformed, so 10.

**Weak signals (4):**

- (+) [local responders] → municipalities procure satellite/mesh backup links for emergency communications (blind spots start closing)
- (+) [peer-to-peer risk sharing] → neighborhood safety apps add offline-to-online incident relays (crowd reporting becomes routine)
- (-) [predictability / telecom dependence] → outage inquiries start focusing on emergency connectivity SLAs (regularity tied to networks)
- (-) [privacy / surveillance] → complaints rise over location-linked “safety” data retention (trust starts fraying)

#### ART 01.002 - Ultra-Low Latency Networks

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these networks enable time-critical remote control, industrial safety loops, teleoperation, and tightly synchronized emergency systems. Institutionally, they move capability toward edge operators and network vendors, while making failover, cyber-hardening, and certification more important. Across ports, hospitals, transport systems, and critical sites, that is plausibly a €100M–1B / 50–500M-hour effect, so 5.

**Weak signals (4):**

- (+) [critical infrastructure operators] → tenders specify sub-10 ms safety-network SLAs (remote control becomes viable)
- (+) [emergency services] → pilots begin for remote vehicle or robot operation (response model starts shifting)
- (+) [insurance / reliability] → insurers discount certified deterministic networks (bounded latency gains value)
- (-) [system integrity] → incident reports cite jitter or lag causing safety fallbacks (timing becomes failure mode)

## ART 01.003 - Edge AI for Sensor Data

**Score: 20 (Impact in GVN 17)**

**Justification (3–5 sentences):** This is a linchpin of the challenger regime because it lets devices detect hazards, classify events, and trigger actions locally instead of sending everything to central authorities. Directly, it enables continuous decentralized protection in homes, streets, vehicles, factories, and utilities even when connectivity is poor; institutionally, it moves judgment into devices and local operators while reducing raw-data sharing. Third-order effects are equally large: machine-triggered alerts, shutdowns, and escalations become normal, and model bias or compromise can also scale instantly. Because this capability is hard to substitute in a pervasive safety architecture and could alter weekly safety conditions for hundreds of thousands of people, it fits 20.

**Weak signals (5):**

- (+) [public procurement] → tenders require on-device anomaly detection by default (local judgment becomes standard)
- (+) [privacy / fairness] → cities prefer camera systems that keep raw video local (acceptance barrier starts falling)
- (+) [operating model] → emergency SOPs accept machine-triggered shutoff or lockdown events (automation enters doctrine)
- (-) [accountability] → regulators demand local-model audit logs after missed detections (device judgment becomes contestable)
- (-) [cybersecurity] → red-team exercises target edge-model poisoning or spoofing (new attack surface opens)

## ART 01.004 - Quantum & High-Precision Sensing

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, this enables detection of subtle structural changes, hidden hazards, GNSS-denied navigation conditions, and anomalous signatures that conventional sensors miss. Institutionally, it reduces dependence on sparse expert measurements and external references, but also concentrates capability in high-assurance operators and creates false-confidence risks. In critical infrastructure, navigation, and forensic uses, the plausible magnitude is sector-wide rather than universal, placing it in the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [critical infrastructure] → pilots deploy precision field sensors for underground or structural anomalies (hidden faults become visible)
- (+) [navigation resilience] → procurement adds GPS-denied sensor requirements (reference independence matters)
- (+) [standards bodies] → certification schemes emerge for quantum field instruments (from lab to operations)
- (-) [decision quality] → investigations cite overconfidence in exotic sensors after misses (precision can mislead)



## ART 01.005 - Micro/Nano Sensor Networks

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, dense patch-like sensor fields convert bridges, buildings, vehicles, public spaces, and logistics chains into continuously observed environments rather than periodically inspected ones. Institutionally, that shifts bottlenecks from sensing hardware to filtering, interpretation, and governance, while embedding surveillance capacity into ordinary materials. Because it can change how large parts of the built environment are monitored week by week, this is transformative but not uniquely indispensable, so 10.

**Weak signals (4):**

- (+) [asset owners] → retrofits specify dense patch sensors on bridges, rails, or facades (inspection turns continuous)
- (+) [municipal control rooms] → live structural/environmental maps appear on operations dashboards (state estimation normalizes)
- (-) [labor / inspections] → maintenance staffing shifts away from routine patrols (manual inspection loses primacy)
- (-) [privacy / workplace power] → worker or tenant disputes target embedded ambient monitoring (monitoring politics intensify)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, this unlocks more continuous sensing in homes, workplaces, care settings, and public spaces by keeping raw personal data local or strongly minimized. Institutionally, it shifts bargaining power toward users, auditors, and standards setters, while also enabling “privacy-washed” surveillance claims if the guarantees are weak. Because it can decide whether pervasive safety monitoring scales socially at all, it has transformative impact on the operating model and fits 10.

**Weak signals (4):**

- (+) [public trust] → procurements require on-device redaction or aggregate-only export (social license starts mattering)
- (+) [regulation] → privacy seals or certification appear for safety sensors (acceptability becomes standardized)
- (+) [evidence systems] → courts accept privacy-preserving logs in investigations (usable without raw capture)
- (-) [civil liberties] → audits expose systems that claimed privacy but exported reconstructable data (trust can snap)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these networks protect long-lived records, identities, and

command links for utilities, hospitals, responders, and autonomous systems against future cryptanalytic breakage and present-day manipulation. Institutionally, they make remote and cross-organizational safety operations more acceptable, while transition failures and uneven upgrades can fragment trust. If critical coordination increasingly depends on networks whose integrity must hold for years, the impact is transformative and fits 10.

#### **Weak signals (4):**

- (+) [national cyber authorities] → post-quantum migration deadlines are set for safety sectors (long-lived data matters)
- (+) [critical operators] → routers/endpoints are replaced for crypto agility, not bandwidth (security becomes upgrade driver)
- (+) [insurance] → premiums differentiate by post-quantum readiness (future decryption risk priced in)
- (-) [system continuity] → incidents expose downgrade or interoperability failures during transition (migration itself becomes risk)

## **ART 01.008 - Integrated Sensing and Communication (ISAC)**

### **Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, ISAC turns communications infrastructure into a distributed sensor layer for motion, crowding, object tracking, and environmental change detection. Institutionally, telecom operators and network vendors become safety actors, while privacy, lawful access, and boundary-setting move to the center. Because everyday wireless infrastructure starts doubling as situational awareness infrastructure, the operating model changes materially and fits 10.

#### **Weak signals (4):**

- (+) [telecom infrastructure] → 6G pilots publish joint sensing APIs (networks start seeing)
- (+) [cities / transport] → operators buy sensing upgrades instead of separate radar layers (functions start merging)
- (-) [privacy governance] → consultations open on notice, consent, or lawful use of radio sensing (boundaries need rewriting)
- (-) [civil liberties] → lawsuits challenge environmental tracking via carrier infrastructure (silent sensing becomes visible)

## **2. Computing Hardware & Non-Von-Neumann Paradigms**

### **ART 02.009 - Compute-in-Memory & Neuromorphic Chips**

#### **Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these chips make always-on local detection practical in wearables, cameras, drones, meters, and alarms under tight power and thermal limits. Institutionally, they reduce cloud dependence and support privacy-preserving deployment, but increase dependence

on specialized hardware and harder-to-audit toolchains. Spread across many safety devices, that is plausibly a €100M–1B / 50–500M-hour effect, so 5.

**Weak signals (4):**

- (+) [device makers] → safety cameras and wearables shift to event-driven inference chips (always-on becomes affordable)
- (+) [backup resilience] → tenders require long local inference under power loss (graceful degradation gains value)
- (+) [privacy / edge control] → municipalities prefer local-processing devices over cloud-heavy alternatives (raw-data export declines)
- (-) [assurance] → certification bodies add special tests for neuromorphic behavior (new hardware needs governability)

## **ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS**

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, better transistors mean tougher, cooler, smaller, lower-power electronics in alarms, radios, sensors, and embedded safety controllers. Institutionally, the main shifts are in supply-chain concentration, export control, and hardware trust rather than in frontline safety practice. That keeps the impact nearer the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [critical electronics] → rugged safety devices advertise extreme-temperature or ultra-low-power operation (hardware margins improve)
- (+) [domestic resilience] → fabs market security-certified specialty nodes for infrastructure controllers (hardware sovereignty matters)
- (+) [field maintenance] → multi-year service intervals become standard for harsh-site electronics (replacement burden falls)
- (-) [market structure] → export controls hit niche device materials used in safety hardware (upstream fragility shows)

## **ART 02.011 - Quantum Computing Platforms**

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct linkage runs through better optimization, cryptography pressure, and simulation for selected security or infrastructure problems. Institutionally, advantage concentrates in a few state or cloud actors, and the most immediate broad effect is forcing earlier security migration elsewhere. That is material, but still bounded and indirect, keeping it in the €10M–100M / 5–50M-hour range, so 3.

**Weak signals (4):**

- (+) [security planners] → pilots test quantum optimization for routing or resource allocation (narrow operational footholds)
- (+) [cyber policy] → migration away from legacy encryption accelerates after quantum milestones (indirect pressure mounts)
- (+) [cloud markets] → quantum services are bundled into infrastructure-risk analytics (from research to tools)
- (-) [power concentration] → public-sector access depends on a few providers or national labs (capability centralizes)

## ART 02.012 - Photonic and Optical Computing

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, optical compute and interconnects improve throughput and heat efficiency in video analytics, telecom cores, and some command-and-control systems.

Institutionally, the shift is mostly toward new vendor stacks and central processing efficiency, not toward a new safety regime. That makes the impact real but partial, closer to the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [command centers] → real-time video analytics clusters pilot optical accelerators (throughput bottlenecks ease)
- (+) [data centers] → operators cite lower cooling loads in security workloads (thermal budget matters)
- (+) [telecom] → optical interconnect upgrades are justified by safety-critical latency needs (communications analytics scale)
- (-) [systems integration] → failures cluster at electro-optic conversion boundaries (hybrid complexity persists)

## ART 02.013 - Next-Gen Memory & Storage

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct gains come through better audit trails, faster recovery of critical system state, and richer retention of sensor logs for forensics and accountability.

Institutionally, that strengthens traceability but also enlarges privacy, breach, and retention-burden questions. The effect is material infrastructure plumbing rather than an operating-model shift, so 3.

**Weak signals (4):**

- (+) [forensics / accountability] → regulators extend mandatory retention of device and machine logs (state capture gains value)
- (+) [critical continuity] → operators adopt non-volatile memory for rapid restart after outages (recovery time drops)
- (+) [edge systems] → local high-endurance storage becomes a procurement requirement (data stays near source)

- (-) [privacy governance] → authorities challenge indefinite retention of safety telemetry (traceability meets rights)

## ART 02.014 - Molecular Computing

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The plausible pathway is niche embedded computation inside chemical or biological environments where electronics are awkward. Broader Safety & Security impact remains indirect unless it couples to mainstream diagnostic, remediation, or sensor systems. Worth monitoring, but limited at GVN scale, so 1.

**Weak signals (4):**

- (+) [hazard diagnostics] → field pilots use molecular logic in toxin or pathogen tests (electronics-free sensing emerges)
- (+) [extreme environments] → programs fund chemical-environment computing where chips fail (niche fit appears)
- (+) [tooling] → patents shift from lab demonstrations to cartridge-like products (commercial form starts forming)
- (-) [operational relevance] → deployments stay confined to specialized instruments, not safety workflows (linkage remains weak)  
Signal density: **LOW** (linkage weak; additional signals would be speculative).

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 - Causal Learning & Reasoning

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, causal AI improves intervention choice: what actually reduces accidents, failures, violence, outbreaks, or false alarms rather than merely correlating with them. Institutionally, it changes accountability because agencies, insurers, and citizens can contest action models using explicit assumptions and counterfactuals, though bad causal graphs can still scale harm. If widely embedded in risk management and public decision support, it changes how safety choices are justified for very large populations, so 10.

**Weak signals (4):**

- (+) [policy design] → tenders require counterfactual analysis before safety interventions (correlation no longer enough)
- (+) [incident review] → dashboards begin showing estimated intervention effects, not only risk scores (decision quality reframed)
- (+) [oversight bodies] → watchdogs request causal audit trails from automated systems (accountability deepens)

- (-) [model risk] → failures are traced to hidden confounders in “causal” models (false certainty becomes visible)

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, it lets hospitals, utilities, municipalities, and devices improve shared safety models without moving raw sensitive data into one central pool. Institutionally, it lowers cross-organization coordination barriers while shifting power toward model governors, secure-hardware suppliers, and standards bodies; uneven participants can still bias outcomes. Because it unlocks large safety datasets that are otherwise unusable, the effect is transformative and fits 10.

**Weak signals (4):**

- (+) [cross-organization safety data] → hospital, utility, or city consortia launch federated anomaly-detection programs (locked data starts flowing)
- (+) [regulation] → privacy authorities approve federated schemes faster than central data lakes (institutional friction falls)
- (+) [small actors] → smaller municipalities join shared models without surrendering raw records (access widens)
- (-) [distribution / fairness] → model drift is traced to dominant participants’ data (shared learning skews power)

## ART 03.017 - Trustworthy AI Systems

**Score: 20 (Impact in GVN 17)**

**Justification (3–5 sentences):** This is a linchpin because high-stakes safety automation only scales if systems are robust, auditable, aligned to rules, and able to fail safely. Directly, it enables dependable AI in infrastructure, emergency response, public services, and personal safety tools; institutionally, it moves trust from individual experts to assurance pipelines, auditors, and monitored platforms. Third-order effects are large in both directions: trustworthy systems accelerate adoption, while publicized assurance failures can freeze whole sectors. Because it is hard to substitute in a mature safety regime and could alter weekly conditions for hundreds of thousands of people, it fits 20.

**Weak signals (5):**

- (+) [public procurement] → tenders require confidence bounds, provenance logs, and fallback modes (assurance becomes mandatory)
- (+) [regulation] → AI assurance or certification schemes appear for critical use cases (trust gets formalized)
- (+) [insurance] → coverage depends on monitored and auditable AI, not raw accuracy (risk transfer changes)
- (-) [public legitimacy] → inquiries after incidents focus on missing overrides or traceability (trust can collapse fast)

- (-) [labor / governance] → unions and civil-rights groups negotiate escalation rules around AI use (power shifts become explicit)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, AutoML lowers the expertise barrier for local agencies and firms to build risk models, alerting systems, and optimization tools. Institutionally, it speeds diffusion of both useful and poorly governed automation, shifting effort from model construction to validation, target-setting, and oversight. Because that can change how many organizations operationalize safety analytics at all, the effect reaches the €100M–1B / 50–500M-hour band, so 5.

**Weak signals (4):**

- (+) [local public agencies] → small municipalities deploy AI safety dashboards without in-house data scientists (capability spreads outward)
- (+) [governance tools] → AutoML platforms add critical-use guardrails and rollback features (oversight becomes productized)
- (-) [model quality] → incident reviews cite bad targets or reward functions from automated model search (speed amplifies mistakes)
- (-) [vendor power] → procurement shifts from consultants to platform subscriptions for core safety analytics (control centralizes in tools)

## ART 03.019 - Collaborative Multi-Agent AI

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, multi-agent AI coordinates sensors, drones, software agents, and human teams for patrol, search, logistics, and incident response over large areas. Institutionally, it shifts operations away from purely hierarchical dispatch toward mixed human-machine orchestration, with new accountability, congestion, and goal-conflict risks. At city, infrastructure, or regional scale, that changes how coverage and reaction are achieved week by week, so 10.

**Weak signals (4):**

- (+) [operations centers] → control rooms adopt shared machine task boards for many agents (dispatch logic changes)
- (+) [emergency services] → swarm-style allocation pilots move from demos to recurring drills (coordination scales outward)
- (+) [standards] → interoperable inter-agent messaging specs appear in public-safety procurements (ecosystem starts forming)
- (-) [governance] → after-action reviews blame failures on agent coordination rules, not only human error (responsibility is reallocated)



## ART 03.020 - Quantum-Accelerated AI Systems

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main path is better optimization and search in a narrow set of hard planning or resource-allocation problems. Institutionally, capability sits with premium compute providers and flagship state programs, limiting broad operating-model change. That keeps the likely effect in the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [critical planners] → hybrid quantum-classical pilots target routing or contingency planning (search bottlenecks get attention)
- (+) [cloud markets] → premium safety analytics offerings bundle quantum subroutines (capability enters services)
- (+) [evaluation culture] → public benchmarks start showing narrow wins over classical baselines (credibility strengthens)
- (-) [access inequality] → only national or very large operators can afford meaningful use (benefit remains concentrated)

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct effects come through faster invention of safer materials, sensors, vaccines, detection methods, and protective procedures. Institutionally, discovery capacity concentrates in labs with strong compute, data, and automation, while dual-use concerns also accelerate. Important upstream, but one step removed from everyday safety delivery, it stays in the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [public safety R&D] → agencies fund closed-loop discovery labs for sensors or protective materials (innovation cycle shortens)
- (+) [patenting] → AI-designed safety tools begin reaching filed patents and field trials (discovery leaves the lab)
- (+) [regulation] → review pathways adapt to AI-generated evidence packages (institutional uptake begins)
- (-) [dual-use security] → security reviews expand around AI-generated biological or chemical insights (upside and misuse co-evolve)

## 4. Human-Machine Interaction & Augmentation

## ART 04.022 - Immersive Augmented & Virtual Reality

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, immersive AR/VR improves responder training, remote expert guidance, incident rehearsal, and situational awareness in complex or hazardous spaces. Institutionally, it redistributes expertise by letting fewer specialists guide more people remotely, while also creating evidence, distraction, and ergonomic risks. Across emergency, industrial, and security contexts, that plausibly reaches the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [training systems] → police, fire, hospital, or utility budgets move into immersive drills (procedural learning changes)
- (+) [remote expertise] → live AR overlays are used in field repairs or emergency support (specialists become remotely present)
- (+) [simulation ecosystems] → procurements require compatibility with digital twins (training and operations connect)
- (-) [field safety] → incident reports cite distraction, calibration drift, or motion sickness in live use (augmentation adds new risk)

## ART 04.023 - Brain-Computer Interfaces (BCI)

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, BCIs can help some users control safety-relevant systems when hands, speech, or conventional interfaces are limiting. Institutionally, they create very sensitive new data rights and workplace coercion questions, which cap widespread deployment. Useful in specialist settings, but still nearer the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [accessibility / operations] → pilots use BCIs for hands-free command in rehabilitation or control support (niche operational fit appears)
- (+) [medical-device governance] → procurement standards start covering neural-data security (safety enters regulation)
- (-) [labor rights] → unions challenge cognitive-monitoring uses in workplaces (consent becomes contested)
- (-) [reliability] → incident reviews compare BCI commands against conventional inputs after failures (trust remains fragile)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these systems reduce injury, extend safe lifting or mobility, and keep scarce personnel productive in hazardous work. Institutionally, they shift expectations around duty of care, employer responsibility, and who benefits from augmentation. The impact is real but occupation-specific, so it remains in the €10M–100M / 5–50M-hour band, hence 3.

**Weak signals (4):**

- (+) [responder workforce] → utilities, warehouses, or rescue teams procure powered exosuits (fatigue becomes partly engineered away)
- (+) [insurance] → worker-compensation schemes begin covering certified devices (augmentation enters normal risk transfer)
- (-) [labor bargaining] → unions negotiate who bears fatigue, productivity, or maintenance burdens (power shifts surface)
- (+) [injury prevention] → after-action reviews attribute fewer musculoskeletal injuries to assistive gear (occupational safety improves)

**ART 04.025 - Haptic and Multi-Sensory Feedback Systems****Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, richer feedback improves remote manipulation, teleoperation, training, and low-visibility tasks where vision alone is insufficient. Institutionally, it supports inclusion and precision, but adds calibration, latency, and overload issues. That keeps the effect material but bounded, closer to the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [remote operations] → bomb disposal, telemedicine, or maintenance tools add force feedback (judgment becomes less visual-only)
- (+) [training systems] → simulators begin requiring tactile channels in procurement (skill transfer deepens)
- (+) [quality control] → operators report lower error rates in delicate tasks with feedback systems (precision improves measurably)
- (-) [human factors] → standards add latency and overload thresholds for haptic safety interfaces (feedback needs governance)

**ART 04.026 - AI Understanding of Human Intent & Context****Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, intent- and context-aware AI can reduce alarm fatigue, improve de-escalation, adapt interfaces under stress, and spot dangerous situations earlier from multimodal cues. Institutionally, it shifts power over interpretation and attention toward platform owners, employers, and authorities, while misclassification or manipulative nudging can create large harms. Because it can reshape everyday interactions with safety systems for very large populations, it is transformative and fits 10.

**Weak signals (4):**

- (+) [emergency interfaces] → contact centers and apps start triaging by inferred distress or intent (signals beat explicit commands)

- (+) [accessibility] → adaptive interfaces gain uptake in care and public-service settings (context-aware support normalizes)
- (-) [privacy / civil liberties] → emotion or intent inference triggers workplace and public-space complaints (interpretive power becomes political)
- (-) [justice / evidence] → courts scrutinize machine-inferred intent in disputes or enforcement cases (meaning attribution becomes contested)

## ART 04.027 - Brain-to-Brain Interfaces

### Score: 1 (Impact in GVN 17)

**Justification (3–5 sentences):** Possible benefits sit in specialized coordination or accessibility niches, but broad Safety & Security linkage remains weak. Most meaningful pathways depend on other mature neurotech and governance layers arriving first. Worth monitoring, but limited at GVN scale, so 1.

### Weak signals (4):

- (+) [research translation] → trials move from novelty demos to task-based coordination experiments (practicality starts getting tested)
  - (+) [ethics governance] → consent protocols appear for multi-user neural channels (institutional scaffolding emerges)
  - (+) [specialist use] → defense or medical programs fund shared-neural communication pilots (niche demand forms)
  - (-) [operational relevance] → deployments stay confined to laboratories and edge cases (broad linkage remains weak)
- Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

### Score: 1 (Impact in GVN 17)

**Justification (3–5 sentences):** The plausible effect is clinical safety and retention support for a limited set of individuals, including some critical workers. That matters, but it does not materially alter how the wider Safety & Security GVN operates. So it stays at 1.

### Weak signals (4):

- (+) [clinical safety] → pilots expand from recall restoration to procedure-support use cases (memory support becomes functional)
  - (+) [workforce resilience] → safety-critical jobs test aids after brain injury or decline (niche continuity value appears)
  - (+) [device governance] → implant standards start covering stored-memory interfaces and security (oversight begins forming)
  - (-) [scale limits] → reimbursement and deployment remain narrow despite technical progress (societal impact stays bounded)
- Signal density: **LOW** (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, self-driving vehicles can reduce fatigue-related crashes, expand evacuation and logistics capacity, and maintain mobility when qualified drivers are scarce. Institutionally, they shift liability toward software stacks, fleet operators, map/data providers, and regulators, while also enlarging cyber and sabotage risks. Because road transport is a weekly safety condition for very large populations, mature autonomy is transformative and fits 10.

**Weak signals (4):**

- (+) [public mobility safety] → cities buy autonomous shuttles for night routes or emergency movement (mobility logic shifts)
- (+) [insurance] → separate premium classes emerge for software-driven fleets (liability reallocates visibly)
- (+) [infrastructure governance] → road agencies publish machine-readable work-zone and incident feeds (roads start serving machines)
- (-) [public trust] → crash investigations focus on software, data, and remote assistance logs (accountability moves upstream)

### ART 05.030 - Drone Swarms & Aerial Robots

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, drone swarms provide persistent search, hazard mapping, perimeter coverage, and rapid situational awareness over large or dangerous areas. Institutionally, they move coverage from sparse human patrols to algorithmic airspace management, with major privacy, misuse, and airspace-safety implications. At wildfire, disaster, border, and industrial scale, that clearly transforms how monitoring and first response are delivered, so 10.

**Weak signals (4):**

- (+) [emergency operations] → agencies procure swarm-capable mission software, not just individual drones (coverage becomes coordinated)
- (+) [aviation governance] → emergency drone corridors or geofenced lanes are designated (airspace starts adapting)
- (+) [response speed] → after-action reviews credit swarms with faster search and mapping than crews (operational proof accumulates)
- (-) [civil liberties] → public complaints and court cases target persistent overflight and automated tracking (acceptance barrier hardens)

## ART 05.031 - Humanoid and General-Purpose Robots

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, humanoids and similar general-purpose robots can take over dirty, dangerous, repetitive, and night-time tasks in spaces built for people. Institutionally, they shift skill toward remote supervisors and integrators while raising labor conflict, safety-certification, and responsibility questions. In hazardous service and maintenance domains, that plausibly reaches the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [hazard exposure] → hospitals, depots, and utilities pilot humanoids for rounds and risky checks (human presence starts thinning)
- (+) [certification] → tenders require safe human-robot interaction proofs (mixed workplaces become normal)
- (-) [labor power] → unions contest replacement of entry-level security or maintenance roles (displacement becomes explicit)
- (-) [operational safety] → incident logs track falls, contact-force exceedances, or near-misses (embodied autonomy faces scrutiny)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main value is safer manipulation in confined, fragile, contaminated, or human-adjacent environments where rigid machines are too risky. Institutionally, the main shifts are in maintenance skills and device certification, not in overall safety governance. That keeps the impact material but bounded, so 3.

**Weak signals (4):**

- (+) [inspection / rescue] → pilots adopt compliant grippers or snake-like robots in tight spaces (new access routes open)
- (+) [human safety] → standards begin testing soft robots around people rather than cages (deployment assumptions change)
- (+) [contamination handling] → hazardous facilities switch from rigid tools to compliant manipulators (contact risk falls)
- (-) [reliability] → maintenance logs highlight material fatigue and cleaning burdens (softness creates new upkeep)

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these platforms maintain continuous presence in air, sea, underground, and damaged environments that are slow or dangerous for people to access. Institutionally, they shift response models toward mission oversight, map sharing, and exception handling, while expanding cyber, communications-loss, and autonomy-assurance issues. Because

they materially change coverage and reaction time across several safety sectors, the impact is transformative and fits 10.

**Weak signals (4):**

- (+) [critical site operators] → ports, rail, offshore, and tunnel managers sign persistent-autonomy service contracts (presence becomes continuous)
- (+) [regulation] → authorities approve longer unsupervised missions in defined corridors (trust moves from pilots to rules)
- (+) [operations] → incident reports show earlier detection from robotic presence, not human patrols (coverage logic changes)
- (-) [security] → cyber exercises specifically target autonomous fleets and shared maps (attack surface becomes recognized)

## **ART 05.034 - Supportive Infrastructure for Autonomy**

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, autonomy-ready infrastructure makes streets, buildings, and facilities safer and more legible for dense machine activity. Institutionally, responsibility shifts from each robot toward shared infrastructure owners and standards setters, while retrofit access can become unequal across places and classes of users. Where adopted, this is a significant €100M–1B / 50–500M-hour enabler, so 5.

**Weak signals (4):**

- (+) [facility operators] → ports, hospitals, or industrial parks install robot-readable markers and docking nodes (environment starts carrying intelligence)
- (+) [building governance] → codes begin defining autonomy-ready corridors or zones (robot legibility enters rules)
- (-) [distribution / equity] → wealthier districts or sites get autonomy upgrades first (resilience becomes uneven)
- (-) [liability] → accident reports blame missing or degraded infrastructure markers, not only robots (responsibility shifts outward)

## **ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics**

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, power beaming extends mission time where charging logistics cap surveillance, inspection, and response coverage. Institutionally, it turns exclusion zones, beam governance, and infrastructure sabotage into safety questions. Useful for selected resilience niches, but still closer to the €10M–100M / 5–50M-hour band than to a system-wide shift, so 3.

**Weak signals (4):**



- (+) [remote monitoring] → drone corridors or border pilots include power-beaming towers (mission duration becomes infrastructural)
- (+) [safety regulation] → exposure and cutoff rules are published for robotic beaming systems (deployment gets formal limits)
- (+) [operations economics] → logs show battery-swap downtime falling sharply in beam-covered zones (use case becomes credible)
- (-) [security] → drills treat beaming nodes as high-value sabotage or weather-failure points (new dependency recognized)

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The clearest value is niche inspection, rescue, and attachment on smooth vertical or overhead surfaces where other methods are awkward. That is concrete, but too narrow to materially change the broader Safety & Security operating model. So it remains a watch item at 1.

**Weak signals (4):**

- (+) [inspection robotics] → vendors add dry-adhesion kits for façade or tank inspection (niche capability becomes productized)
  - (+) [rescue tools] → responders test climbing tools on smooth vertical surfaces (access value gets validated)
  - (+) [standards] → durability tests emerge for adhesion cycles under dust and wear (field-readiness improves)
  - (-) [operational fit] → failure reports keep citing contamination-sensitive grip loss (breadth remains constrained)
- Signal density: **LOW** (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, this shortens production of custom protective gear, sensorized parts, and emergency spares. Institutionally, it shifts some resilience from global suppliers to local fabrication hubs, but certification and quality assurance remain the hard constraint. That makes the linkage real but partial, keeping it nearer the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [preparedness supply] → hospitals or utilities stock certified printable spare designs (local fabrication becomes contingency)

- (+) [procurement] → emergency frameworks include local print bureaus for critical items (sourcing diversifies)
- (+) [standards] → certification expands to printed electronics inside safety equipment (complexity becomes acceptable)
- (-) [quality governance] → enforcement actions target uncertified printed parts after failures (speed meets reliability limits)

## ART 06.038 - Digital Twin & Simulation-Driven Production

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, digital twins improve failure forecasting, safer process changes, and faster recovery in factories and critical supply chains. Institutionally, they reduce information asymmetry between operators, engineers, insurers, and regulators, though they also create dependence on data quality and software vendors. Across critical production environments, that plausibly lands in the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [industrial safety] → regulators accept twin-based validation in maintenance planning (simulation starts counting operationally)
- (+) [factory operations] → live twin synchronization becomes a procurement requirement for critical lines (physical and digital stay coupled)
- (+) [insurance] → underwriters request simulation evidence of risk reduction (twins gain institutional authority)
- (-) [liability] → incident reviews compare real failures to ignored or missing twin warnings (model neglect becomes blameworthy)

## ART 06.039 - Reconfigurable & Agile Factories

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, reconfigurable factories help societies switch faster into emergency production of medical, protective, or repair-critical goods. Institutionally, they strengthen local strategic autonomy but also concentrate control in orchestration software and module suppliers. The effect is material yet indirect to frontline safety delivery, so 3.

**Weak signals (4):**

- (+) [preparedness planning] → governments contract flexible lines for emergency goods (capacity becomes strategic)
- (+) [operational readiness] → factories rehearse rapid recipe or module swaps (agility gets tested, not assumed)
- (+) [skills] → workforce training shifts toward cross-cell oversight rather than single-line specialization (human roles broaden)
- (-) [verification burden] → regulators report new failure modes after frequent reconfiguration (agility creates fresh risk)

## ART 06.040 - Circular & Sustainable Manufacturing

### Score: 3 (Impact in GVN 17)

**Justification (3–5 sentences):** Directly, this reduces waste-handling hazards and dependence on fragile virgin-material supply chains, which helps strategic regularity. Institutionally, it raises traceability, contamination-control, and product-passport demands rather than changing how safety is delivered day to day. That keeps the impact material but indirect, so 3.

### Weak signals (4):

- (+) [material security] → procurement rewards recycled-content critical goods with verified provenance (resource resilience gains value)
- (+) [waste risk] → advanced sorting lines add continuous contamination sensing (safety shifts into material data)
- (-) [product integrity] → recalls trace failures to poorly qualified recirculated inputs (circularity meets trust barrier)
- (+) [governance] → product passports become mandatory for recovered material streams (traceability becomes infrastructure)

## ART 06.041 - Bio-fabrication technologies

### Score: 1 (Impact in GVN 17)

**Justification (3–5 sentences):** The main linkage is through health security and a few specialized biological supplies rather than the broader Safety & Security operating model. Unless biomanufacturing becomes a routine resilience asset for emergency care or protective materials, impact remains narrow. So it is worth watching, but only at 1.

### Weak signals (4):

- (+) [medical resilience] → emergency medicine programs test locally fabricated tissue patches or substitutes (niche continuity use appears)
- (+) [hospital procurement] → resilience plans include small biofab capacity for scarce inputs (from research to preparedness)
- (+) [regulation] → faster review paths emerge for standardized constructs used in emergencies (institutional opening begins)
- (-) [scale limits] → facilities remain confined to specialist hospitals and labs (broad GVN effect stays weak)  
Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

### Score: 3 (Impact in GVN 17)

**Justification (3–5 sentences):** Directly, programmable materials can self-deploy, self-adjust, or self-seal in shelters, wearables, seals, and protective systems. Institutionally, they reduce manual adjustment and maintenance but create new certification questions around trigger conditions and failure modes. That keeps the impact material but bounded, so 3.

**Weak signals (4):**

- (+) [protective equipment] → vendors pilot humidity- or heat-responsive components (adaptation moves into materials)
- (+) [infrastructure repair] → self-closing seals or adaptive inserts enter maintenance catalogs (manual intervention declines)
- (+) [certification] → standards add transformation-cycle and trigger tests (dynamic behavior becomes governable)
- (-) [failure analysis] → incidents examine mis-triggering under unusual conditions (programmability adds new uncertainty)

**ART 06.043 - Volumetric Additive Manufacturing****Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main path is faster production of complex emergency parts or medical components with less manual handling. That is useful, but broad Safety & Security effects stay limited unless certified distributed production scales widely. So it remains a low-priority watch item at 1.

**Weak signals (4):**

- (+) [rapid replacement] → hospitals or labs pilot one-shot printing of time-critical parts (speed advantage becomes operational)
  - (+) [standards] → benchmark geometries are defined for volumetrically printed safety items (certification starts forming)
  - (+) [procurement] → contingency plans mention volumetric printers for spare shortages (preparedness use appears)
  - (-) [adoption breadth] → deployments stay within specialist labs, not general safety supply chains (linkage remains narrow)
- Signal density: **LOW** (linkage weak; additional signals would be speculative).

**7. Advanced Materials & Nano-engineering****ART 07.044 - Metamaterials for Novel Optics & Connectivity****Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, metamaterials improve antennas, shielding, wave steering, detection, and signature control in cluttered or contested environments. Institutionally, capability shifts into surfaces and retrofits, broadening who can field advanced sensing or communications while raising new regulatory and security questions. Across telecom, critical infrastructure, and security applications, that is plausibly a €100M–1B / 50–500M-hour effect, so 5.

**Weak signals (4):**

- (+) [communications resilience] → public buildings or vehicles add reconfigurable radio surfaces (coverage moves into materials)
- (+) [sensing precision] → procurements specify flat-lens or wave-shaping components for detection systems (form factor starts mattering)
- (-) [regulation] → authorities open cases on hidden wave steering or interference liabilities (novel control needs new rules)
- (+) [incident performance] → operators credit improved detection or connectivity through clutter or smoke (field value becomes visible)

## ART 07.045 - Room-Temperature Superconductors

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, room-temperature superconductors would strengthen grid reliability, compact high-current systems, and some sensing or magnetic-security applications. Institutionally, they revalue network design and strategic materials while creating new high-consequence failure and sabotage points. If actually deployable in critical infrastructure, the effect is easily in the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [grid continuity] → utilities pilot superconducting links at critical bottlenecks (losses and footprint fall)
- (+) [sensing platforms] → high-performance sensors shrink because cryogenics are removed (precision becomes deployable)
- (+) [standards] → quench and fault-management rules are written for ambient systems (new failure mode gets formalized)
- (-) [security] → resilience exercises treat superconducting nodes as strategic single points of failure (dependency becomes visible)

## ART 07.046 - Self-Healing & Smart Polymers

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these materials slow degradation in pipes, coatings, cables, building elements, and protective gear, reducing hidden failures and downtime. Institutionally, maintenance shifts away from frequent inspection toward condition monitoring and activation protocols, while warranty and end-of-life questions get harder. Because this can cut incident frequency across many ordinary assets, the impact is significant and fits 5.

**Weak signals (4):**

- (+) [infrastructure durability] → road, pipe, and façade specs start requiring self-healing materials (inspection logic starts changing)
- (+) [insurance] → policies reward certified crack-arrest or self-repair coatings (lifetime risk gets repriced)

- (+) [maintenance] → service intervals lengthen after field validation of healing cycles (manual burden declines)
- (-) [claims validation] → recalls follow when “healing” fails under real weathering (marketing meets accountability)

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct value comes from anti-corrosion, anti-fouling, decontamination, low-friction, and safer surface behavior in infrastructure and protective equipment. Institutionally, some safety effort shifts from repeated cleaning and replacement toward material choice and lifecycle monitoring, while nanoparticle handling and scarce-input dependence also matter. That is a broad €100M–1B / 50–500M-hour class of effect, so 5.

**Weak signals (4):**

- (+) [critical facilities] → water, food, and hospital sites adopt advanced anti-fouling or self-sanitizing coatings (surface control gains value)
- (+) [maintenance economics] → corrosion-related downtime falls in coated asset classes (lifetime benefits become legible)
- (+) [certification] → standards begin covering wear indicators and catalytic surfaces (performance gets formalized)
- (-) [worker safety] → handling rules tighten around nanoparticle application or removal (upstream risks become visible)

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these materials improve failure margins in harsh, high-load, high-temperature, or corrosive safety-critical equipment. Institutionally, they slow maintenance cycles, alter stockpiling logic, and move risk into qualification and joining processes rather than routine replacement. In critical hardware and infrastructure, that lands comfortably in the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [critical hardware] → bridge, grid, turbine, or defense contracts specify HEA components (materials move into live assets)
- (+) [lifecycle planning] → replacement intervals are extended after field data, not just lab tests (reliability starts compounding)
- (+) [strategic resilience] → stockpiles begin listing advanced alloy feedstocks (materials become security-relevant)
- (-) [manufacturing] → bottlenecks in machining or joining delay adoption despite demand (qualification remains decisive)

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The strongest link is indirect: reducing climate-driven instability and improving air-handling control around industrial or enclosed environments. Institutionally, this creates new monitoring, permitting, and energy-tradeoff questions more than a direct change in everyday safety delivery. That keeps the plausible impact material but secondary, so 3.

**Weak signals (4):**

- (+) [industrial safety] → high-risk sites include capture modules in compliance and continuity plans (air handling gets upgraded)
- (+) [resilience policy] → public strategies link capture to industrial continuity or hazard reduction (linkage becomes explicit)
- (+) [operations] → sorbent replacement contracts enter routine plant safety budgets (materials become operational assets)
- (-) [maintenance risk] → leaks or downtime trace back to degraded capture media or poor regeneration (new upkeep burden appears)

## ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these composites improve lightweight protection, vehicle structures, drones, and some self-sensing components. Institutionally, they can move inspection from periodic checks to embedded condition monitoring, but also raise handling and recycling issues. Useful, but mostly as an enabling material layer, so 3.

**Weak signals (4):**

- (+) [protective systems] → self-sensing composite skins enter vehicle or unmanned-platform specs (materials start reporting condition)
- (+) [weight-sensitive assets] → procurement demands weight reduction plus fatigue monitoring (performance tradeoff changes)
- (-) [workplace safety] → nanoparticle handling rules tighten in composite repair and manufacturing (benefits come with exposure concerns)
- (-) [failure modes] → recalls focus on interfaces and joints rather than bulk material strength (integration becomes the bottleneck)

## ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, smart thermal materials cut overheating risk, improve passive fire and heat management, and stabilize buildings, batteries, electronics, and shelters.



Institutionally, they reduce dependence on constant operator intervention and reshape building and equipment standards. Because thermal failures are widespread and expensive, the effect is broad enough for 5.

**Weak signals (4):**

- (+) [building resilience] → retrofits add phase-change or radiative-cooling materials to critical facilities (passive control gains priority)
- (+) [fire and battery safety] → codes incorporate adaptive thermal layers or thermal buffers (heat governance moves into materials)
- (+) [outage resilience] → incident reports show longer safe operation during cooling failure (materials buy response time)
- (-) [quality assurance] → insurers demand proof against cycle degradation or fire-toxicity drift (durability becomes central)

## **ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors**

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The key linkage is strategic resilience: safer motors, actuators, and generators with less exposure to concentrated supply chains. Institutionally, this matters through procurement stability and domestic manufacturing more than through everyday safety operations. That makes it material but indirect, so 3.

**Weak signals (4):**

- (+) [critical manufacturing] → public procurement favors rare-earth-light actuation in safety sectors (supply security becomes criterion)
- (+) [domestic industry] → magnet plants receive resilience subsidies or strategic status (upstream dependence gets politicized)
- (+) [equipment design] → motor vendors redesign around different thermal and magnetic profiles (system adaptation begins)
- (-) [performance limits] → operators still reserve top-tier applications for legacy magnets (substitution stays partial)

## **ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination**

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these membranes improve clean-water security while lowering the labor and energy burden of keeping decentralized water systems safe. Institutionally, they move risk from constant operator attention toward membrane replacement, monitoring, and concentrate management. That is material for resilience but still secondary to the overall safety regime, so 3.

**Weak signals (4):**

- (+) [water security] → containerized desal units appear in island, military, or disaster plans (distributed supply gains credibility)
- (+) [operations] → utilities monitor membrane fouling remotely instead of by routine visits (oversight shifts to telemetry)
- (+) [procurement] → long cleaning intervals become a key selection criterion (operator burden becomes visible)
- (-) [environmental governance] → incidents focus on concentrate handling or membrane disposal (new externalities surface)

## ART 07.054 - Ultra-wide-bandgap Power Semiconductors

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these devices improve efficiency, robustness, and compactness in converters for grids, vehicles, sensors, and backup systems. Institutionally, they strengthen many other safety-critical systems at once while making module packaging and material supply more strategic. That system-wide enabling effect is plausibly in the €100M–1B / 50–500M-hour band, so 5.

**Weak signals (4):**

- (+) [backup power] → microgrids and fleet chargers specify higher-temperature power modules (space and cooling constraints ease)
- (+) [critical electronics] → vendors market quieter, lighter resilient converters around UWBG modules (performance shifts become visible)
- (+) [standards] → thermal-cycling and extreme-voltage certification expands for new packages (operational confidence builds)
- (-) [failure analysis] → field problems cluster in packaging and interfaces, not the semiconductor core (integration remains decisive)

## ART 07.055 - Solid Hydrogen Storage Materials

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, solid hydrogen storage can make backup power, remote equipment, and some mobility systems safer and easier to site than compressed or cryogenic alternatives. Institutionally, risk shifts from tank pressure toward cartridge quality, thermal management, and material cycling. That makes the impact real but niche, so 3.

**Weak signals (4):**

- (+) [remote continuity] → telecom or remote-site backups replace gas cylinders with solid-storage cartridges (handling burden eases)
- (+) [regulation] → transport and siting rules are written specifically for solid hydrogen modules (deployment becomes thinkable)
- (+) [insurance] → premiums favor lower-blast-zone solid systems in dense areas (safety advantage gets priced)

- (-) [asset durability] → maintenance logs show cycle degradation or slow hydrogen release under field conditions (materials remain limiting)

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, mature fusion would recast energy security from imported fuels and weather dependence toward domestically managed, continuous electricity and high-grade heat. Institutionally, it centralizes capability in a few high-security facilities with heavy robotics, regulation, and specialist oversight, while a major outage or security failure would be systemically important. In a 5.5M society, one or two such assets could materially shape the weekly continuity of hospitals, data infrastructure, industry, and water systems, so 10.

**Weak signals (4):**

- (+) [strategic continuity] → national resilience plans reserve future fusion output for critical infrastructure clusters (energy security logic shifts)
- (+) [operations model] → hot-cell robotics and digital-twin maintenance become standard procurement items (human exposure is engineered down)
- (+) [regulation] → fusion-specific emergency and security frameworks appear, distinct from fission (institutional category separates)
- (-) [system risk] → grid operators treat fusion outages as national strategic-risk scenarios (single assets become pivotal)

### ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main path is steadier local electricity and heat for critical services with lower fuel-transport dependence. Institutionally, SMRs shift security, waste, and siting conflicts to a local scale and can concentrate bargaining power around specific sites. That is highly significant for resilience but still infrastructure-specific, placing it in the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [critical services] → hospitals, campuses, or industrial clusters pursue dedicated SMR studies (local baseload becomes a safety strategy)
- (+) [emergency governance] → passive-safety assumptions appear in planning exercises and public communication (new nuclear framing spreads)
- (-) [local legitimacy] → community consent and protest mechanisms harden around siting (trust becomes a deployment bottleneck)

- (+) [system planning] → grid operators designate SMRs for black-start or island-support roles (resilience value becomes explicit)

## ART 08.058 - Thin-film solar cells

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, thin-film solar spreads generation onto roofs, facades, vehicles, shelters, and devices where rigid panels are awkward, supporting more decentralized safety infrastructure. Institutionally, it lowers some installer bottlenecks and supports local autonomy, while creating new inspection, degradation, and fire-code issues. Because it can strengthen many local protection systems at once, the plausible magnitude reaches the €100M–1B / 50–500M-hour band, so 5.

**Weak signals (4):**

- (+) [distributed resilience] → emergency shelters, vehicles, and public buildings adopt solar skins rather than separate panels (power moves into surfaces)
- (+) [device autonomy] → procurements require self-powered signs, sensors, or beacons (local continuity gets cheaper)
- (+) [manufacturing shift] → safety-critical products add energy-harvesting laminates at factory stage (installation burden moves upstream)
- (-) [building safety] → codes tighten around inspection and fire behavior of integrated solar surfaces (ubiquity raises oversight needs)

## ART 08.059 - Bionic Leaf Technology

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main relevance is niche distributed production of low-carbon fuels or chemical feedstocks for hard-to-connect sites. Broader Safety & Security pathways are indirect unless such panels become routine resilience assets in remote operations. So it remains a low-priority watch item at 1.

**Weak signals (4):**

- (+) [remote continuity] → isolated-site pilots pair artificial-photosynthesis panels with backup systems (fuel-from-light gets field tested)
- (+) [defense/disaster logistics] → programs test solar-to-fuel tiles where gas delivery is difficult (niche security value appears)
- (+) [regulation] → containment rules emerge for reactive intermediates in field units (from lab concept to deployable tech)
- (-) [adoption breadth] → procurement interest remains limited to edge cases (linkage stays weak)

Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, long-duration storage reduces blackout risk, sustains emergency loads, and makes critical infrastructure less fragile to supply-demand shocks. Institutionally, it shifts resilience planning toward dispatch software, site safety, and ownership of flexibility assets, while also creating fire, cyber, and market-power risks. Because continuity of power is a weekly safety condition for very large populations, mature storage is transformative and fits 10.

**Weak signals (4):**

- (+) [grid governance] → codes start requiring long-duration storage on critical feeders (continuity becomes a planning rule)
- (+) [public services] → hospitals, water utilities, and shelters sign capacity contracts with storage sites (resilience becomes contractual)
- (+) [outage management] → incident reports show storage sustaining services through multi-hour failures (proof moves from forecasts to events)
- (-) [siting / safety] → community opposition focuses on fire risk or private control of resilience assets (distributional politics intensify)

## ART 08.061 - Solid-State Batteries

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, solid-state batteries make vehicles, drones, tools, and backup systems safer and lighter, with less cooling burden and lower thermal-runaway risk. Institutionally, they reduce some insurance and maintenance friction while increasing dependence on interface quality and specialized supply chains. Spread across many mobile safety systems, that plausibly reaches the €100M–1B / 50–500M-hour range, so 5.

**Weak signals (4):**

- (+) [fire safety] → codes treat solid-state installations differently from liquid-electrolyte packs (risk profile visibly changes)
- (+) [public-safety fleets] → first responders preferentially procure solid-state packs for vehicles or equipment (safety premium becomes acceptable)
- (+) [insurance] → premiums fall for certified storage rooms or fleets using solid-state systems (risk transfer starts rewarding chemistry)
- (-) [field reliability] → failures concentrate at interfaces or low-temperature performance edges (new limits replace old ones)

## ART 08.062 - Green Hydrogen & Power-to-X

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, Power-to-X improves long-duration fuel security for backup generation, transport, and critical industry when electricity alone is not enough.

Institutionally, it widens the resilience role of ports, storage hubs, certification systems, and utilities, while adding handling, sabotage, and water-allocation concerns. That is a significant €100M–1B / 50–500M-hour class of effect, so 5.

**Weak signals (4):**

- (+) [fuel continuity] → emergency fuel reserves begin including hydrogen-derived carriers (molecular resilience becomes policy)
- (+) [critical facilities] → hospitals, data centers, or ports sign green-fuel offtake for backup use (clean fuels enter continuity planning)
- (+) [traceability] → regulators standardize origin and safety certificates for stored molecules (trust moves into documentation)
- (-) [site safety] → incident exercises focus on leak detection, ventilation, and sabotage around hydrogen hubs (new hazard model forms)

## ART 08.063 - High-Efficiency Wind Turbines

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The pathway is broader energy resilience through more local clean generation and better condition monitoring in harsh sites. Institutionally, the main shifts are in maintenance logistics, grid balancing, and siting conflict rather than in direct safety delivery. That keeps the GVN effect material but indirect, so 3.

**Weak signals (4):**

- (+) [energy resilience] → local resilience plans count high-efficiency wind in contingency portfolios (generation enters safety logic)
- (+) [asset monitoring] → turbine OEMs market self-monitoring for storm, icing, and structural risk (operability gets safer)
- (-) [siting conflict] → emergency-access, aviation, or radar concerns dominate public disputes (security externalities stay salient)
- (+) [maintenance labor] → remote and robotic inspections replace more manual turbine access (hazard exposure declines)

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, it can supply remote, temporary, or disrupted sites without fuel convoys or new cables. Institutionally, beam control, exclusion zones, and mispointing risks become safety issues, limiting the breadth of deployment. That makes it useful for selected resilience cases but still closer to the €10M–100M / 5–50M-hour band, so 3.

**Weak signals (4):**

- (+) [disaster response] → agencies test beam-powered field bases or equipment (cable-free continuity becomes plausible)

- (+) [regulation] → beam-safety and automatic cutoff rules are published (deployment gets institutional boundaries)
- (+) [remote operations] → mining, military, or infrastructure sites buy rectenna-equipped systems (niche markets form)
- (-) [security] → exercises simulate misalignment, spoofing, or orbital segment failure (control risk becomes operational)

## ART 08.065 - Advanced geothermal technology

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, advanced geothermal provides stable local electricity and heat independent of weather or imported fuel, which supports continuity in critical services and industries. Institutionally, it shifts attention toward drilling supply chains, seismic monitoring, and subsurface governance instead of daily fuel logistics. In places where geology and policy align, that is significant enough for 5.

**Weak signals (4):**

- (+) [critical heat/power] → hospitals, campuses, and district-heating systems commission deep geothermal resilience studies (baseload localism strengthens)
- (+) [operations] → drilling pilots target critical-load clusters rather than merchant power markets (security use case sharpens)
- (-) [risk governance] → seismic and well-integrity monitoring requirements tighten (subsurface externalities become central)
- (+) [finance] → performance insurance lowers borrowing costs for geothermal serving essential loads (institutional confidence grows)

## ART 08.066 - Resilient microgrids

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, microgrids keep essential loads running through wider-grid failures and move some energy-security responsibility toward sites and communities. Institutionally, they redistribute power toward local asset owners, software operators, and inverter vendors, while raising interoperability, equity, and cyber issues. Because they directly realize the shift from centralized support toward decentralized proactive continuity, they are transformative and fit 10.

**Weak signals (4):**

- (+) [local continuity] → municipalities require island-capable power for water, telecom, and shelter sites (resilience gets localized)
- (+) [regulation] → interconnection rules simplify intentional islanding and reconnection (institutional friction falls)
- (+) [insurance] → discounts appear for sites with tested black-start and island modes (reliability gets priced)



- (-) [distribution / fairness] → debates intensify over which neighborhoods or sites get microgrids first (security becomes uneven)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, next-gen editing improves control over pathogens, vectors, inherited risks, and some biological safety hazards. Institutionally, it expands the reach of prevention but intensifies biosecurity, consent, and unequal-access conflicts at the same time. Because both upside and downside are large yet governed through specialized systems, the overall magnitude fits 5.

**Weak signals (4):**

- (+) [health security] → national countermeasure programs fund rapid-edit platforms (editing enters preparedness doctrine)
- (+) [governance] → ethics and security review become mandatory for major editing deployments (institutional salience rises)
- (-) [equity / discrimination] → insurers or employers test the edges of edited-risk status in decisions (genomic power shifts outward)
- (-) [biosecurity] → biocontainment standards tighten around multiplex or hard-to-trace editing workflows (misuse concern grows)

### ART 09.068 - mRNA Therapies & Vaccines

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, mRNA platforms shorten response time to outbreaks and some acute health threats, strengthening population safety and recovery. Institutionally, they favor agile manufacturing and fast procurement, while also magnifying misinformation, trust, and adverse-event politics. Health security relevance is high, but the main operating model shift stays within a major sector, so 5.

**Weak signals (4):**

- (+) [preparedness capacity] → governments keep warm manufacturing lines for rapid response (speed becomes strategic asset)
- (+) [supply security] → local fill-finish or stockpiling capacity enters resilience contracts (dependence is managed)
- (+) [regulatory tempo] → batch release becomes more software-driven and faster (response cycle compresses)
- (-) [public trust] → misinformation spikes during rollout planning or updates (social stability becomes co-dependent)

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main effect is food-system resilience and lower exposure to some zoonotic, supply, and contamination risks. Institutionally, security shifts from land and herd management toward bioprocess reliability, energy, and input supply. That is material for societal stability but still indirect to the broader Safety & Security regime, so 3.

**Weak signals (4):**

- (+) [food security] → national preparedness strategies include cultured or microbial protein capacity (new resilience layer appears)
- (+) [critical inputs] → media, CO<sub>2</sub>, and electricity are treated as food-security dependencies (risk profile relocates)
- (-) [market concentration] → protests target ownership concentration of resilient food production assets (power shifts become visible)
- (+) [standards] → contamination and traceability rules harden for cell-based foods (institutionalization begins)

## ART 09.070 - Organoids & Tissue Engineering

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, organoids and tissue constructs improve hazard testing, toxicology, and treatment selection with faster and often more human-relevant feedback. Institutionally, they shift evidence standards and reduce dependence on scarce samples, but also require new validation regimes. That makes the impact material yet upstream, so 3.

**Weak signals (4):**

- (+) [hazard testing] → regulators accept organoid data in chemical or drug safety submissions (evidence stack changes)
- (+) [public health labs] → rapid hazard panels using organoids enter emergency toxicology workflows (fidelity becomes operational)
- (+) [data governance] → biobanks and hospitals form standard-sharing agreements around tissue models (ecosystem starts scaling)
- (-) [representativeness] → disputes focus on whether models generalize across populations (trust remains conditional)

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, designer microbes support biosensing, remediation, adaptive manufacturing, and controlled breakdown of hazards. Institutionally, they deepen both resilience and biosecurity risk, because the same programmability can be diverted or escape governance. The upside and downside together are easily large enough for 5.

**Weak signals (4):**

- (+) [environmental safety] → water, waste, or industrial sites pilot engineered microbes for detection or remediation (living response systems form)
- (+) [governance] → approvals begin requiring kill-switches or nutrient dependencies (containment becomes standard)
- (+) [industrial resilience] → venture funding shifts from pharma-only uses toward infrastructure and safety uses (market broadens)
- (-) [security] → monitoring expands for illicit synthesis or release risks (dual-use pathway becomes concrete)

**ART 09.072 - Microbiome Engineering****Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The most plausible gains are targeted infection control, environmental quality management, and reduced reliance on broad harsh interventions. Institutionally, microbiome steering changes stewardship practices but remains context-dependent and reversible only imperfectly. That makes it material but bounded, so 3.

**Weak signals (4):**

- (+) [infection control] → hospitals or care facilities trial microbiome-based prevention (narrow intervention logic advances)
- (+) [environmental management] → wastewater or soil programs add community-level microbiome metrics (invisible states get governed)
- (+) [regulation] → narrower approval paths appear for microbiome “nudges” than for full GM releases (policy starts differentiating)
- (-) [ecosystem stability] → temporary or rebound effects force cautious rollout rules (predictability remains incomplete)

**ART 09.073 - Precision Medicine & Genomic Diagnostics****Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, this supports earlier detection of individual risk, better triage, and more targeted prevention, which strongly matches the challenger regime’s self-diagnostics and individual responsibility. Institutionally, it redistributes power toward those who control interpretation, consent, and access, and can worsen discrimination if safeguards lag. Large but not regime-defining, the overall magnitude fits 5.

**Weak signals (4):**

- (+) [self-diagnostics] → primary care portals begin issuing actionable genomic risk alerts (personalized prevention becomes routine)
- (+) [data control] → personal data wallets start carrying selective genomic credentials (sharing shifts toward the individual)

- (-) [fairness] → anti-discrimination rules expand to cover genomic inference (harm pathway becomes politically salient)
- (-) [behavioral effects] → controversy grows over false reassurance or over-surveillance from genetic risk scores (interpretation starts reshaping conduct)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these platforms speed safer testing of drugs, chemicals, and some threat scenarios with richer continuous readouts. Institutionally, they move evidence generation into standardized platforms and can reduce some high-risk experimentation, but are still upstream to operational safety systems. So the score remains 3.

**Weak signals (4):**

- (+) [chemical safety] → labs replace more animal or surrogate tests with chip-based panels (testing fidelity improves)
- (+) [public health response] → agencies procure chip cartridges for rapid hazard assessment (lab tools become emergency tools)
- (+) [standards] → interoperable biosignal outputs and calibration routines are defined (evidence gets normalized)
- (-) [decision authority] → disputes continue over whether chip results alone justify action (institutional trust still incomplete)

## ART 09.075 - Biological Aging & Longevity Barriers

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main pathway is slower decline in health, recovery, and cognitive reliability for older populations and some safety-critical workers. Institutionally, it raises access inequality and pressure-to-remain-in-service issues more than it changes frontline safety doctrine. That keeps the impact material but indirect, so 3.

**Weak signals (4):**

- (+) [workforce continuity] → public employers pilot anti-frailty or senescence-targeted programs (service-life expectations extend)
- (+) [career structures] → retirement and fitness policies shift in some safety professions (human-capital planning adapts)
- (-) [equity] → disputes emerge over who can afford performance-preserving therapies (resilience becomes stratified)
- (-) [safety monitoring] → long-term surveillance focuses on cancer or abnormal-growth risks (benefit stays conditional)

## ART 09.076 - Engineered Living Materials

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, engineered living materials can make infrastructure more self-repairing and more legible about early degradation. Institutionally, they shift part of safety stewardship from manual inspection toward care of living components and condition monitoring. That is real, but still a partial and early infrastructural pathway, so 3.

**Weak signals (4):**

- (+) [infrastructure maintenance] → pilots use self-sealing concrete or responsive facades in public works (repair starts becoming endogenous)
- (+) [inspection practice] → manuals teach how to read biological condition signals in materials (maintenance culture changes)
- (+) [procurement] → longer-life, low-maintenance living composites enter hard-to-access asset trials (access constraints drive uptake)
- (-) [biosecurity] → standards focus on survivability and containment of living components (novel failure modes need governance)

## ART 09.077 - Gene Drive Pest Control

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, gene drives could reduce vector-borne disease and some invasive-species harms with far less repetitive human labor. Institutionally, they create unusually large governance, consent, transboundary, and reversibility questions, so negative impact magnitude is also high. Significant but contested and domain-specific, it fits 5.

**Weak signals (4):**

- (+) [public health] → consultations shift from research ethics to release governance (deployment starts looking real)
- (+) [cross-border coordination] → neighboring jurisdictions negotiate shared monitoring for target species (spillover becomes acknowledged)
- (+) [comparative policy] → agencies formally compare gene drives with recurring pesticide programs (persistent biological control gains traction)
- (-) [ecological control] → resistance or containment studies dominate redesign cycles (governance risk remains central)

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** Safety linkage is mainly neonatal or reproductive care in specialized settings, plus a few research and conservation uses. Those effects are meaningful, but too narrow to alter the broader Safety & Security operating model. So the score remains 1.

**Weak signals (4):**

- (+) [neonatal safety] → ex-vivo gestation support extends to longer windows in intensive care (clinical potential strengthens)
- (+) [research governance] → ethics rules clearly separate synthetic embryo models from embryo research (institutional pathway clarifies)
- (+) [specialist planning] → remote or high-risk medicine scenarios start mentioning artificial-gestation support (edge-use cases appear)
- (-) [scale] → deployment remains confined to elite clinical research centers (broad linkage stays weak)  
Signal density: **LOW** (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, mega-constellations provide resilient connectivity, positioning augmentation, and rapid orbital situational awareness across the whole society. Institutionally, they shift dependence from terrestrial monopolies toward global operators and space-governance arrangements, while creating jamming, cyber, and debris vulnerabilities. Because communications and risk visibility for hundreds of thousands can depend on them weekly, the effect is transformative and fits 10.

**Weak signals (4):**

- (+) [emergency continuity] → response plans require satellite fallback for telecom outages (space links become normal backup)
- (+) [risk visibility] → operations dashboards ingest near-real-time orbital imagery or change alerts (space data enters daily practice)
- (+) [insurance] → continuity premiums differentiate organizations with independent satellite paths (resilience gets priced)
- (-) [security] → jamming or anti-satellite incident drills are treated as civil-protection scenarios (dependency becomes strategic)

### ART 10.080 - Space Resource Utilization (SRU)

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The plausible link is long-run strategic materials security, but that sits far from everyday safety operations in this GVN. Unless returned materials materially displace terrestrial critical-mineral bottlenecks, impact stays limited. So it is worth monitoring, but only at 1.

**Weak signals (4):**

- (+) [strategic materials] → mineral-security plans begin mentioning off-world sources (linkage would need policy uptake)

- (+) [regulation] → chain-of-custody rules are drafted for returned concentrates (operational relevance would need formalization)
- (+) [buyers] → critical-material users sign options on pilot return missions (market linkage would need to form)
- (-) [current practice] → terrestrial resilience planning continues without SRU assumptions (broad impact remains weak)  
Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct relevance is confined to extreme isolation settings such as shelters, submarines, polar sites, and a few hazardous facilities. That is real, but too niche to materially shift the overall Safety & Security operating model. So the score stays at 1.

**Weak signals (4):**

- (+) [civil defense] → advanced air/water recycling appears in shelter modernization plans (extreme-isolation relevance grows)
- (+) [remote facilities] → offshore or polar sites adopt more closed-loop utility systems (resupply risk drives use)
- (+) [safety standards] → trace-toxin and microbial monitoring rules harden for closed habitats (specialist governance expands)
- (-) [scope] → procurement remains limited to isolated facilities, not mainstream safety systems (linkage stays narrow)  
Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, HAPs can restore communications, sensing, and navigation support quickly over disaster zones, remote areas, or temporarily degraded networks. Institutionally, they add a recoverable middle layer between terrestrial and orbital systems, but bring airspace, spectrum, and observation-governance issues. That is significant for continuity and rapid response, though not dominant in everyday safety, so 5.

**Weak signals (4):**

- (+) [disaster response] → civil-protection agencies contract stratospheric coverage after storms or wildfires (restoration model changes)
- (+) [telecom resilience] → licenses include HAP contingency service clauses (middle-layer infrastructure gets normalized)
- (+) [operations] → post-disaster comparisons show faster service restoration with HAP support (value becomes measurable)



- (-) [civil liberties] → public concern rises over persistent overhead observation by recoverable platforms (acceptance gets politicized)

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, decentralized trust networks can harden audit trails, credentials, consent records, and provenance across parties that do not fully trust each other. Institutionally, they shift trust from single operators toward protocol governors, node operators, and wallet custodians, while creating usability, fraud, and bridge risks. In selected safety workflows that is significant enough for 5, but not a universal fix.

**Weak signals (4):**

- (+) [shared records] → provenance, identity, or evidence pilots move from closed trials to mandated use (tamper-evidence gains traction)
- (+) [regulation] → authorities accept selectively disclosed verifiable credentials in safety workflows (institutional legitimacy grows)
- (-) [security] → insurers focus on key loss and bridge exploits rather than generic hype (real risk pricing emerges)
- (-) [governance] → major incidents expose failures in supposedly decentralized oversight (trust shifts, not disappears)

### ART 11.084 - Platform Cooperatives & Fair Work

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main pathway is fairer coordination of security, care, delivery, and local resilience work through more transparent platform rules and payouts. Institutionally, that affects bargaining power and contestability more than direct incident prevention. So the impact is material but indirect, keeping it in the 3 range.

**Weak signals (4):**

- (+) [local resilience labor] → municipalities favor co-op platforms in safety-adjacent procurement (ownership model starts mattering)
- (+) [worker bargaining] → audited payout and ranking transparency becomes contractual (fairness moves into operations)
- (+) [service continuity] → insurers or financiers back worker-owned dispatch and care apps (institutional confidence appears)
- (-) [scale limits] → co-op models struggle to match incumbent platform liquidity in crises (coordination ceiling remains)

## ART 11.085 - Open Data Sharing Marketplaces

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these marketplaces speed access to fragmented risk, maintenance, environmental, and incident data that smaller actors otherwise cannot use. Institutionally, they shift bargaining power around who can price, gatekeep, or verify safety-relevant information, while low-quality or withdrawn data can also magnify harm. That coordination effect is significant enough for 5.

**Weak signals (4):**

- (+) [risk intelligence] → insurers, utilities, and municipalities buy standardized datasets via marketplaces (data access starts scaling)
- (+) [compliance] → procurement requires machine-readable provenance and usage terms (trust moves into metadata)
- (+) [smaller actors] → organizations join shared analytics without bespoke integration projects (coordination costs fall)
- (-) [market integrity] → disputes rise over misleading quality scores or dataset withdrawal (data governance becomes operational)

## ART 11.086 - Secure & Resilient Social Platforms

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, secure resilient social platforms improve crisis communication, local coordination, whistleblowing, and community warning when mainstream systems fail or are manipulated. Institutionally, they reduce dependence on a few dominant intermediaries and make moderation, identity, and continuity more inspectable, while still giving bad actors robust channels if governance is weak. Because public trust and real-time coordination are central to predictable ground rules, mature deployment is transformative and fits 10.

**Weak signals (4):**

- (+) [public communication] → agencies maintain official channels on federated or resilient networks, not only dominant platforms (coordination diversifies)
- (+) [community resilience] → civic groups migrate sensitive coordination to portable encrypted spaces (trust infrastructure shifts)
- (-) [system fragility] → censorship or outage events trigger migration to resilient alternatives (stress reveals dependency)
- (-) [moderation legitimacy] → transparency reports on moderation and rule changes become a key adoption factor (governance becomes differentiator)

## ART 11.087 - Collective Open Innovation Networks

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** Direct value comes from faster cross-organizational problem-solving on sensors, procedures, resilience tools, and threat analysis. Institutionally, they lower coordination

costs and preserve failed pathways as reusable knowledge, but are mainly upstream to operational deployment. So the GVN effect is real yet bounded, at 3.

**Weak signals (4):**

- (+) [problem solving] → agencies run open challenge platforms with shared safety testbeds (innovation starts opening outward)
- (+) [procurement] → challenge performance links directly to later contracts (experimentation begins affecting deployment)
- (+) [governance] → standard IP and data-use templates reduce collaboration friction (institutional scaffolding improves)
- (-) [incentives] → participation remains uneven unless organizers fund validation and follow-through (coordination still needs support)

## ART 11.088 - Scalable Decentralized Governance

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, scalable decentralized governance can make local rule-setting, pooled-resource allocation, and community response faster and more auditable. Institutionally, it changes who gets to decide and how legitimacy is proved, while creating manipulation and participation-fatigue risks. That is significant in a GVN explicitly shifting away from only top-down control, so 5.

**Weak signals (4):**

- (+) [community safety governance] → local groups adopt digital voting for resilience spending or mutual-aid funds (rules start moving closer to citizens)
- (+) [auditability] → digitally governed pools publish tamper-evident decision logs (legitimacy becomes inspectable)
- (-) [manipulation risk] → bot-voting or collusion incidents drive stronger identity requirements (scale creates attack surface)
- (-) [participation burden] → delegation and sampling tools become necessary to keep decisions workable (governance must evolve)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these networks scale preparedness, safety training, and verified competence across dispersed populations and smaller organizations. Institutionally, they shift gatekeeping from single institutions toward credential protocols and platform operators, while creating fraud and assessment-integrity issues. Because safety depends heavily on trained people and trusted capabilities, the effect fits 5.

**Weak signals (4):**

- (+) [workforce preparedness] → regulated safety courses move into continuously updated digital networks (training supply expands)
- (+) [portable trust] → employers accept machine-verifiable skill credentials in place of local certificates (verification gets cheaper)
- (+) [simulation] → drills auto-issue cryptographically signed records after assessed performance (practice and proof merge)
- (-) [integrity] → regulators audit AI tutoring bias and cheating in high-stakes assessment (scalability meets trust challenge)

## ART 11.090 - Prediction-Market Forecasting Platforms

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, prediction markets can improve threat anticipation, resource allocation, and policy timing by converting dispersed knowledge into measured probabilities. Institutionally, they challenge opaque expert judgment while creating gaming, legitimacy, and settlement problems of their own. As a foresight layer for complex safety decisions, the plausible impact is significant enough for 5.

**Weak signals (4):**

- (+) [risk foresight] → ministries, insurers, or utilities run internal forecast markets on incident risks (probability becomes a management tool)
- (+) [decision culture] → dashboards start showing calibrated probabilities rather than binary warnings (uncertainty becomes operational)
- (-) [governance] → settlement committees and audit trails become formal after disputed outcomes (market truth needs institutions)
- (-) [manipulation] → anomalous trading triggers investigations and tighter identity controls (forecasting systems attract gaming)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score: 20 (Impact in GVN 17)**

**Justification (3–5 sentences):** This is a linchpin because pervasive decentralized safety systems cannot scale if alarms, sensors, vehicles, gateways, and controls remain in incompatible vendor silos. Directly, interoperability turns heterogeneous devices into composable safety infrastructure; institutionally, it shifts power from proprietary lock-in toward standards bodies, integrators, and operators, while also making correlated failure a larger systemic risk. Because the challenger regime depends on mass coordination among many devices and actors, and this layer is hard to substitute at scale, it fits 20.

**Weak signals (5):**

- (+) [public procurement] → tenders ban non-interoperable safety devices (vendor lock-in starts losing legitimacy)
- (+) [certification] → secure interoperability logos become mandatory in critical-device markets (standards move from optional to decisive)
- (+) [operations] → response platforms auto-discover mixed device fleets without custom integration (composability starts becoming real)
- (-) [systemic risk] → outages reveal whether common standards create correlated failure paths (shared infrastructure cuts both ways)
- (-) [power politics] → lobbying intensifies over standard definitions, profiles, and compliance costs (governance becomes strategic)

## ART 12.092 - Interoperable Digital Twin Ecosystems

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, interoperable twin ecosystems give multiple actors a shared, live, explainable state model of critical assets and environments. Institutionally, they reduce information asymmetry between owners, regulators, insurers, and responders, while creating new liability disputes when virtual and physical states diverge. Because this changes how complex safety decisions are coordinated across organizations, the effect is transformative and fits 10.

**Weak signals (4):**

- (+) [multi-party coordination] → regulators and owners begin using the same live twin during audits (shared state becomes actionable)
- (+) [procurement] → twin portability across vendors becomes mandatory (models stop being one-platform islands)
- (+) [operations] → emergency exercises rehearse interventions inside shared twins before field action (pre-action simulation becomes normal)
- (-) [liability] → disputes emerge when twin warnings were ignored or proved wrong (model authority becomes contestable)

## ART 12.093 - Global Supply Chain Traceability Networks

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, traceability networks reduce counterfeits, speed recalls, secure critical inputs, and make provenance visible during disruption. Institutionally, they shift bargaining power toward actors controlling identifiers, standards, and verification gateways, while also exposing smaller suppliers to heavier compliance. Because predictability of goods and inputs is core to safety and security, mature traceability is transformative and fits 10.

**Weak signals (4):**

- (+) [critical supplies] → medicines, PPE, food, and infrastructure parts gain mandatory end-to-end traceability (provenance becomes a safety layer)

- (+) [regulatory operations] → customs and regulators query shared provenance networks rather than paper files (verification becomes real-time)
- (+) [recall management] → recalls become faster and more targeted because batch histories are instantly available (reaction time compresses)
- (-) [market access] → small suppliers complain about data-entry or certification burdens (power shifts toward network insiders)

## ART 12.094 - Personal Data Portability & Trust Frameworks

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these frameworks let individuals share identity, health, training, and device data selectively and reversibly across institutions. Institutionally, they rebalance control from platforms and agencies toward users, while introducing wallet-recovery, phishing, and digital-exclusion risks. Because the challenger regime depends on empowered individuals rather than only centralized data custody, the impact is transformative and fits 10.

**Weak signals (4):**

- (+) [individual responsibility] → services accept portable consent receipts and data-wallet credentials (data control moves closer to users)
- (+) [administrative friction] → onboarding times fall as repeated form-filling and checks disappear (sharing becomes infrastructure)
- (-) [fraud] → case patterns shift from database leaks to wallet compromise and social engineering (risk surface migrates)
- (-) [inclusion] → assistance programs emerge for users unable to manage credentials safely (autonomy creates a new divide)

## ART 12.095 - Interoperable Digital Currency Payment Networks

**Score: 3 (Impact in GVN 17)**

**Justification (3–5 sentences):** The main value is continuity of trusted payments across crises, borders, and disconnected systems, plus lower fraud and reconciliation overhead. Institutionally, power shifts among banks, wallets, states, and infrastructure providers more than among frontline safety actors. That makes the linkage real but indirect, so 3.

**Weak signals (4):**

- (+) [crisis support] → emergency cash-transfer programs start using interoperable digital wallets (payment continuity gains safety role)
- (+) [essential services] → shelters or utilities accept cross-network or offline vouchers (resilience enters payment design)
- (+) [governance] → regulators harmonize transaction-limit and selective-disclosure rules (systems start speaking to each other)
- (-) [system risk] → outages expose routing or compliance-data dependencies across connected rails (interoperability adds new fragility)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, machine-readable regulation lets safety, compliance, and emergency rules operate at machine speed across forms, devices, firms, and agencies.

Institutionally, it shifts discretion from manual interpreters toward code publishers and version governance, while poor encoding can propagate mistakes at scale. Since predictable ground rules are explicit in this GVN, turning rules into operable digital infrastructure is transformative and fits 10.

**Weak signals (4):**

- (+) [regulatory predictability] → agencies publish binding machine-readable rule packages alongside legal text (rules become executable)
- (+) [organizational burden] → software vendors stop manually re-implementing the same compliance logic (interpretation cost falls)
- (+) [change management] → rule updates are accompanied by tests and versioned logs (regulation starts behaving like software)
- (-) [legal legitimacy] → courts examine whether coded rules faithfully captured legal intent (translation becomes politically salient)

## ART 12.097 - Open Metaverse Interoperability Protocols

**Score: 1 (Impact in GVN 17)**

**Justification (3–5 sentences):** The clearest paths are training, simulation, and some secure remote collaboration across immersive spaces. Those are useful, but the broader Safety & Security linkage is secondary unless immersive coordination becomes routine infrastructure. So this stays at 1.

**Weak signals (4):**

- (+) [training ecosystems] → emergency training platforms exchange assets and identities across vendors (interoperable simulation begins)
  - (+) [remote collaboration] → public-safety simulations require cross-world asset portability (multi-platform workflows emerge)
  - (+) [governance] → moderation and provenance fields are added to immersive drill standards (safety rules enter protocol design)
  - (-) [operational breadth] → adoption remains mostly inside training and niche collaboration (broad linkage stays weak)
- Signal density: **LOW** (linkage weak; additional signals would be speculative).

## ART 12.098 - Content Authenticity Infrastructure

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, content authenticity infrastructure helps distinguish attributable, traceable media from manipulated content in emergencies, investigations, public communication, and platform moderation. Institutionally, it shifts trust from ad hoc judgment to



provenance chains and certification ecosystems, while also creating new power over who receives “authentic” status and how anonymous evidence is treated. Given the GVN’s dependence on trust and predictable ground rules, that is transformative and fits 10.

**Weak signals (4):**

- (+) [information integrity] → phones, cameras, drones, and editing tools enable credentials by default (provenance starts becoming normal)
- (+) [operational trust] → emergency agencies accept only provenance-bearing media for some decisions (authenticity begins gating action)
- (-) [platform governance] → major platforms prominently label missing or broken credential chains (unverified media gets downgraded)
- (-) [civil-liberties balance] → journalists and whistleblowers push for privacy-preserving authenticity modes (credibility and anonymity collide)

## **ART 12.099 - Privacy-Preserving Collaboration Protocols**

**Score: 10 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, these protocols let agencies, firms, hospitals, and utilities compute joint safety insights without surrendering raw sensitive data. Institutionally, they reduce legal and contractual friction while moving dependence toward cryptographic infrastructure and safe-output governance. Because fragmented sensitive data is a core inhibitor of proactive safety, mature privacy-preserving collaboration is transformative and fits 10.

**Weak signals (4):**

- (+) [cross-sector analytics] → threat, health, or infrastructure analyses move from central pools to MPC-style networks (joint insight becomes possible)
- (+) [regulation] → authorities approve shared computation where raw-data sharing was blocked (institutional barrier breaks)
- (+) [distribution] → smaller participants join collaborations previously dominated by data-rich incumbents (coordination widens)
- (-) [performance bottlenecks] → outages or latency issues in secure computation start affecting live operations (privacy becomes infrastructure load)

## **ART 12.100 - Manufacturing-specific standards, conformance testing & certification infrastructure**

**Score: 5 (Impact in GVN 17)**

**Justification (3–5 sentences):** Directly, this lowers adoption risk for new safety-relevant manufacturing methods and makes quality claims easier to trust across sites. Institutionally, it shifts power toward test labs, certification bodies, and machine-readable evidence systems, while potentially slowing innovation if standards lag. Because dependable production of critical goods underpins regularity and trust, the overall impact is significant and fits 5.

**Weak signals (4):**

- (+) [critical supply trust] → buyers require machine-readable conformance certificates with batches (quality proof becomes portable)
- (+) [insurance / contracts] → benchmark jobs and shared test artifacts appear in procurement language (comparison gets standardized)
- (+) [audit practice] → auditors rely more on digital evidence than bespoke site reports (verification scales better)
- (-) [innovation friction] → firms complain that certification cycles are slower than technology change (assurance can become bottleneck)

## GVN 18: Collaboration and Trust ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score:** 20 (Impact in GVN 18)

**Justification (3–5 sentences):**

Global Broadband Connectivity is a core enabler of the challenger regime described in the GVN: it brings people, firms, and communities into continuous access to platforms, reputation systems, crowdfunding, and cross-border collaboration. Its 2nd-order effect is to weaken geography-based gatekeeping by shifting trust formation toward persistent digital identities, ratings, escrow, and remote verification, while also intensifying platform dependency. The 3rd-order effects are strong network effects: once more actors are always connected, collaboration norms, market access, and transparency loops compound, but scams, surveillance, and winner-take-most intermediaries also scale faster. This is a plausible linchpin of the shift from hierarchical trust to digitally mediated trust, so a 20 is justified. Without this layer, the challenger-regime operating model in the GVN is much weaker.

**Weak signals (9):**

- (+) [Platform access equality] → remote communities adopt satellite/mesh or equivalent broadband as a primary channel for work, payments, and public services (new actors enter trust networks)
- (+) [Cross-border collaboration] → SMEs from previously weak-coverage areas start selling and sourcing through international platforms (distance stops blocking trust)
- (+) [Reputation economy] → verified ratings, escrow, and digital identity use rises sharply after coverage upgrades (trust becomes portable)
- (+) [Crowdfunding/crowdsourcing] → peripheral projects reach funding and contributor pools previously concentrated in cities (gatekeepers lose control)

- (+) [Risk management] → insurers, banks, or buyers begin accepting real-time remote verification from field locations (remote proof becomes normal)
- (+) [Public authorities] → universal-connectivity programs are bundled with digital identity, education, or procurement systems (institutional dependence forms)
- (-) [Fraud and scams] → complaint volumes rise in newly connected populations using unfamiliar platforms (attack surface expands)
- (-) [Platform power] → a few access/network providers become de facto gateways for commerce or identity services (bargaining power concentrates)
- (-) [Privacy protection] → court cases or regulatory probes target traffic metadata retention or satellite/mesh surveillance practices (trust-surveillance conflict sharpens)

## ART 01.002 - Ultra-Low Latency Networks

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Ultra-Low Latency Networks mainly affects this GVN by making remote interaction feel reliable enough for live coordination, negotiation, telepresence, and shared digital workspaces. Its institutional effect is narrower: some sectors may start to trust remote supervision or intervention in place of co-location, but the underlying trust architecture still depends on other platforms, identities, and rules. Feedback effects matter only where low delay changes behavior at scale; otherwise this stays an enabling improvement rather than a new operating model. The plausible magnitude is therefore material but limited, consistent with a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Remote collaboration quality] → procurement starts specifying millisecond-grade service levels for shared workspaces or teleoperations (distance frictions fall)
- (+) [Trust in remote presence] → regulators or certifiers accept remote supervision where on-site presence was previously required (remote oversight becomes credible)
- (+) [Shared situational awareness] → disputes over lag, desynchronization, or failed handoffs decline in platform-mediated workflows (coordination becomes smoother)
- (-) [Equality of participation] → premium low-latency service tiers emerge only for large firms or urban zones (benefits skew upward)
- (-) [Market structure] → edge-network control concentrates in a few providers with proprietary service guarantees (dependency deepens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.003 - Edge AI for Sensor Data

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Edge AI for Sensor Data raises the quality of machine-verifiable evidence inside collaborations by turning raw video, audio, and sensor streams into local summaries, alerts, and compliance signals. That matters institutionally because buyers, insurers, platforms, and regulators can rely less on manual inspection and more on distributed evidence, while privacy improves when raw data stays near the source. The main negative pathway is opaque or biased edge models becoming unchallengeable gatekeepers in ratings, safety, or fraud detection. If deployed across logistics, public services, and marketplace quality control, the impact can plausibly reach the significant band, supporting a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Transparency] → contracts and audits begin accepting edge-generated event logs instead of full raw recordings (proof becomes cheaper)
- (+) [Privacy protection] → organizations procure on-device analytics specifically to avoid centralizing personal data (trust barrier eases)
- (+) [Risk management] → insurers or compliance teams offer discounts when shared assets use certified edge anomaly detection (fewer blind spots)
- (+) [Quality incentives] → platforms start using device-side verification for delivery, maintenance, or condition claims (reputation gets harder to fake)
- (+) [Inter-organizational collaboration] → field partners share summaries rather than raw feeds in joint operations (data-sharing friction falls)
- (-) [Accountability] → appeal cases rise against automated local judgments that are hard to inspect after the fact (hidden gatekeeping appears)
- (-) [Power distribution] → a small set of model vendors control what counts as a valid event or anomaly (trust logic centralizes)
- (-) [Labor] → manual inspectors or verifiers are displaced without clear redress channels (oversight becomes thinner)
- (-) [Security] → spoofing or adversarial attacks on edge models trigger visible false positives/negatives in shared workflows (confidence becomes fragile)

**ART 01.004 - Quantum & High-Precision Sensing**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Quantum & High-Precision Sensing has plausible niche value where trust depends on extremely precise measurement, authentication, or tamper detection, but those use cases are narrow relative to this GVN. Its stronger effects sit in specialized science, defense, navigation, or industrial metrology rather than in the everyday operating model of collaboration and trust. The aggregate impact is therefore concrete but limited, fitting a 1. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Risk management] → specialized audits or critical-infrastructure contracts start requiring these measurements (niche trust use appears)
- (+) [Authenticity] → high-value goods or facilities use precision signatures to verify status or origin (tamper evidence improves)
- (-) [Access] → deployment stays confined to defense, labs, or large operators (benefits remain narrow)
- (-) [Power distribution] → a few vendors or states control the sensitive instruments and calibration chains (trust tools centralize)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 01.005 - Micro/Nano Sensor Networks**

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Micro/Nano Sensor Networks matters to this GVN mainly by making shared physical conditions easier to observe and evidence easier to collect. That can reduce disputes over asset state, delivery conditions, workplace safety, or infrastructure performance, and it can support new forms of reputation and insurance. Still, the technology does not by itself define who is trusted, how data is governed, or how conflicts are resolved; those institutional layers remain elsewhere. The likely effect is material but limited, consistent with a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Transparency] → contracts begin referencing sensor-derived condition logs for deliveries, shared assets, or maintenance (proof gets cheaper)
- (+) [Risk management] → insurers or certifiers accept dense telemetry in place of some manual inspections (coordination load falls)
- (+) [Quality incentives] → marketplaces reward verified condition or usage data rather than self-reported claims (harder to fake quality)
- (-) [Privacy] → objections rise when ambient sensing starts capturing worker, customer, or resident behavior (social license matters)
- (-) [Power distribution] → platform owners control the gateways and dashboards that interpret sensor evidence (visibility centralizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 01.006 - Privacy-Preserving Pervasive Sensing**

**Score:** 10 (Impact in GVN 18)

**Justification (3–5 sentences):**

Privacy-Preserving Pervasive Sensing directly addresses one of the GVN's stated inhibitors: the tension between transparency and privacy. In direct use, it allows continuous observation, verification, and optimization in workplaces, supply chains, and public spaces while sharing only constrained outputs rather than raw personal data. Its 2nd-order effect is large because it can unlock collaborations that were previously blocked by data protection law, reputational risk, or social resistance; its 3rd-order risk is that "privacy-preserving" claims can legitimize wider monitoring and harder-to-contest algorithmic control. If adopted in major public and commercial systems, it can reshape collaboration patterns for hundreds of thousands of people, so 10 is warranted. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

**Weak signals (9):**

- (+) [Privacy protection] → regulators or data protection authorities approve sensor deployments that keep raw data on-device (legal barrier softens)
- (+) [Transparency] → procurement rules require privacy-preserving telemetry rather than blanket bans on sensing (new middle ground appears)
- (+) [Cross-border collaboration] → multinational projects choose local-processing architectures to avoid personal-data transfers (jurisdiction friction drops)
- (+) [Trust] → labor unions, tenants, or patient groups accept monitoring only when third-party tests confirm non-export of raw data (social license forms)
- (+) [Risk management] → insurers or compliance teams start accepting aggregated sensor proofs with cryptographic attestations (evidence becomes shareable)
- (+) [Reputation systems] → platforms use privacy-preserving proofs of task completion or condition instead of identity-heavy surveillance (less over-collection)
- (-) [Accountability] → watchdog groups document cases where "private" sensing still enables opaque scoring or exclusion (trust claims are contested)
- (-) [Power distribution] → certified secure chips and privacy stacks are supplied by a small vendor set (infrastructure dependence grows)
- (-) [Security] → high-profile breaches of supposedly privacy-preserving devices trigger rapid loss of social acceptance (legitimacy becomes brittle)

**ART 01.007 - Quantum-Resilient and Secure Communication Networks**

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Quantum-Resilient and Secure Communication Networks strengthens the trust substrate for cross-organizational collaboration by reducing fear of interception, impersonation, and long-term data exposure. Its biggest 2nd-order effect is institutional: sectors that hesitate to share sensitive records, negotiate remotely, or automate high-stakes workflows become more willing to do so when communication integrity is auditable. The negative pathway is concentration in certified hardware, complex migration costs, and a false sense of security when non-cryptographic vulnerabilities remain. That makes it an important but not standalone shaper of the GVN, consistent with a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Trust] → public procurement or sector standards start requiring post-quantum-secure messaging for identity, payment, or records exchange (baseline trust rises)
- (+) [Risk management] → boards approve longer-lived data sharing once retrospective decryption risk is priced in (collaboration horizon extends)
- (+) [Cross-border collaboration] → federated projects cite secure metadata protection as a reason to include more partners (coordination broadens)
- (+) [Accountability] → contracts reference crypto-agility or secure-routing obligations in inter-organizational workflows (security becomes contractual)
- (+) [Institutional adoption] → managed migration programs appear for courts, banks, hospitals, or procurement networks (trust infrastructure upgrades)
- (-) [Equality] → high-assurance secure networking remains affordable only for large organizations at first (trust gap widens)
- (-) [Market structure] → certified secure hardware ecosystems become concentrated and export-controlled (dependency increases)
- (-) [Security] → incidents show that endpoint compromise still defeats strong transport security (overconfidence gets punished)
- (-) [Regulatory conflict] → law-enforcement or national-security disputes over strong encryption intensify (governance friction rises)

**ART 01.008 - Integrated Sensing and Communication (ISAC)**

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Integrated Sensing and Communication (ISAC) matters to this GVN mainly by making shared physical conditions easier to observe and evidence easier to collect. That can reduce disputes over asset state, delivery conditions, workplace safety, or infrastructure performance, and it can support new forms of reputation and insurance. Still, the technology does not by itself define who is trusted, how data is governed, or how conflicts are resolved; those institutional layers remain elsewhere. The likely effect is material but limited, consistent with a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Transparency] → contracts begin referencing sensor-derived condition logs for deliveries, shared assets, or maintenance (proof gets cheaper)
- (+) [Risk management] → insurers or certifiers accept dense telemetry in place of some manual inspections (coordination load falls)
- (+) [Quality incentives] → marketplaces reward verified condition or usage data rather than self-reported claims (harder to fake quality)



- (-) [Privacy] → objections rise when ambient sensing starts capturing worker, customer, or resident behavior (social license matters)
- (-) [Power distribution] → platform owners control the gateways and dashboards that interpret sensor evidence (visibility centralizes)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Compute-in-Memory & Neuromorphic Chips affects this GVN by enabling more data processing close to where information is generated, which can support private, always-on, low-latency collaboration tools. Its institutional significance is mostly indirect: if more trust, monitoring, and decision logic can run on-device or at the edge, dependence on remote clouds and centralized data pooling falls somewhat. But the operating model of trust still changes only through applications built on top of the hardware. That supports a material-but-limited score of 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Privacy protection] → vendors market on-device compliance, moderation, or verification functions that previously required cloud processing (local trust tools become feasible)
- (+) [Resilience] → critical collaboration systems continue operating during connectivity loss because local inference is good enough (central dependence falls)
- (+) [Access] → low-power devices in public or remote settings gain useful intelligence without heavy backhaul (participation broadens modestly)
- (-) [Power distribution] → specialized hardware toolchains remain controlled by a few suppliers (benefits route through vendor ecosystems)
- (-) [Accountability] → decisions made on-device become harder to inspect after the fact (local opacity can rise)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Novel transistor technologies and materials that leap past silicon CMOS limits matters to the GVN mainly as a back-end performance enabler for other systems such as privacy-preserving AI, secure communication, and large collaboration platforms. By itself it does not change who trusts whom, how reputations travel, or how rules are enforced. Its most plausible effects are concentrated in cost, scale, and ownership of digital infrastructure, so the direct GVN impact remains limited. A score of 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Digital trust infrastructure] → major collaboration or compliance workloads become cheaper to run at scale on this hardware class (back-end leverage appears)
- (+) [Privacy protection] → more workloads move from centralized clouds to local or edge environments because compute cost falls (some decentralization becomes feasible)
- (-) [Power distribution] → capacity remains concentrated in a few fabs, cloud providers, or proprietary toolchains (bargaining power centralizes)
- (-) [Open collaboration] → closed software stacks limit who can adapt the hardware to trust-critical uses (benefits stay narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Quantum Computing Platforms has a non-trivial GVN impact because mature quantum computing would alter the security assumptions under which many digital trust systems were built, while also improving some optimization tasks. The main pathway is 2nd-order and disruptive: organizations would need to re-evaluate long-term secrecy, authentication, and concentration of computational advantage. However, those effects are mediated through other technologies and governance responses rather than through direct collaboration features. That supports a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Risk management] → organizations classify longer data-retention and cryptographic migration plans as board-level collaboration risks (security assumptions change)
- (+) [Coordination] → access to quantum optimization services is used in complex market, routing, or scheduling collaborations (new advantage appears)
- (+) [Governance] → sector guidance starts differentiating 'quantum-safe' and legacy trust arrangements (institutional response emerges)
- (-) [Power distribution] → only a few actors can afford meaningful quantum capacity (computational bargaining power concentrates)

- (-) [Trust] → concern grows that old signatures or archives may become retrospectively vulnerable (confidence in records is shaken)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Photonic and Optical Computing matters to the GVN mainly as a back-end performance enabler for other systems such as privacy-preserving AI, secure communication, and large collaboration platforms. By itself it does not change who trusts whom, how reputations travel, or how rules are enforced. Its most plausible effects are concentrated in cost, scale, and ownership of digital infrastructure, so the direct GVN impact remains limited. A score of 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Digital trust infrastructure] → major collaboration or compliance workloads become cheaper to run at scale on this hardware class (back-end leverage appears)
- (+) [Privacy protection] → more workloads move from centralized clouds to local or edge environments because compute cost falls (some decentralization becomes feasible)
- (-) [Power distribution] → capacity remains concentrated in a few fabs, cloud providers, or proprietary toolchains (bargaining power centralizes)
- (-) [Open collaboration] → closed software stacks limit who can adapt the hardware to trust-critical uses (benefits stay narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Next-Gen Memory & Storage matters to the GVN mainly as a back-end performance enabler for other systems such as privacy-preserving AI, secure communication, and large collaboration platforms. By itself it does not change who trusts whom, how reputations travel, or how rules are enforced. Its most plausible effects are concentrated in cost, scale, and ownership of digital infrastructure, so the direct GVN impact remains limited. A score of 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Digital trust infrastructure] → major collaboration or compliance workloads become cheaper to run at scale on this hardware class (back-end leverage appears)
- (+) [Privacy protection] → more workloads move from centralized clouds to local or edge environments because compute cost falls (some decentralization becomes feasible)

- (-) [Power distribution] → capacity remains concentrated in a few fabs, cloud providers, or proprietary toolchains (bargaining power centralizes)
- (-) [Open collaboration] → closed software stacks limit who can adapt the hardware to trust-critical uses (benefits stay narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score:** 0 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Even in mature form, Molecular Computing Underdevelopment has no clear broad pathway to the operating model of collaboration and trust described in the GVN. Its plausible uses are too specialized and too far removed from transparency, reputation, governance, payment, or everyday digital coordination. Any future impact would likely arrive only through highly indirect downstream applications. That keeps the score at 0. This stays below any meaningful material anchor for this GVN.

### **Weak signals (4):**

- (+) [Watchpoint: niche collaboration] → pilot use appears inside biosecurity, lab verification, or molecular record-keeping workflows (a concrete trust use would be emerging)
- (+) [Watchpoint: standards] → regulators or labs define reproducible interfaces between molecular computation outputs and digital audit systems (linkage would strengthen)
- (-) [Relevance] → most deployments stay inside experimental biotech rather than shared coordination systems (linkage remains weak)
- (-) [Access] → the technology remains too specialized to alter mass collaboration practices (impact stays negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 - Causal Learning & Reasoning

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Causal Learning & Reasoning matters because collaboration often fails when parties cannot agree on causes, side effects, or who is responsible for outcomes. Directly, it can improve intervention design, dispute analysis, and policy or marketplace tuning; institutionally, it makes collaborative decisions more legible to funders, regulators, and participants. The negative pathway is overconfidence in causal models that encode hidden biases or become a technocratic substitute for negotiation. If embedded in major policy, insurance, and platform decision loops, the effect is

significant enough for a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

### Weak signals (9):

- (+) [Transparency] → dashboards in procurement, welfare, or platform governance start showing counterfactual explanations for decisions (causes become discussable)
- (+) [Risk management] → joint projects run causal scenario testing before changing incentives or rules (missteps become cheaper to avoid)
- (+) [Trust] → independent reviewers start demanding causal audit trails rather than only predictive accuracy (accountability deepens)
- (+) [Collaboration quality] → A/B test results are linked to explicit causal graphs in shared governance processes (evidence becomes reusable)
- (+) [Regulation] → guidance or standards begin distinguishing causal claims from mere correlations in high-stakes systems (higher bar appears)
- (-) [Power distribution] → a small number of platforms define the causal ontology used in large ecosystems (interpretive power centralizes)
- (-) [Justice] → affected groups challenge causal models that encode normative assumptions as facts (legitimacy contest emerges)
- (-) [Security] → actors game the variables that models treat as causal levers (trust shifts into optimization battles)
- (-) [Decision rights] → managers defer to causal dashboards instead of negotiation with workers, users, or communities (voice can narrow)

## ART 03.016 - Federated & Privacy-Preserving Learning

**Score:** 10 (Impact in GVN 18)

### Justification (3–5 sentences):

Federated & Privacy-Preserving Learning directly unlocks collaboration across fragmented, sensitive datasets without forcing parties to surrender raw information to a central owner. That is highly aligned with the GVN's need to combine transparency, trust, and privacy: hospitals, municipalities, firms, and devices can co-produce intelligence while keeping control over local data. Its 3rd-order effects are large because shared models can become new infrastructure for markets and public services, while failures around bias, governance, or update leakage can undermine trust across entire networks. In a 5.5M-person society this can plausibly reshape everyday collaboration at scale, supporting a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### Weak signals (9):

- (+) [Privacy protection] → major consortia launch joint-model programs explicitly without central data pooling (privacy bottleneck breaks)

- (+) [Cross-organizational collaboration] → smaller organizations join shared AI efforts because raw-data transfer is no longer required (participation broadens)
- (+) [Trust] → data-sharing negotiations shift from ownership fights to model-governance terms (coordination costs fall)
- (+) [Risk management] → regulators approve distributed learning schemes that would previously have been blocked (legal pathway opens)
- (+) [Quality] → local models show measurable gains from multi-party participation without raw-data export (value becomes visible)
- (+) [Bargaining power] → sector-level model cooperatives emerge to counter hyperscaler data monopolies (ownership structures diversify)
- (-) [Accountability] → disputes arise over who is responsible when a shared model harms someone but no party held all data (liability blurs)
- (-) [Power distribution] → aggregation infrastructure is controlled by a small set of orchestrators or hardware vendors (new chokepoints appear)
- (-) [Security] → model inversion or poisoned updates trigger public failures in supposedly privacy-preserving collaborations (confidence can collapse)

## ART 03.017 - Trustworthy AI Systems

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Trustworthy AI Systems is one of the most direct routes to scaling cooperation beyond face-to-face trust, because it aims to make automated decisions predictable, auditable, and contestable. Inside the GVN it can reduce the need for manual supervision in marketplaces, compliance, moderation, and resource allocation; institutionally it can shift trust from specific organizations toward monitored socio-technical processes. The downside is equally systemic: whoever sets the rules, fairness definitions, and escalation thresholds gains quiet power over collaboration itself. If adopted in major public and commercial decision systems, it can transform how trust is realized, which justifies a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### **Weak signals (9):**

- (+) [Trust] → public tenders or enterprise procurements require audit trails, confidence indicators, and fallback modes for AI-mediated decisions (higher baseline set)
- (+) [Transparency] → users gain usable appeals and explanation records in platform ranking, pricing, or moderation systems (contestability rises)
- (+) [Risk management] → insurers price AI systems differently when they include monitored safe modes and versioned governance (adoption becomes insurable)
- (+) [Cross-organizational collaboration] → partners agree to shared AI tooling because behavior is easier to verify and monitor (joint use becomes acceptable)

- (+) [Justice] → standards bodies publish sector-specific fairness and accountability tests that vendors actually certify against (social acceptability rises)
- (+) [Labor] → oversight work shifts from manual checking to review of flagged edge cases (supervision model changes)
- (-) [Power distribution] → a few firms dominate the tooling that defines what counts as 'trustworthy' (meta-governance centralizes)
- (-) [Legitimacy] → watchdogs expose gaps between certified trustworthiness claims and real user outcomes (credibility can erode fast)
- (-) [Security] → adversarial or data-poisoning incidents in certified systems trigger calls for human-only control in sensitive areas (backlash risk rises)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Automated Machine Learning (AutoML) can lower the skill barrier for building and maintaining collaborative digital services, which matters for smaller organizations that currently cannot afford strong data or AI teams. That can widen participation in marketplace tooling, risk scoring, matching, or moderation, but it also makes it easier to deploy badly governed models. Because the institutional effect runs through proliferation of AI-mediated coordination rather than through a new trust mechanism itself, the impact is material but limited. A 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Access] → small organizations launch AI-based matching, compliance, or support tools without specialist teams (participation barrier falls)
- (+) [Transparency] → model lineage and auto-generated documentation become standard enough for external review (basic auditability improves)
- (+) [Coordination] → experimentation cycles for collaborative platforms shorten markedly (governance and product rules update faster)
- (-) [Risk management] → incidents rise from poorly specified automated rules being deployed by non-experts (cheap deployment creates noise)
- (-) [Power distribution] → a few cloud vendors set the default pipelines and guardrails for many actors (tooling dependence deepens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.019 - Collaborative Multi-Agent AI

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Collaborative Multi-Agent AI can materially alter collaboration by moving coordination work from



humans into swarms of software agents that negotiate roles, monitor states, and execute routines across organizations. The 2nd-order effect is a new layer of institutional dependence on protocol design: who can deploy agents, whose agents get priority, and how disputes are resolved becomes a governance question. Feedback loops are strong where many small interactions are automated, but harmful cascades or collusive behaviors can also spread faster than humans can intervene. That makes the impact significant, but still contingent on broader trust infrastructure, so a 5 fits. That is consistent with the significant €100M–1B / 50–500M person-hour band.

#### **Weak signals (9):**

- (+) [Coordination] → organizations start exposing APIs and task protocols specifically for agent-to-agent negotiation (machine collaboration becomes normal)
- (+) [Transparency] → shared logs of agent decisions are demanded in procurement or platform agreements (automated behavior must be inspectable)
- (+) [Risk management] → escalation rules define when agents must hand control back to humans (governance layer appears)
- (+) [Productivity] → multi-party workflows report faster resolution of routine coordination tasks after agent deployment (person-hours shift materially)
- (+) [Access] → smaller firms use off-the-shelf agents to join ecosystems previously requiring dedicated staff (barriers fall)
- (-) [Power distribution] → dominant platforms privilege their own agents' protocols and timing advantages (ecosystem power tilts)
- (-) [Security] → coordinated agent failures or collusion events trigger market-wide disruption (automation fragility becomes visible)
- (-) [Accountability] → disputes rise over who is liable for autonomous multi-agent commitments (responsibility diffuses)
- (-) [Labor] → clerical and coordination roles shrink faster than governance capacity adapts (social friction grows)

## **ART 03.020 - Quantum-Accelerated AI Systems**

**Score:** 1 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Quantum-Accelerated AI Systems may eventually sharpen planning or optimization in complex coordination settings, but for this GVN its impact is mostly indirect and contingent on very specific problem classes. It does not by itself solve the core trust bottlenecks around transparency, privacy, legitimacy, or governance. The most plausible systemic issue is concentration of advanced capability in a few providers. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

#### **Weak signals (4):**

- (+) [Coordination] → niche high-complexity planning tasks shift to hybrid quantum-AI services (specialized value appears)
- (+) [Risk management] → a few sectors use it for harder scenario search or allocation problems (limited collaboration benefit emerges)
- (-) [Power distribution] → only large providers can access the compute stack (capability concentration rises)
- (-) [Relevance] → mainstream collaboration tools see little direct change from the technology (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

AI-Driven Autonomous Scientific Discovery influences this GVN mainly through open-innovation ecosystems: it can accelerate how hypotheses, data, and experiments are shared and validated across institutions. Its direct relevance to collaboration and trust is therefore strongest in research, R&D, and policy evidence networks rather than in society-wide everyday coordination. The positive case is faster collective learning; the negative case is concentrated control over discovery pipelines and harder verification of machine-generated claims. That makes a 3 appropriate. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Open innovation] → research consortia let AI systems propose experiments and document rationales in shared workspaces (collective learning speeds up)
- (+) [Transparency] → negative results and machine-generated hypotheses are archived in searchable, auditable form (evidence becomes more reusable)
- (+) [Access] → smaller labs gain capabilities previously limited to well-funded discovery teams (research participation broadens)
- (-) [Trust] → peer reviewers or funders struggle to verify AI-generated chains of reasoning or prioritization (credibility burden rises)
- (-) [Power distribution] → compute-rich labs or vendors dominate autonomous discovery platforms (innovation power concentrates)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

### ART 04.022 - Immersive Augmented & Virtual Reality

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Immersive Augmented & Virtual Reality can raise trust and cooperativeness by making remote collaboration more embodied: people can share viewpoint, context, and spatial detail rather than relying on text or flat video alone. Institutionally this matters where training, inspection, negotiation, and design currently depend on travel or hard-to-transfer tacit knowledge. The main downside is deeper behavioral capture and new asymmetries between those who can participate in rich environments and those limited to basic interfaces. The resulting shift is significant but not foundational, so a 5 is appropriate. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Transparency] → remote audits, maintenance, or design reviews move from 2D calls to shared immersive sessions (context becomes easier to verify)
- (+) [Trust] → sectors with scarce experts standardize AR-guided remote assistance rather than travel-heavy supervision (co-presence becomes credible)
- (+) [Collaboration] → project teams report lower rework or misunderstanding after immersive coordination is adopted (shared mental models improve)
- (+) [Access] → rural or mobility-limited participants join high-value collaborative work without relocation (participation broadens)
- (+) [Training] → credentialing bodies accept immersive practical assessments or simulations (skills become easier to demonstrate)
- (-) [Privacy] → work platforms capture gaze, gesture, and environment data that trigger labor or consumer complaints (surveillance intensifies)
- (-) [Equality] → premium collaboration environments are available only to well-funded institutions (participation stratifies)
- (-) [Platform power] → a few spatial-computing platforms lock in identity, assets, and interaction rules (switching costs rise)
- (-) [Authenticity] → fraud cases involving manipulated avatars or synthetic environments reduce confidence in remote presence (presence becomes contestable)

**ART 04.023 - Brain-Computer Interfaces (BCI)**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Brain-Computer Interfaces (BCI) could eventually affect communication and participation, but within this GVN its plausible impact remains narrow and highly contingent on safety, ethics, and adoption. The technology may enable new forms of accessibility or high-bandwidth interaction for some users, yet it also raises deep concerns around consent, manipulation, and data sensitivity. Those issues make the collaboration-and-trust effects real but limited in aggregate. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Inclusion] → disability-focused or high-specialty collaboration pilots show clear participation gains (niche value appears)
- (+) [Trust] → strict consent and neural-data governance protocols are published and adopted (social license would be forming)
- (-) [Privacy] → controversies erupt over neural-data capture, retention, or inference (trust cost stays high)
- (-) [Power distribution] → early capability remains restricted to medical, military, or elite institutional settings (broad GVN impact stays low)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Advanced Prosthetics & Exoskeletons has a real but narrow link to this GVN through inclusion: better physical assistance can let more people participate in work, training, and collaboration. That is socially meaningful, but the aggregate effect on the operating model of trust and cooperation is limited compared with digital identity, payment, provenance, or governance infrastructure. The most important systemic issues are affordability and who gets access. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Inclusion] → organizations redesign tasks or roles so more people can participate using assistive hardware (participation broadens)
- (+) [Trust] → insurers or employers begin treating these devices as normal accommodations rather than exceptional cases (institutional acceptance grows)
- (-) [Equality] → access is concentrated among affluent employers or users (inclusion gains stay uneven)
- (-) [Labor power] → enhancement uses create pressure on others to adopt or keep pace (cooperation mixes with coercion)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Haptic and Multi-Sensory Feedback Systems has a real but narrow link to this GVN through inclusion: better physical assistance can let more people participate in work, training, and collaboration. That is socially meaningful, but the aggregate effect on the operating model of trust and cooperation is limited compared with digital identity, payment, provenance, or governance infrastructure. The most important systemic issues are affordability and who gets access. A 1 is

appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

#### **Weak signals (4):**

- (+) [Inclusion] → organizations redesign tasks or roles so more people can participate using assistive hardware (participation broadens)
- (+) [Trust] → insurers or employers begin treating these devices as normal accommodations rather than exceptional cases (institutional acceptance grows)
- (-) [Equality] → access is concentrated among affluent employers or users (inclusion gains stay uneven)
- (-) [Labor power] → enhancement uses create pressure on others to adopt or keep pace (cooperation mixes with coercion)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 04.026 - AI Understanding of Human Intent & Context**

**Score:** 10 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

AI Understanding of Human Intent & Context can transform the GVN because many collaboration failures come from misread context, fragmented attention, and poorly adapted interfaces rather than lack of raw information. Directly, it can personalize communication, detect overload or ambiguity, and lower barriers for people whose speech, behavior, or accessibility needs differ from dominant norms. At the same time, it creates a powerful surveillance and influence layer: platforms that infer intent can nudge decisions, rank sincerity, and steer interactions in ways users may not fully see. Because it can reshape everyday mediated communication for large populations, a transformative score of 10 is justified. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

#### **Weak signals (9):**

- (+) [Trust] → collaboration tools start adapting timing, modality, or prompts based on measured confusion or overload (miscommunication costs fall)
- (+) [Inclusion] → accessibility services shift from static settings to live context-aware assistance (more people can participate effectively)
- (+) [Risk management] → conflict, fraud, or burnout detection is integrated into workplace or platform workflows (early intervention becomes possible)
- (+) [Transparency] → users are shown why systems inferred a given intent or context before acting on it (inference becomes contestable)
- (+) [Quality of collaboration] → customer-support, mediation, or learning systems show measurable gains from context-aware interaction (value is observed)
- (-) [Privacy] → organizations begin collecting gaze, tone, movement, and behavioral signals far beyond traditional inputs (surveillance deepens)

- (-) [Power distribution] → platforms use intent models to steer choices, labor pacing, or pricing without explicit consent (behavioral control grows)
- (-) [Justice] → marginalized communication styles are misread and trigger exclusion or lower trust scores (bias becomes embodied)
- (-) [Legitimacy] → public backlash follows high-profile cases of 'emotion AI' or intent scoring used in employment, policing, or welfare (social license becomes fragile)

## ART 04.027 - Brain-to-Brain Interfaces

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Brain-to-Brain Interfaces could eventually affect communication and participation, but within this GVN its plausible impact remains narrow and highly contingent on safety, ethics, and adoption. The technology may enable new forms of accessibility or high-bandwidth interaction for some users, yet it also raises deep concerns around consent, manipulation, and data sensitivity. Those issues make the collaboration-and-trust effects real but limited in aggregate. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Inclusion] → disability-focused or high-specialty collaboration pilots show clear participation gains (niche value appears)
- (+) [Trust] → strict consent and neural-data governance protocols are published and adopted (social license would be forming)
- (-) [Privacy] → controversies erupt over neural-data capture, retention, or inference (trust cost stays high)
- (-) [Power distribution] → early capability remains restricted to medical, military, or elite institutional settings (broad GVN impact stays low)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Memory Prostheses could eventually affect communication and participation, but within this GVN its plausible impact remains narrow and highly contingent on safety, ethics, and adoption. The technology may enable new forms of accessibility or high-bandwidth interaction for some users, yet it also raises deep concerns around consent, manipulation, and data sensitivity. Those issues make the collaboration-and-trust effects real but limited in aggregate. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Inclusion] → disability-focused or high-specialty collaboration pilots show clear participation gains (niche value appears)
- (+) [Trust] → strict consent and neural-data governance protocols are published and adopted (social license would be forming)
- (-) [Privacy] → controversies erupt over neural-data capture, retention, or inference (trust cost stays high)
- (-) [Power distribution] → early capability remains restricted to medical, military, or elite institutional settings (broad GVN impact stays low)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Self-Driving Vehicles affects this GVN through verified remote action: people can coordinate, inspect, or intervene at distance with less reliance on local human presence. That can improve transparency and responsiveness in shared operations, but it also moves trust toward platform operators, remote supervisors, and liability regimes. The main systemic issues are surveillance, labor displacement, and who controls exception handling. The resulting impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Transparency] → shared operations use robotic logs, maps, or video as accepted evidence in inspections and service delivery (remote proof improves)
- (+) [Risk management] → hazardous or remote tasks shift to remotely supervised robots rather than local ad hoc arrangements (coordination becomes safer)
- (+) [Access] → scarce experts oversee more sites through teleoperation or exception handling (distance matters less)
- (-) [Labor] → local roles lose bargaining power as physical presence becomes less necessary (coordination power shifts)
- (-) [Accountability] → disputes rise over who is liable when remote or autonomous action fails across organizational boundaries (trust remains institution-dependent)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 05.030 - Drone Swarms & Aerial Robots

**Score:** 3 (Impact in GVN 18)



**Justification (3–5 sentences):**

Drone Swarms & Aerial Robots affects this GVN through verified remote action: people can coordinate, inspect, or intervene at distance with less reliance on local human presence. That can improve transparency and responsiveness in shared operations, but it also moves trust toward platform operators, remote supervisors, and liability regimes. The main systemic issues are surveillance, labor displacement, and who controls exception handling. The resulting impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Transparency] → shared operations use robotic logs, maps, or video as accepted evidence in inspections and service delivery (remote proof improves)
- (+) [Risk management] → hazardous or remote tasks shift to remotely supervised robots rather than local ad hoc arrangements (coordination becomes safer)
- (+) [Access] → scarce experts oversee more sites through teleoperation or exception handling (distance matters less)
- (-) [Labor] → local roles lose bargaining power as physical presence becomes less necessary (coordination power shifts)
- (-) [Accountability] → disputes rise over who is liable when remote or autonomous action fails across organizational boundaries (trust remains institution-dependent)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.031 - Humanoid and General-Purpose Robots

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Humanoid and General-Purpose Robots affects this GVN through verified remote action: people can coordinate, inspect, or intervene at distance with less reliance on local human presence. That can improve transparency and responsiveness in shared operations, but it also moves trust toward platform operators, remote supervisors, and liability regimes. The main systemic issues are surveillance, labor displacement, and who controls exception handling. The resulting impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Transparency] → shared operations use robotic logs, maps, or video as accepted evidence in inspections and service delivery (remote proof improves)
- (+) [Risk management] → hazardous or remote tasks shift to remotely supervised robots rather than local ad hoc arrangements (coordination becomes safer)
- (+) [Access] → scarce experts oversee more sites through teleoperation or exception handling (distance matters less)

- (-) [Labor] → local roles lose bargaining power as physical presence becomes less necessary (coordination power shifts)
- (-) [Accountability] → disputes rise over who is liable when remote or autonomous action fails across organizational boundaries (trust remains institution-dependent)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Soft Robotics & Bio-Inspired Machines has a plausible but narrow influence on this GVN through specialized remote handling or safer task execution. It may improve trust in certain inspections or services, yet the effect is confined to niche operational settings rather than the wider social operating model of collaboration and trust. The impact therefore stays limited. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Risk management] → niche sectors adopt the technology for tasks too risky or awkward for people (specialized coordination benefit appears)
- (+) [Transparency] → remote handling data is used in audits or maintenance records (some machine-verifiable evidence appears)
- (-) [Access] → deployment remains limited to specialized operators (broad social effect stays small)
- (-) [Power distribution] → know-how concentrates in a few vendors or service providers (coordination gains stay narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Fully Autonomous Drones, Robots & Underwater Vehicles affects this GVN through verified remote action: people can coordinate, inspect, or intervene at distance with less reliance on local human presence. That can improve transparency and responsiveness in shared operations, but it also moves trust toward platform operators, remote supervisors, and liability regimes. The main systemic issues are surveillance, labor displacement, and who controls exception handling. The resulting impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Transparency] → shared operations use robotic logs, maps, or video as accepted evidence in inspections and service delivery (remote proof improves)

- (+) [Risk management] → hazardous or remote tasks shift to remotely supervised robots rather than local ad hoc arrangements (coordination becomes safer)
- (+) [Access] → scarce experts oversee more sites through teleoperation or exception handling (distance matters less)
- (-) [Labor] → local roles lose bargaining power as physical presence becomes less necessary (coordination power shifts)
- (-) [Accountability] → disputes rise over who is liable when remote or autonomous action fails across organizational boundaries (trust remains institution-dependent)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.034 - Supportive Infrastructure for Autonomy

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Supportive Infrastructure for Autonomy affects this GVN through verified remote action: people can coordinate, inspect, or intervene at distance with less reliance on local human presence. That can improve transparency and responsiveness in shared operations, but it also moves trust toward platform operators, remote supervisors, and liability regimes. The main systemic issues are surveillance, labor displacement, and who controls exception handling. The resulting impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Transparency] → shared operations use robotic logs, maps, or video as accepted evidence in inspections and service delivery (remote proof improves)
- (+) [Risk management] → hazardous or remote tasks shift to remotely supervised robots rather than local ad hoc arrangements (coordination becomes safer)
- (+) [Access] → scarce experts oversee more sites through teleoperation or exception handling (distance matters less)
- (-) [Labor] → local roles lose bargaining power as physical presence becomes less necessary (coordination power shifts)
- (-) [Accountability] → disputes rise over who is liable when remote or autonomous action fails across organizational boundaries (trust remains institution-dependent)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Optical/Microwave Power Beaming for Persistent Robotics has a plausible but narrow influence on

this GVN through specialized remote handling or safer task execution. It may improve trust in certain inspections or services, yet the effect is confined to niche operational settings rather than the wider social operating model of collaboration and trust. The impact therefore stays limited. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

#### **Weak signals (4):**

- (+) [Risk management] → niche sectors adopt the technology for tasks too risky or awkward for people (specialized coordination benefit appears)
- (+) [Transparency] → remote handling data is used in audits or maintenance records (some machine-verifiable evidence appears)
- (-) [Access] → deployment remains limited to specialized operators (broad social effect stays small)
- (-) [Power distribution] → know-how concentrates in a few vendors or service providers (coordination gains stay narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

**Score:** 0 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Even in mature form, Gecko-Inspired Dry-Adhesion Mobility & Manipulation has no clear broad pathway to the GVN's core values of transparency, trust, and collaboration. It may be useful operationally in specific maintenance or mobility tasks, but those uses do not amount to a meaningful change in how trust is created or governed across society. Any linkage would be speculative without much stronger evidence of adoption into collaboration infrastructure. The score is 0. This stays below any meaningful material anchor for this GVN.

#### **Weak signals (4):**

- (+) [Watchpoint: niche evidence use] → the technology becomes standard in audit, access, or inspection workflows (a concrete trust linkage would emerge)
- (+) [Watchpoint: standards] → insurers or regulators create formal evidence or safety standards around its use (institutional relevance would rise)
- (-) [Relevance] → deployments remain purely operational and isolated from shared governance or trust systems (linkage stays weak)
- (-) [Adoption] → few non-specialist organizations ever use it in collaborative workflows (impact remains negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Multi-Material & Hybrid 3D Printing can support more distributed and flexible production partnerships, which matters to the GVN where collaboration often stalls on supplier coordination and trust in custom or local capability. Its direct effect is to shorten handoffs and make smaller-batch collaboration more feasible; institutionally, it shifts some trust from long supplier histories toward digital recipes, quality records, and certification. But most trust effects remain mediated by standards, contracts, and market power rather than the production method itself. That supports a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Collaboration] → organizations use distributed or rapidly reconfigured production partnerships instead of single fixed suppliers (coordination becomes more flexible)
- (+) [Transparency] → digital recipes and process data start substituting for some supplier-specific tacit knowledge (capability becomes easier to inspect)
- (+) [Access] → smaller local producers win work on speed or customization rather than only scale (entry broadens modestly)
- (-) [Trust] → buyers still hesitate without strong certification of quality consistency (technology alone is insufficient)
- (-) [Power distribution] → platform or OEM owners keep control over files, specs, and approval rights (openness remains conditional)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 06.038 - Digital Twin & Simulation-Driven Production

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Digital Twin & Simulation-Driven Production matters to this GVN because trust in distributed production and service networks often depends on whether all parties can see the same state of an asset or process. Directly, shared twins reduce disputes about condition, performance, and responsibility; institutionally, they allow suppliers, operators, certifiers, and customers to collaborate around a common evidence layer instead of fragmented reports. The main negative pathway is asymmetric visibility, where one party controls the model assumptions or data resolution and therefore defines reality for everyone else. In sectors with complex assets and many stakeholders, that is large enough for a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Transparency] → contracts begin naming the shared twin as the reference state for maintenance or performance disputes (common evidence layer forms)
- (+) [Risk management] → insurers or financiers use live twin data when pricing downtime or asset risk (trust shifts from paperwork to telemetry)
- (+) [Collaboration] → suppliers, operators, and certifiers access the same synchronized model rather than separate reports (coordination cost falls)
- (+) [Quality incentives] → design changes are trialed in shared simulations before implementation across partner networks (joint learning improves)
- (+) [Public authorities] → regulated infrastructure starts exposing limited twin views to external auditors (oversight becomes more continuous)
- (-) [Power distribution] → the twin platform owner controls model fidelity, API access, or change rights (informational power centralizes)
- (-) [Accountability] → disputes emerge when the twin diverges from field reality but decisions were made from the model (trust becomes model-dependent)
- (-) [Security] → manipulation or spoofing of live twin data triggers costly coordination failures (shared evidence becomes a target)
- (-) [Labor] → local experiential knowledge is downgraded relative to centralized dashboards (voice shifts upward)

## ART 06.039 - Reconfigurable & Agile Factories

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Reconfigurable & Agile Factories can support more distributed and flexible production partnerships, which matters to the GVN where collaboration often stalls on supplier coordination and trust in custom or local capability. Its direct effect is to shorten handoffs and make smaller-batch collaboration more feasible; institutionally, it shifts some trust from long supplier histories toward digital recipes, quality records, and certification. But most trust effects remain mediated by standards, contracts, and market power rather than the production method itself. That supports a 3. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Collaboration] → organizations use distributed or rapidly reconfigured production partnerships instead of single fixed suppliers (coordination becomes more flexible)
- (+) [Transparency] → digital recipes and process data start substituting for some supplier-specific tacit knowledge (capability becomes easier to inspect)
- (+) [Access] → smaller local producers win work on speed or customization rather than only scale (entry broadens modestly)
- (-) [Trust] → buyers still hesitate without strong certification of quality consistency (technology alone is insufficient)

- (-) [Power distribution] → platform or OEM owners keep control over files, specs, and approval rights (openness remains conditional)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.040 - Circular & Sustainable Manufacturing

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Circular & Sustainable Manufacturing is important because circular production depends on transparent histories, shared standards, and trust in non-virgin inputs. Directly, it can increase collaboration across producers, recyclers, logistics actors, and buyers who need verifiable information on origin, composition, and quality. Its 3rd-order effects include new data-rich material marketplaces and product-passport regimes, but also new exclusion if small actors cannot meet traceability and certification requirements. The combination is significant enough to justify a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

### **Weak signals (9):**

- (+) [Transparency] → buyers begin requiring digital product passports or batch histories for recycled/bio-derived inputs (trust in non-virgin materials rises)
- (+) [Collaboration] → recyclers, manufacturers, and logistics firms integrate data flows to keep materials in verified loops (ecosystem coordination deepens)
- (+) [Quality] → price discounts for recycled content shrink where sensor- and process-backed certification becomes available (confidence improves)
- (+) [Risk management] → insurers or regulators accept continuous provenance data instead of only end-stage declarations (evidence burden changes)
- (+) [Market access] → small local recovery streams gain entry to higher-value supply chains once quality is machine-verifiable (inclusion expands)
- (-) [Bargaining power] → dominant buyers dictate passport and disclosure formats that smaller suppliers struggle to meet (power asymmetry grows)
- (-) [Fraud] → falsified sustainability or recycled-content claims trigger visible enforcement cases (trust premium is contested)
- (-) [Privacy/commercial secrecy] → firms resist disclosure of process data needed for circular trust (openness and confidentiality collide)
- (-) [Regulation] → cross-border differences in waste and product classifications slow interoperable loops (institutional friction persists)

## ART 06.041 - Bio-fabrication technologies

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Bio-fabrication technologies has only a limited connection to this GVN. It can create new



collaborative arrangements around specialized biological production, but the relevant trust issues are mostly confined to expert, regulated ecosystems rather than broad everyday collaboration. The aggregate social impact on how cooperation is organized therefore remains small. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Specialized collaboration] → shared facilities or contract-manufacturing models emerge around the technology (niche ecosystem forms)
- (+) [Trust] → regulators define traceability and quality protocols that allow more external partners to participate (institutional legitimacy grows)
- (-) [Access] → high capex and specialized skills keep participation concentrated (GVN reach stays narrow)
- (-) [Governance] → ethical or biosafety controversies slow multi-party collaboration (social license remains fragile)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

4D Printed & Programmable Materials can matter in niche design or production collaborations, but it does not by itself reconfigure the broader operating model of collaboration and trust. Its effects are mainly operational: faster prototyping, adaptable parts, or specialized materials can support innovation projects, yet trust still depends on certification and procurement structures. The likely aggregate impact is limited. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Open innovation] → the technology appears in collaborative prototyping or pilot programs (some partnership value emerges)
- (+) [Transparency] → new testing or certification methods are created so buyers can trust outputs (institutional pathway appears)
- (-) [Access] → usage stays confined to specialist manufacturers and design teams (broad GVN effect remains small)
- (-) [Power distribution] → IP over materials, files, or process parameters remains concentrated (collaboration stays conditional)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Volumetric Additive Manufacturing (Layerless 3D Printing) can matter in niche design or production collaborations, but it does not by itself reconfigure the broader operating model of collaboration and trust. Its effects are mainly operational: faster prototyping, adaptable parts, or specialized materials can support innovation projects, yet trust still depends on certification and procurement structures. The likely aggregate impact is limited. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Open innovation] → the technology appears in collaborative prototyping or pilot programs (some partnership value emerges)
- (+) [Transparency] → new testing or certification methods are created so buyers can trust outputs (institutional pathway appears)
- (-) [Access] → usage stays confined to specialist manufacturers and design teams (broad GVN effect remains small)
- (-) [Power distribution] → IP over materials, files, or process parameters remains concentrated (collaboration stays conditional)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Metamaterials for Novel Optics & Connectivity has a material but supporting role in this GVN because it can make communication and sensing infrastructure more capable, compact, or widely deployable. That can indirectly improve transparency, access, and coordination, especially where line-of-sight, interference, or device form factors currently constrain collaboration tools. Still, the trust effects arrive through the systems built on top of the materials rather than from the materials themselves. A 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Connectivity] → infrastructure upgrades use these materials to expand coverage or sensing in hard-to-serve spaces (communication quality improves)
- (+) [Transparency] → new sensing or antenna form factors make shared situational data cheaper to obtain (evidence gets denser)

- (+) [Access] → smaller or retrofittable devices lower deployment barriers for collaboration infrastructure (entry improves modestly)
- (-) [Power distribution] → key designs or fabrication capacity stay concentrated in specialist suppliers (benefits route through incumbents)
- (-) [Security/privacy] → better sensing or RF control also deepens surveillance capability (trust effects stay mixed)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.045 - Room-Temperature Superconductors

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Room-Temperature Superconductors primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 - Self-Healing & Smart Polymers

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Self-Healing & Smart Polymers primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Nano-Catalysts & Advanced Coatings primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

High-Entropy Alloys & Advanced Metals primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Graphene and Nanotube Composites for Lightweight Strength primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter

indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Smart Thermal Materials for Energy-Efficient Heating & Cooling primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Rare-Earth-Free Magnets for Sustainable Motors primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

**Score:** 0 (Impact in GVN 18)

**Justification (3–5 sentences):**

Even in mature form, Nano-Engineered Membranes for Low-Energy Desalination has no clear broad pathway to the GVN's core operating model. It may be valuable for water, fuel, or other sector-specific systems, but the link to collaboration-and-trust outcomes is too indirect and too contingent to score above 0. Any stronger linkage would require a new governance or platform layer not implied by the ART itself. The score is 0. This stays below any meaningful material anchor for this GVN.

**Weak signals (4):**

- (+) [Watchpoint: governance layer] → new traceability, market, or sharing systems form around the material (a real trust linkage would be emerging)
- (+) [Watchpoint: public controversy] → the material becomes central to high-visibility allocation or safety disputes (institutional relevance would increase)
- (-) [Relevance] → deployment stays inside utility or industrial back-end systems (linkage remains weak)



- (-) [Scale] → no observable change appears in participation, transparency, or trust practices (impact remains negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Ultra-wide-bandgap (UWBG) power semiconductors primarily affects this GVN as a background enabler of infrastructure reliability, durability, or efficiency. Those gains can matter indirectly for collaboration systems, but they do not by themselves change how transparency, trust, or governance are organized. The strongest pathways are through cost, uptime, and supply-chain concentration. A 1 is appropriate. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure reliability] → trusted digital or physical systems start using the material to reduce downtime or maintenance (background support appears)
- (+) [Risk management] → insurers, certifiers, or procurement specs mention the material for resilience-critical components (indirect trust link appears)
- (-) [Power distribution] → supply remains concentrated in a few firms, regions, or protected IP portfolios (dependency can increase)
- (-) [Relevance] → most deployments stay too far downstream from visible collaboration practices (GVN impact remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

**Score:** 0 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Even in mature form, Solid Hydrogen Storage Materials for Safe, Dense Fuel has no clear broad pathway to the GVN's core operating model. It may be valuable for water, fuel, or other sector-specific systems, but the link to collaboration-and-trust outcomes is too indirect and too contingent to score above 0. Any stronger linkage would require a new governance or platform layer not implied by the ART itself. The score is 0. This stays below any meaningful material anchor for this GVN.

### **Weak signals (4):**

- (+) [Watchpoint: governance layer] → new traceability, market, or sharing systems form around the material (a real trust linkage would be emerging)
- (+) [Watchpoint: public controversy] → the material becomes central to high-visibility allocation or safety disputes (institutional relevance would increase)

- (-) [Relevance] → deployment stays inside utility or industrial back-end systems (linkage remains weak)
- (-) [Scale] → no observable change appears in participation, transparency, or trust practices (impact remains negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Fusion Energy Reactors can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 08.057 - Small Modular Fission Reactors (SMRs)

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Small Modular Fission Reactors (SMRs) can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or

cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 08.058 - Thin-film solar cells**

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Thin-film solar cells can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 08.059 - Bionic Leaf Technology**

**Score:** 0 (Impact in GVN 18)

**Justification (3–5 sentences):**

Even in mature form, Bionic Leaf Technology has no clear broad pathway to the collaboration-and-trust operating model described in the GVN. It may be technically interesting, but the implied effects are too speculative and too far removed from transparency, privacy, governance, or platform-mediated cooperation. Without a clearer institutional pathway, the linkage remains too weak. The score is 0. This stays below any meaningful material anchor for this GVN.

**Weak signals (4):**

- (+) [Watchpoint: market creation] → a visible data, coordination, or certification ecosystem forms around the technology (a real GVN pathway would be emerging)
- (+) [Watchpoint: local governance] → communities or platforms start coordinating directly around the output of the technology (linkage would strengthen)
- (-) [Relevance] → deployments remain isolated pilots or specialized infrastructure with no effect on everyday cooperation (impact stays negligible)
- (-) [Adoption] → the technology never becomes embedded in mainstream service, payment, or platform layers (linkage remains weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 08.060 - Grid-Scale Energy Storage**

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Grid-Scale Energy Storage has a material but indirect effect on this GVN by making energy availability more predictable for the digital and physical systems through which collaboration now runs. It can also enable new local coordination and certification arrangements around flexible energy use, especially where energy sharing or low-carbon claims matter. Still, those collaboration gains are secondary to its core infrastructure role. A 3 is appropriate. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Resilience] → data centers, communications hubs, or community services use the technology to maintain continuity through grid stress (coordination uptime improves)
- (+) [Transparency] → markets begin tracking charge/discharge services or green-molecule provenance through standardized records (new trust data appears)
- (+) [Collaboration] → industrial or regional actors coordinate around shared flexible-energy assets (new interdependence forms)
- (-) [Power distribution] → high-capex ownership concentrates control over flexibility revenues or energy assurance (benefits skew upward)
- (-) [Governance] → disputes arise over who gets priority use during scarcity or curtailment events (resource-sharing politics emerge)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.061 - Solid-State Batteries

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Solid-State Batteries can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 - Green Hydrogen & Power-to-X

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Green Hydrogen & Power-to-X has a material but indirect effect on this GVN by making energy availability more predictable for the digital and physical systems through which collaboration now runs. It can also enable new local coordination and certification arrangements around flexible energy use, especially where energy sharing or low-carbon claims matter. Still, those collaboration gains are secondary to its core infrastructure role. A 3 is appropriate. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Resilience] → data centers, communications hubs, or community services use the technology to maintain continuity through grid stress (coordination uptime improves)
- (+) [Transparency] → markets begin tracking charge/discharge services or green-molecule provenance through standardized records (new trust data appears)
- (+) [Collaboration] → industrial or regional actors coordinate around shared flexible-energy assets (new interdependence forms)

- (-) [Power distribution] → high-capex ownership concentrates control over flexibility revenues or energy assurance (benefits skew upward)
- (-) [Governance] → disputes arise over who gets priority use during scarcity or curtailment events (resource-sharing politics emerge)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

High-Efficiency Wind Turbines can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 - Wireless & Space-Based Power Transfer

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Wireless & Space-Based Power Transfer can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)

- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Advanced geothermal technology can strengthen the reliability of the energy systems on which digital collaboration depends, but its direct link to the GVN is weak. The most plausible effects are indirect: lower outage risk, different infrastructure ownership, or new certification claims. Those can matter locally, yet they do not by themselves redefine trust, transparency, or cooperation across society. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Infrastructure resilience] → trusted digital or public-service systems cite the technology for continuity planning (background reliability improves)
- (+) [Market claims] → new certification or origin-tracking rules appear around output from the technology (niche trust layer appears)
- (-) [Power distribution] → ownership remains concentrated in capital-intensive projects or incumbents (collaboration model barely changes)
- (-) [Relevance] → users experience it mainly as a generic energy source, not as a new trust mechanism (GVN linkage stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Resilient microgrids can materially reshape collaboration and trust at community and organizational level because it combines local resource sharing with visible, automated rules for balancing supply and demand. Directly, it increases resilience and lets energy users become co-governors or co-producers; institutionally, it shifts bargaining power away from purely centralized utilities toward local coordination mechanisms. Feedback effects are strong where energy-sharing communities build data, payment, and governance layers around the microgrid, but inequity can grow if only affluent sites can form them. That makes the impact significant for this GVN, supporting a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.



**Weak signals (9):**

- (+) [Communality] → neighborhoods, campuses, or industrial parks create formal local energy-sharing agreements (cooperative governance appears)
- (+) [Transparency] → participants receive live visibility into production, storage, and allocation rules rather than opaque utility bills (shared state becomes legible)
- (+) [Risk management] → critical services cite islanding capability when selecting sites or partners (resilience becomes trust-relevant)
- (+) [Market structure] → local balancing and settlement platforms emerge around microgrids (new collaboration markets form)
- (+) [Access] → communities use microgrids to support public shelters, connectivity, or social services during outages (social trust deepens)
- (-) [Equality] → affluent districts or firms secure resilience while others stay exposed to centralized outages (resilience gap widens)
- (-) [Governance] → conflicts arise over who gets priority power during islanded operation (scarcity decisions become political)
- (-) [Security] → cyber incidents or faulty dispatch rules in local control systems damage trust in community governance (automation legitimacy matters)
- (-) [Regulation] → interconnection, tariff, or licensing disputes slow community-led models (institutional lock-in resists change)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Next-Generation Gene Editing has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)

- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)
- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

mRNA Therapies & Vaccines has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)
- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)
- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Cellular Agriculture & Cultured Meat has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create

new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

#### **Weak signals (5):**

- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)
- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)
- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 09.070 - Organoids & Tissue Engineering**

**Score:** 1 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Organoids & Tissue Engineering has some plausible relevance for specialized collaborative ecosystems, but its broad effect on the GVN's operating model is limited. The main issues are narrow: data governance, ethics, and who gets access in specific clinical or research settings. Those are meaningful, yet they do not amount to a society-wide shift in transparency, reputation, or decentralized trust. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

#### **Weak signals (4):**

- (+) [Specialized collaboration] → new partnerships or shared platforms form around the technology in research or care delivery (niche coordination value appears)
- (+) [Trust] → ethics and audit protocols become standardized enough for wider institutional use (legitimacy improves in-domain)
- (-) [Access] → cost and expertise keep use concentrated in specialist centers (broad GVN effect stays small)
- (-) [Governance] → ethical controversy or unclear consent rules slow cross-organizational adoption (trust remains localized)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Synthetic Biology & Designer Microbes has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)
- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)
- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 - Microbiome Engineering

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Microbiome Engineering has some plausible relevance for specialized collaborative ecosystems, but its broad effect on the GVN's operating model is limited. The main issues are narrow: data governance, ethics, and who gets access in specific clinical or research settings. Those are meaningful, yet they do not amount to a society-wide shift in transparency, reputation, or decentralized trust. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Specialized collaboration] → new partnerships or shared platforms form around the technology in research or care delivery (niche coordination value appears)
- (+) [Trust] → ethics and audit protocols become standardized enough for wider institutional use (legitimacy improves in-domain)

- (-) [Access] → cost and expertise keep use concentrated in specialist centers (broad GVN effect stays small)
- (-) [Governance] → ethical controversy or unclear consent rules slow cross-organizational adoption (trust remains localized)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Precision Medicine & Genomic Diagnostics has a strong but domain-specific link to the GVN because it turns highly sensitive biological information into shared decisions across patients, providers, labs, payers, and researchers. Directly, it can improve confidence that care, screening, and resource allocation are tailored rather than arbitrary; institutionally, it raises the stakes of consent, portability, and trust in data intermediaries. The 3rd-order risks are unequal access, genetic discrimination, and model bias that can damage trust in both healthcare and data-sharing ecosystems. Given the scale of health-system coordination, a 5 is justified. That is consistent with the significant €100M–1B / 50–500M person-hour band.

### **Weak signals (9):**

- (+) [Trust] → patients are offered portable genomic or molecular reports that can be reused across providers (trust becomes less institution-bound)
- (+) [Privacy protection] → consent dashboards or fine-grained data-sharing controls become standard in diagnostics workflows (control becomes explicit)
- (+) [Cross-organizational collaboration] → hospitals, insurers, and labs adopt shared evidence standards for genomic decision support (coordination improves)
- (+) [Quality] → reimbursement begins rewarding validated personalized pathways instead of one-size-fits-all treatment assumptions (evidence becomes more granular)
- (+) [Risk management] → clinicians receive auditable uncertainty and population-bias notes with recommendations (trust is more conditional)
- (-) [Equality] → access gaps appear between groups whose data is well represented and those still poorly covered (trust becomes uneven)
- (-) [Discrimination] → employment, insurance, or social controversies emerge around secondary use of genomic risk scores (social trust is strained)
- (-) [Market power] → a few labs or platform intermediaries control interpretation updates and reference datasets (dependency rises)
- (-) [Security] → breaches of genomic repositories have long-lived reputational effects because data is hard to revoke (harm is durable)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Organs-on-Chips & Bio-Computational Hybrids has some plausible relevance for specialized collaborative ecosystems, but its broad effect on the GVN's operating model is limited. The main issues are narrow: data governance, ethics, and who gets access in specific clinical or research settings. Those are meaningful, yet they do not amount to a society-wide shift in transparency, reputation, or decentralized trust. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Specialized collaboration] → new partnerships or shared platforms form around the technology in research or care delivery (niche coordination value appears)
- (+) [Trust] → ethics and audit protocols become standardized enough for wider institutional use (legitimacy improves in-domain)
- (-) [Access] → cost and expertise keep use concentrated in specialist centers (broad GVN effect stays small)
- (-) [Governance] → ethical controversy or unclear consent rules slow cross-organizational adoption (trust remains localized)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

Biological Aging & Longevity Barriers has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

**Weak signals (5):**

- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)
- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)

- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.076 - Engineered Living Materials

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Engineered Living Materials has some plausible relevance for specialized collaborative ecosystems, but its broad effect on the GVN's operating model is limited. The main issues are narrow: data governance, ethics, and who gets access in specific clinical or research settings. Those are meaningful, yet they do not amount to a society-wide shift in transparency, reputation, or decentralized trust. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Specialized collaboration] → new partnerships or shared platforms form around the technology in research or care delivery (niche coordination value appears)
- (+) [Trust] → ethics and audit protocols become standardized enough for wider institutional use (legitimacy improves in-domain)
- (-) [Access] → cost and expertise keep use concentrated in specialist centers (broad GVN effect stays small)
- (-) [Governance] → ethical controversy or unclear consent rules slow cross-organizational adoption (trust remains localized)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Gene Drive Pest Control has a material GVN impact mainly through governance, legitimacy, and public trust rather than through day-to-day collaboration tools. Directly, it can create new collaborative research, production, or public-health systems; institutionally, it raises sharper questions about consent, risk distribution, and who is allowed to decide on behalf of others. The negative pathway is important: controversy, unequal access, or opaque control can damage trust well beyond the immediate domain. That makes a 3 plausible. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**



- (+) [Trust] → authorities, researchers, and affected communities establish visible consent, oversight, or monitoring arrangements (institutional legitimacy is being built)
- (+) [Collaboration] → multi-party consortia share data, protocols, or production capacity around the technology (cooperation broadens)
- (+) [Transparency] → public registries or audit trails are created for trials, releases, or product claims (visibility improves)
- (-) [Justice] → protests, litigation, or equity disputes show that benefits and risks are unevenly distributed (social trust is tested)
- (-) [Biosecurity/governance] → concern grows over cross-border spillovers, misuse, or weak accountability (trust cost rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score:** 1 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Artificial Wombs & Synthetic Embryos has some plausible relevance for specialized collaborative ecosystems, but its broad effect on the GVN's operating model is limited. The main issues are narrow: data governance, ethics, and who gets access in specific clinical or research settings. Those are meaningful, yet they do not amount to a society-wide shift in transparency, reputation, or decentralized trust. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

### **Weak signals (4):**

- (+) [Specialized collaboration] → new partnerships or shared platforms form around the technology in research or care delivery (niche coordination value appears)
- (+) [Trust] → ethics and audit protocols become standardized enough for wider institutional use (legitimacy improves in-domain)
- (-) [Access] → cost and expertise keep use concentrated in specialist centers (broad GVN effect stays small)
- (-) [Governance] → ethical controversy or unclear consent rules slow cross-organizational adoption (trust remains localized)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 10. Space & Aeronautical Engineering

## ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score:** 10 (Impact in GVN 18)

**Justification (3–5 sentences):**

Satellite Mega-Constellations & Space Internet is a major trust-and-collaboration infrastructure because it extends connectivity and observational transparency beyond where terrestrial systems reach. Directly, it can connect remote users and provide shared situational awareness; institutionally, it reduces dependence on national or local bottlenecks but increases dependence on a small number of constellation operators and orbital governance regimes. Its 3rd-order effects are large: reputation systems, payments, remote work, crisis coordination, and supply-chain monitoring all become harder to geographically exclude, while surveillance and information asymmetries can also expand. As a major pathway to broad digital inclusion and monitoring, it merits a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

**Weak signals (9):**

- (+) [Platform access equality] → households, field teams, or vessels use satellite internet as primary access for work and transactions (connectivity barrier drops)
- (+) [Transparency] → organizations subscribe to near-real-time space-based monitoring for logistics, infrastructure, or environmental verification (shared visibility broadens)
- (+) [Crisis collaboration] → emergency procedures rely on constellation links when terrestrial networks fail (resilience becomes social infrastructure)
- (+) [Cross-border collaboration] → firms in remote or mobile operations join digital marketplaces and remote-support ecosystems (distance loses force)
- (+) [Public authorities] → procurement or subsidy programs treat LEO connectivity as part of universal service obligations (institutional normalization)
- (-) [Market structure] → a few constellation providers become gatekeepers for connectivity and Earth-observation layers (power concentrates)
- (-) [Privacy] → disputes rise over routine remote monitoring of farms, ships, sites, or communities (transparency-surveillance tension grows)
- (-) [Security] → cyber, jamming, or debris events show how much collaboration has become dependent on orbital infrastructure (single-failure dependence appears)
- (-) [Geopolitics] → cross-border data access or sanction disputes over constellation services affect who can collaborate with whom (sovereignty conflict intensifies)

## ART 10.080 - Space Resource Utilization (SRU)

**Score:** 1 (Impact in GVN 18)

**Justification (3–5 sentences):**

Space Resource Utilization (SRU) has only a limited connection to this GVN. Its trust and coordination problems are real, but they mostly concern specialized aerospace, resource, or mission-governance communities rather than broad social collaboration. The aggregate effect on the

mainstream operating model of trust remains small. A 1 fits. That keeps the effect below the material €10–100M / 5–50M person-hour anchors for this GVN.

**Weak signals (4):**

- (+) [Specialized collaboration] → public-private consortia form common governance and chain-of-custody protocols around the technology (niche trust value appears)
- (+) [Transparency] → independent assay, tracking, or telemetry standards are created (institutional legitimacy would rise)
- (-) [Relevance] → most activity stays inside specialized aerospace markets (broad GVN linkage stays weak)
- (-) [Power distribution] → a few mission operators or states dominate access and rule-setting (benefits remain concentrated)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 10.081 - Closed-Loop Life Support System**

**Score:** 0 (Impact in GVN 18)

**Justification (3–5 sentences):**

Even in mature form, Closed-Loop Life Support System has no meaningful broad pathway into the GVN's mainstream collaboration-and-trust model. It may matter for isolated mission environments, but not enough to affect transparency, reputation, payment, governance, or everyday cross-organizational cooperation in a 5.5M-person society. Any broader linkage would be speculative. The score is 0. This stays below any meaningful material anchor for this GVN.

**Weak signals (4):**

- (+) [Watchpoint: spillover protocols] → mission-control governance tools are reused in terrestrial collaboration systems (a linkage would emerge)
- (+) [Watchpoint: public adoption] → the technology starts serving non-space civilian coordination needs (relevance would rise)
- (-) [Relevance] → deployment remains confined to niche space operations (linkage stays weak)
- (-) [Scale] → no observable effect appears in everyday trust or collaboration infrastructures (impact remains negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 10.082 - High-Altitude Platforms & Balloons**

**Score:** 3 (Impact in GVN 18)

**Justification (3–5 sentences):**

High-Altitude Platforms & Balloons has a material but bounded GVN impact because it can extend

connectivity and monitoring into remote or disrupted areas more flexibly than fixed terrestrial infrastructure. That can help restore or sustain collaboration where trust would otherwise fail under outage, weak coverage, or lack of local presence. However, it is usually a complement to broader platform and network systems rather than a new trust architecture in its own right. A 3 is appropriate. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

#### **Weak signals (5):**

- (+) [Platform access equality] → emergency, rural, or temporary operations use the platforms for primary connectivity (coordination gaps narrow)
- (+) [Transparency] → high-altitude sensing becomes part of shared situational awareness in logistics or crisis response (visibility improves modestly)
- (+) [Risk management] → public authorities or firms pre-contract deployable HAP service for outages or events (resilience becomes institutionalized)
- (-) [Market structure] → only a few operators control service corridors and payload ecosystems (dependence concentrates)
- (-) [Privacy/regulation] → public concern rises over persistent aerial monitoring or contested airspace use (social license constrains uptake)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **11. Digital Platforms & Collective-Intelligence Systems**

### **ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)**

**Score:** 20 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Decentralized Trust Networks (Web3 & Blockchain) is explicitly named in the GVN as a challenger-regime mechanism, because it allows records, transactions, and rules to be verified without relying entirely on a central trusted third party. Directly, it can support shared ledgers, programmable commitments, portable identity claims, tokenized incentives, and multi-party audit trails; institutionally, it redistributes trust from organizations toward protocols, node operators, and smart-contract governance. The 3rd-order effects are profound: new reputation markets, funding mechanisms, and cooperative forms can emerge, but so can scams, irreversible errors, and new concentrations around wallets, stablecoins, or infrastructure providers. This is a plausible linchpin of the GVN's most important operating-model shift, so 20 is justified. Without this layer, the challenger-regime operating model in the GVN is much weaker.

#### **Weak signals (9):**

- (+) [Transparency] → shared ledgers are used as the reference record in cross-organizational transactions or supply relationships (common truth layer forms)

- (+) [Trust] → escrow, credential, or registry functions move from bespoke intermediaries to programmable contracts (trust shifts into code)
- (+) [Crowdfunding/crowdsourcing] → tokenized or contract-based funding models are used for civic, creative, or local infrastructure projects (financing intermediation changes)
- (+) [Identity and reputation] → verifiable credentials or portable reputation proofs are accepted across multiple platforms (trust becomes more transferable)
- (+) [Governance] → multi-stakeholder projects use on-chain voting, treasury controls, or rule execution (coordination costs fall for some groups)
- (+) [Interoperability] → public-sector or enterprise systems start consuming blockchain-based attestations without requiring users to understand wallets (mainstream embedding begins)
- (-) [Fraud and scams] → scam typologies shift from simple payment fraud to smart-contract exploits, rug pulls, or oracle manipulation (risk surface mutates)
- (-) [Power distribution] → custody, stablecoin, bridge, or RPC providers capture effective control despite decentralized rhetoric (new chokepoints emerge)
- (-) [Regulation] → courts or regulators are forced to define liability for irreversible code execution and protocol governance failures (institutional settlement lags)

## ART 11.084 - Platform Cooperatives & Fair Work

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Platform Cooperatives & Fair Work directly changes who owns and governs digital collaboration infrastructure, not just how efficiently it runs. Inside the GVN, that can materially increase trust by making pricing, ranking, penalties, and payouts more legible and contestable; institutionally, it shifts bargaining power from investors and dominant platforms toward workers or users. Feedback effects are large because transparent governance and shared upside can deepen loyalty and participation, while coordination failures or factional capture can still damage trust. Where platform work and service marketplaces are large, this is transformative enough for a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### **Weak signals (9):**

- (+) [Trust] → members can inspect payout, ranking, and fee rules through plain-language dashboards (platform power becomes legible)
- (+) [Communality] → workers or users buy equity-like stakes or governance rights in the platform they depend on (shared incentives deepen)
- (+) [Justice] → dispute-resolution outcomes and policy changes are published with auditable rationale (fairness becomes contestable)
- (+) [Bargaining power] → public procurement or municipal programs favor cooperative platforms in selected sectors (institutional demand appears)

- (+) [Access] → pooled benefits, insurance, or training are attached to platform membership rather than employer status (collective infrastructure grows)
- (-) [Governance] → turnout falls and a small active minority captures rule changes (participation burden can hollow trust)
- (-) [Fraud/collusion] → voting blocs, fake members, or insider favoritism become visible governance problems (co-op form is stress-tested)
- (-) [Capital access] → growth slows where financing must avoid control dilution (scale pressure appears)
- (-) [Market structure] → dominant investor-owned platforms imitate participatory features without giving real control (trustwashing risk appears)

## ART 11.085 - Open Data Sharing Marketplaces

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Open Data Sharing Marketplaces goes to the heart of the GVN by turning data exchange from a bespoke high-trust negotiation into a more standardized, auditable, and priced collaboration. Directly, it can make needs, opportunities, and data assets visible; institutionally, it creates new rules for provenance, consent, payment, and liability across organizations that do not fully trust one another. The biggest 3rd-order effect is a broader market for collaborative intelligence, but also new asymmetries if brokers or dominant schemas dictate who can participate and on what terms. Because it can reorganize cross-boundary cooperation at scale, it merits a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### **Weak signals (9):**

- (+) [Transparency] → datasets are listed with machine-readable quality, provenance, and usage terms rather than informal bilateral descriptions (search costs fall)
- (+) [Trust] → buyers can verify who accessed what data, under which consent, and with what output restrictions (auditability improves)
- (+) [Cross-organizational collaboration] → small organizations start buying or contributing data through standardized contracts instead of custom legal work (entry barriers fall)
- (+) [Risk management] → compute-to-data options are used where raw export was previously blocked (sensitive collaboration becomes feasible)
- (+) [Incentives] → contributors are paid or credited based on actual usage rather than one-time opaque deals (participation incentives improve)
- (-) [Power distribution] → marketplace operators or schema owners become gatekeepers over discoverability and pricing (data chokepoints form)
- (-) [Privacy] → re-identification or misuse cases trigger visible enforcement actions despite formal controls (trust can unravel fast)
- (-) [Market fairness] → dominant buyers squeeze smaller contributors through standard terms (bargaining asymmetry persists)

- (-) [Governance] → disputes over dataset ownership, derivative rights, or withdrawal become common enough to require formal arbitration layers (institutional complexity rises)

## ART 11.086 - Secure & Resilient Social Platforms

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Secure & Resilient Social Platforms is central to the GVN because much modern collaboration, mobilization, and reputation formation flows through social platforms. Directly, stronger privacy, portability, and resilience can keep coordination intact under outage, blocking, or harassment; institutionally, they reduce dependence on a single intermediary to maintain identity, archives, and group continuity. Feedback effects are powerful because secure networks can sustain communities through shocks, but can also complicate moderation, accountability, and law-enforcement access. Given the breadth of mediated social cooperation, a 10 is justified. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### **Weak signals (9):**

- (+) [Trust] → groups migrate to platforms that preserve message integrity, account recovery, and community continuity through outages (reliability becomes a trust factor)
- (+) [Portability] → users move social graphs, archives, or reputation signals between services without losing participation (lock-in weakens)
- (+) [Risk management] → civil society, schools, or workplaces adopt resilient channels for crisis coordination rather than ad hoc tools (coordination continuity improves)
- (+) [Privacy protection] → end-to-end encrypted group spaces become default even for mainstream communities (secure collaboration normalizes)
- (+) [Transparency] → moderation and policy changes are published with auditable logs or appeals (rule changes become inspectable)
- (-) [Governance] → harmful-content incidents reveal the trade-off between strong privacy and effective moderation (trust splits along values)
- (-) [Platform power] → hosted-node providers or app stores remain hidden chokepoints despite decentralization claims (dependency persists)
- (-) [Security] → account-takeover or key-recovery failures become salient public controversies (usability-security tension remains)
- (-) [Regulation] → states pressure providers over traceability, lawful access, or content takedowns (political conflict intensifies)

## ART 11.087 - Collective Open Innovation Networks

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Collective Open Innovation Networks directly serves the GVN goal: it is about getting strangers



and organizations to cooperate productively around shared problems. Directly, it reduces search and coordination costs for expertise, evidence, and experimentation; institutionally, it can reallocate innovation power away from closed hierarchies toward more open and reputation-based networks. The 3rd-order effect is path dependent: successful networks compound because prior work, failed approaches, and contributor reputation become reusable public capital, but IP conflicts and hidden asymmetries can still fracture trust. Because it changes how collaborative problem-solving is organized, it deserves a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

#### **Weak signals (9):**

- (+) [Transparency] → challenge briefs, evidence, and validation criteria are posted in standardized, reusable formats (coordination becomes easier to enter)
- (+) [Trust] → contributors accumulate portable reputation from verified past performance across multiple networks (credibility becomes transferable)
- (+) [Access] → smaller firms, freelancers, and public-interest teams win work previously reserved for incumbent contractors (search barriers fall)
- (+) [Risk management] → organizers use secure sandboxes and versioned audit trails to open sensitive problems to wider participation (controlled openness emerges)
- (+) [Innovation quality] → failed approaches remain searchable and cited rather than disappearing into private inboxes (learning loops strengthen)
- (-) [Power distribution] → network owners or benchmark setters quietly shape what kinds of solutions are legible and fundable (agenda-setting centralizes)
- (-) [IP/governance] → disputes rise over ownership of branch merges, model outputs, or reused experiments (trust requires new rules)
- (-) [Labor] → open competition pressures prices downward for some expert work (collaboration and precarity coexist)
- (-) [Security] → adversarial submissions or synthetic evidence contaminate challenge pipelines (verification load rises)

## **ART 11.088 - Scalable Decentralized Governance**

**Score:** 10 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Scalable Decentralized Governance is highly relevant because collaboration at scale fails when groups cannot make binding, legible decisions without excessive overhead. Directly, it can encode proposals, voting, budgeting, and delegated decision rights into inspectable workflows; institutionally, it redistributes authority from opaque administrators toward rule-based collective processes. Its 3rd-order effect is double-edged: large groups may coordinate faster and with better auditability, but software-defined governance can also harden power asymmetries or make manipulation feel legitimate because it is procedural. For digitally mediated collaboration, this is transformative enough for a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

**Weak signals (9):**

- (+) [Transparency] → organizations publish proposal histories, vote outcomes, and budget execution in structured, searchable form (decision trails become visible)
- (+) [Trust] → members can delegate, revoke, or verify representation without relying on informal hierarchy (collective control becomes inspectable)
- (+) [Coordination] → pooled-resource communities or multi-party projects adopt software-governed treasury and access rules (overhead falls)
- (+) [Justice] → contested decisions include auditable proofs of quorum, eligibility, and tallying (procedural legitimacy rises)
- (+) [Access] → intermittent participants engage through lightweight delegation or asynchronous voting rather than meetings only (participation broadens)
- (-) [Manipulation] → fake identities, vote-buying, or agenda gaming become visible attack categories (governance layer is contested)
- (-) [Power distribution] → software architects or major token/credential holders dominate rule changes (formal process masks inequality)
- (-) [Legitimacy] → communities reject automated execution when outcomes feel substantively unfair despite procedural validity (rules-code gap widens)
- (-) [Regulation] → legal systems challenge whether software-based decisions meet fiduciary, labor, or public-law obligations (institutional mismatch appears)

**ART 11.089 - Digital Learning Networks and Skill Credentialing**

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Digital Learning Networks and Skill Credentialing affects the GVN by making skills and capabilities easier to learn, verify, and share across organizational boundaries. Directly, it can reduce mistrust around hiring, contracting, and participation in collaborative projects; institutionally, it weakens dependence on a small set of incumbent credential issuers. The negative pathway is credential inflation, hidden model bias in assessment, and new dependence on platform-managed identity. Because the effect is broad but not as foundational as payment or identity infrastructure, a 5 fits. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Trust] → employers, project organizers, or public programs accept portable machine-verifiable skill credentials (competence becomes easier to prove)
- (+) [Access] → people gain recognized credentials from modular learning instead of only long formal programs (entry barriers fall)
- (+) [Transparency] → assessment rubrics and evidence requirements are published alongside credentials (claims become inspectable)

- (+) [Collaboration] → platforms match teams partly on verified capabilities rather than only self-description or legacy degrees (search improves)
- (+) [Risk management] → high-stakes credentials add human review and audit trails for contested cases (trust improves)
- (-) [Power distribution] → a few assessment platforms or wallet providers dominate what skills count (credential gatekeeping reappears)
- (-) [Justice] → model bias or coaching inequality skews outcomes across groups (merit claims are contested)
- (-) [Privacy] → detailed learning and behavior logs become part of employability scoring (surveillance risk grows)
- (-) [Fraud] → fake issuers or compromised wallets force new verification and revocation routines (trust layer is tested)

## ART 11.090 - Prediction-Market Forecasting Platforms

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Prediction-Market Forecasting Platforms can improve collaboration where groups repeatedly act under uncertainty and currently rely on slow meetings, politics, or untracked intuition. Directly, it turns dispersed expectations into explicit probabilities; institutionally, it can change how projects, budgets, and risk decisions are justified. The downside is gaming, thin participation, and misuse of market-looking numbers as a substitute for democratic legitimacy or substantive deliberation. The likely impact is significant but bounded, so a 5 is appropriate. That is consistent with the significant €100M–1B / 50–500M person-hour band.

### **Weak signals (9):**

- (+) [Transparency] → major projects or public programs publish forecast questions and probability updates alongside plans (assumptions become explicit)
- (+) [Risk management] → teams use forecast markets before committing funding, schedules, or policy changes (coordination becomes more evidence-linked)
- (+) [Learning] → forecasters receive tracked calibration scores that influence future trust or responsibility (judgment becomes measurable)
- (+) [Cross-functional collaboration] → disagreements are decomposed into linked forecast questions rather than binary political arguments (conflict becomes more structured)
- (+) [Governance] → audit logs show who changed a forecast, why, and against what resolution rules (accountability improves)
- (-) [Manipulation] → attempts to move prices for political or strategic reasons become visible and force countermeasures (trust depends on market integrity)
- (-) [Participation inequality] → the same small expert group dominates liquidity and shapes organizational belief (voice can narrow)

- (-) [Legitimacy] → staff or citizens reject decisions justified mainly by market odds in value-laden issues (forecasting meets democratic limits)
- (-) [Verification] → disputes over outcome resolution or ambiguous question wording undermine confidence (settlement quality matters)

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Universal IoT Interoperability Standards matters because collaboration increasingly depends on many devices owned by different parties exchanging trustworthy data without bespoke integration. Directly, common discovery, identity, and permission rules reduce friction and ambiguity; institutionally, they lower vendor lock-in and make failure, update, and provenance pathways more legible. The negative pathway is that certified interoperability can still concentrate power in schema owners, certification bodies, or chip vendors. Given the number of organizations and assets touched, the impact is significant enough for a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Transparency] → new devices advertise standardized capability and data schemas that multiple organizations can consume without custom adapters (integration costs fall)
- (+) [Trust] → signed updates, auditable access logs, and hardware identities become baseline procurement requirements (device behavior becomes more legible)
- (+) [Risk management] → insurers or regulators reward fleets that can prove patch status and data provenance through standard interfaces (compliance gets easier)
- (+) [Market access] → smaller device vendors win contracts by passing interoperability tests instead of building bespoke integrations (gatekeeping falls)
- (+) [Collaboration] → shared environments let devices from different owners coordinate under common permission models (multi-party workflows improve)
- (-) [Power distribution] → a few certification profiles or platform gateways become mandatory chokepoints (openness can narrow in practice)
- (-) [Security] → large-scale exploits spread faster when many devices share the same standard stack (common-mode risk rises)
- (-) [Legacy inequality] → actors unable to replace old devices are excluded from newer trusted ecosystems (transition costs matter)

- (-) [Governance] → disputes over versioning, revocation, or mandatory security features become commercially and politically salient (rules remain contested)

## ART 12.092 - Interoperable Digital Twin Ecosystems

**Score:** 5 (Impact in GVN 18)

**Justification (3–5 sentences):**

Interoperable Digital Twin Ecosystems matters because many collaborative decisions are delayed or distorted when each organization maintains a different representation of the same asset. Directly, it makes state, assumptions, and history more portable across tools and owners; institutionally, it reduces dependence on a single contractor or software stack to mediate trust around complex systems. The main risk is that interoperability creates the appearance of consensus while disagreements over model quality, liability, or access rights remain unresolved. For sectors with shared assets and long lifecycles, this supports a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

**Weak signals (9):**

- (+) [Transparency] → twin packages travel across owners, contractors, and regulators without full remodelling (shared facts persist)
- (+) [Trust] → maintenance, inspection, and simulation outputs reference the same portable state model (fewer translation disputes)
- (+) [Risk management] → access policies and uncertainty bounds are attached to exchanged twins rather than handled ad hoc (governance matures)
- (+) [Market structure] → asset owners demand twin portability in procurement to avoid vendor lock-in (bargaining power shifts)
- (+) [Collaboration] → audits or interventions are rehearsed on a shared twin before field work begins (coordination improves)
- (-) [Accountability] → parties disagree over whose model update is authoritative after incidents (portable data does not end politics)
- (-) [Power distribution] → cloud or standard-setter control over reference schemas shapes what can be seen or optimized (meta-control centralizes)
- (-) [Security] → common interfaces widen the attack surface for model tampering or data poisoning (shared representations become targets)
- (-) [Legacy exclusion] → smaller operators struggle to produce twins at the required fidelity and are sidelined (participation can narrow)

## ART 12.093 - Global Supply Chain Traceability Networks

**Score:** 10 (Impact in GVN 18)

**Justification (3–5 sentences):**

Global Supply Chain Traceability Networks directly advances the GVN's transparency and risk-

management goals by making product and material histories visible across organizational boundaries. Directly, it reduces search, audit, and dispute costs; institutionally, it changes bargaining power because claims about origin, handling, and compliance become harder to hide and easier to verify. Its 3rd-order effects are large: procurement, reputation, sanctions, sustainability claims, and counterfeit control all start to depend on shared provenance data, while smaller actors can also be excluded if compliance costs are too high. Because it can transform how trust is realized in trade and collaboration, a 10 is justified. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

#### **Weak signals (9):**

- (+) [Transparency] → products or batches carry portable digital histories that buyers and auditors actually query in routine transactions (provenance becomes operational)
- (+) [Trust] → counterfeit, contamination, or compliance disputes are resolved faster using shared event histories (verification costs fall)
- (+) [Risk management] → recalls or sanctions actions use network-wide trace data instead of manual document chases (response speeds improve)
- (+) [Cross-border collaboration] → suppliers from new jurisdictions gain access by proving origin and handling through standard records (entry expands)
- (+) [Quality incentives] → price premiums emerge for verified handling or low-risk provenance rather than unverifiable claims (better behavior is rewarded)
- (-) [Power distribution] → dominant buyers impose data requirements that push weaker suppliers into dependency or exclusion (compliance becomes leverage)
- (-) [Privacy/commercial secrecy] → participants resist sharing data needed for trust because it exposes margins, routes, or clients (openness limits appear)
- (-) [Fraud] → forged tags, scanner abuse, or insider data tampering become specialized attack categories (provenance systems are gamed)
- (-) [Governance] → disputes over who can correct or overwrite bad records become legally salient (common truth needs rule-setting)

## **ART 12.094 - Personal Data Portability & Trust Frameworks**

**Score:** 10 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Personal Data Portability & Trust Frameworks directly addresses the GVN's tension between openness and privacy by giving individuals reusable control over how trust-relevant data moves across services. Directly, it reduces repeated verification and lets people share only needed attributes; institutionally, it weakens the hold of incumbent platforms over identity, consent, and switching costs. The 3rd-order effect is a different operating model for digital trust: credentials, consent receipts, and revocation become portable infrastructure, while phishing, wallet capture, and ecosystem fragmentation create new risks. Because this can reshape everyday interactions across many sectors, it merits a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

**Weak signals (9):**

- (+) [Trust] → users grant time-bound, field-level access instead of handing over entire accounts or PDFs (data sharing becomes more controlled)
- (+) [Transparency] → consent receipts, access logs, and revocation histories are visible to ordinary users (permissioning becomes inspectable)
- (+) [Bargaining power] → switching between services no longer means losing accumulated profile or proof data (platform lock-in weakens)
- (+) [Cross-organizational collaboration] → public and private services accept the same portable proofs for onboarding or eligibility (verification friction drops)
- (+) [Privacy protection] → selective-disclosure proofs are used in mainstream transactions rather than only expert niches (less over-collection)
- (-) [Security] → wallet phishing or account recovery failures become visible mass harms (control concentrates in recovery channels)
- (-) [Power distribution] → device makers or wallet providers become quiet new identity intermediaries (control shifts, not disappears)
- (-) [Inclusion] → people with low digital literacy struggle to manage permissions, recovery, and fraud risks (agency becomes unequal)
- (-) [Governance] → incompatible schemas or conflicting legal obligations keep portability partial across sectors (promise can fragment)

**ART 12.095 - Interoperable Digital Currency Payment Networks**

**Score:** 10 (Impact in GVN 18)

**Justification (3–5 sentences):**

Interoperable Digital Currency Payment Networks goes to the core of collaboration and trust because payment reliability determines whether people will transact, fund, and cooperate across boundaries. Directly, interoperable digital payments reduce reconciliation delays and small-transaction friction; institutionally, they weaken gatekeeping by siloed rails and make cross-platform or cross-currency coordination more automatic. The 3rd-order effects are large: crowdfunding, micropayments, platform work, remittances, and machine-to-machine settlements can all expand, while surveillance, exclusion rules, and liquidity chokepoints can also harden. That breadth makes a 10 appropriate. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

**Weak signals (9):**

- (+) [Trust] → payments clear across different currency or wallet systems without manual bridge steps (transaction certainty rises)
- (+) [Crowdfunding/crowdsourcing] → small cross-border contributions become routine because fees and settlement delays fall (collective funding broadens)



- (+) [Platform work] → workers receive payouts across rails and jurisdictions without waiting for batch settlement (income coordination improves)
- (+) [Risk management] → conditional or rule-based payments are embedded in collaborative contracts (dispute resolution becomes more automated)
- (+) [Access] → offline or low-connectivity payment modes are used in disrupted or peripheral areas (participation becomes more resilient)
- (-) [Power distribution] → routing nodes, liquidity providers, or wallet platforms capture control over interoperability (new intermediaries emerge)
- (-) [Privacy] → fine-grained programmable payments increase traceability of behavior and relationships (financial surveillance risk rises)
- (-) [Regulation] → mismatched AML, sanctions, or consumer-protection rules become visible blockers in cross-rail transactions (coordination meets law)
- (-) [Security] → bridge failures, routing exploits, or identity errors produce public trust shocks (interoperability must earn legitimacy)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Machine-Readable Regulation (Rules as Code) directly targets one of the GVN's named risks and inhibitors: conflict with regulations and the high coordination cost of compliance. Directly, machine-readable rules can make obligations visible earlier and allow software to check them consistently; institutionally, they shift trust from case-by-case interpretation toward versioned, testable rule packages. The 3rd-order effect is a new compliance operating model for platforms, supply chains, and public services, but also a risk that encoded rules become rigid, opaque, or politically contested faster than humans can adapt them. Because it can transform how collaboration is permitted and governed, 10 is warranted. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

### **Weak signals (9):**

- (+) [Transparency] → agencies publish rules with executable tests and change logs rather than PDF-only guidance (compliance becomes more legible)
- (+) [Risk management] → organizations run sandbox checks on new rules before systems or contracts go live (fewer surprise violations)
- (+) [Cross-border collaboration] → multi-jurisdiction workflows consume machine-readable rule packages instead of bespoke legal mappings (coordination costs fall)
- (+) [Access] → smaller actors use rule-as-code tooling to meet obligations previously affordable only with specialist counsel (compliance capability broadens)
- (+) [Trust] → automated decisions show which clauses and parameters were applied in each case (decisions become more traceable)

- (-) [Justice] → encoded rules expose how much discretion or ambiguity had been masking political choices (legitimacy conflicts intensify)
- (-) [Power distribution] → vendors that control translation layers or reference implementations shape practical compliance (private meta-governance grows)
- (-) [Accountability] → courts confront cases where software followed the code package but violated legal intent or fairness expectations (code-text gaps surface)
- (-) [Update burden] → organizations struggle with constant version changes across authorities, creating new operational dependence (coordination shifts, not vanishes)

## ART 12.097 - Open Metaverse Interoperability Protocols

**Score:** 3 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Open Metaverse Interoperability Protocols could modestly improve collaboration by reducing lock-in between immersive environments and allowing identity, assets, and settings to move across them. That has some relevance for reputation portability and shared workspaces, but it remains contingent on broader adoption of immersive interaction itself. The main institutional issue is whether open standards actually reduce platform power or simply create new certified gateways. The likely impact is material but limited, so a 3 fits. That puts the plausible magnitude in the material €10–100M / 5–50M person-hour band.

### **Weak signals (5):**

- (+) [Trust] → users move identity, credentials, or assets between immersive services without starting from zero (portability improves)
- (+) [Collaboration] → organizations reuse spatial environments and training assets across vendors (switching costs fall modestly)
- (+) [Transparency] → common rights and provenance metadata travel with virtual objects (ownership becomes clearer)
- (-) [Platform power] → dominant engines or stores still control practical interoperability (openness can be partial)
- (-) [Access] → benefits remain confined to organizations already using immersive environments (broad GVN effect stays bounded)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 - Content Authenticity Infrastructure

**Score:** 10 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Content Authenticity Infrastructure is increasingly central to trust because collaboration now depends on whether media, records, and claims can be attributed and their transformation histories checked. Directly, it helps people and systems distinguish traceable content from unprovenanced copies; institutionally, it creates common expectations about capture, editing, and AI use across

platforms and workflows. The 3rd-order effects are large because provenance checking can become a default gate in journalism, procurement, social platforms, and civic processes, while non-adoption or spoofing can create new exclusion and credibility contests. Given the scale of mediated information exchange, this deserves a 10. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

#### **Weak signals (9):**

- (+) [Trust] → browsers, messaging tools, or operating systems display provenance summaries by default (verification enters everyday use)
- (+) [Transparency] → cameras, generators, and editing tools attach standardized credentials at creation and modification steps (lineage becomes portable)
- (+) [Risk management] → sensitive workflows accept only credentialed media or flag missing provenance for review (triage costs fall)
- (+) [Authorship] → disputes over who created or edited content are resolved through shared credential checks (ownership becomes easier to prove)
- (+) [Public discourse] → newsrooms, agencies, and courts reference provenance status when deciding what evidence to trust (institutional norms form)
- (-) [Power distribution] → certified devices or platforms gain a large trust premium over open or low-cost tools (credibility can centralize)
- (-) [Exclusion] → authentic but uncredentialed grassroots content is discounted because it lacks signed lineage (truth and provenance diverge)
- (-) [Security] → key compromise or fake-certification scandals damage confidence in the whole infrastructure (trust can fail systemically)
- (-) [Governance] → fights intensify over whether provenance should be mandatory, optional, or privacy-limited in public spaces (policy conflict grows)

## **ART 12.099 - Privacy-Preserving Collaboration Protocols**

**Score:** 10 (Impact in GVN 18)

#### **Justification (3–5 sentences):**

Privacy-Preserving Collaboration Protocols maps directly onto the GVN goal because it lets parties cooperate on sensitive information without demanding full interpersonal or institutional trust. Directly, it turns some forms of joint analysis, planning, and verification into machine-enforced collaboration; institutionally, it reduces the need for central custodians and lowers the legal burden of data pooling. Its 3rd-order effect is to widen the set of organizations that can collaborate regularly, while also creating dependence on hard-to-audit cryptographic infrastructure and specialized operators. Because it can change how trust is technically produced across many sectors, a 10 is justified. If adopted in major systems, it could reshape weekly collaboration for hundreds of thousands of people.

#### **Weak signals (9):**

- (+) [Trust] → organizations run joint computations without creating a central raw-data repository (cooperation no longer requires full exposure)
- (+) [Privacy protection] → regulators accept secure collaborative analytics where ordinary data sharing would be blocked (permission space widens)
- (+) [Cross-organizational collaboration] → competitors or agencies launch shared-risk or fraud models without disclosing underlying records (new alliances become possible)
- (+) [Risk management] → safe-output rules and audit logs are attached to collaborative computations (governance becomes more explicit)
- (+) [Access] → smaller actors join sector-wide analytics because they do not need their own large secure data lake (participation broadens)
- (-) [Power distribution] → MPC coordinators, key custodians, or specialized vendors become indispensable intermediaries (trust shifts to new experts)
- (-) [Legibility] → non-specialists struggle to understand what the protocols actually guarantee (social trust lags technical trust)
- (-) [Performance inequality] → only well-funded consortia can bear the latency and engineering overhead at first (benefits skew upward)
- (-) [Security] → implementation flaws or side-channel leaks produce trust shocks that are hard for outsiders to evaluate (credibility becomes brittle)

## ART 12.100 - Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

**Score:** 5 (Impact in GVN 18)

### **Justification (3–5 sentences):**

Manufacturing standards + conformance testing + certification infrastructure matters because collaborative manufacturing networks depend on shared confidence that machines, processes, and outputs are comparable across sites. Directly, it reduces qualification time and measurement disputes; institutionally, it turns tacit know-how into auditable claims that buyers, regulators, and insurers can rely on. The downside is slower innovation or exclusion if certification regimes are expensive and dominated by incumbent players. For manufacturing-heavy collaboration, this is significant enough for a 5. That is consistent with the significant €100M–1B / 50–500M person-hour band.

### **Weak signals (9):**

- (+) [Trust] → buyers accept certified machine/process profiles from multiple suppliers without repeating full local trials (qualification costs fall)
- (+) [Transparency] → conformance results and machine-readable certificates are attached to recipes, batches, or equipment states (claims become portable)
- (+) [Risk management] → insurers and regulators reference standard benchmark artifacts and digital test traces (measurement disputes shrink)

- (+) [Market access] → smaller manufacturers win work by passing shared conformance suites instead of relying on prior relationships (entry barriers fall)
- (+) [Coordination] → multi-site production transfers become faster because equivalence is pre-tested (distributed collaboration improves)
- (-) [Power distribution] → a few labs or standards groups define the tests that determine market legitimacy (certification becomes leverage)
- (-) [Innovation] → novel processes are delayed because no conformance path exists yet (standardization can freeze experimentation)
- (-) [Fraud] → certificate spoofing or stale test data become visible problems (trust depends on lifecycle governance)
- (-) [Cost burden] → smaller firms complain that recurring audit fees outweigh collaboration gains (participation can narrow)

## GVN 19: Existential Meaning ART Impact

### 1. Sensing, Measurement & Connectivity

#### ART 01.001 - Global Broadband Connectivity

**Score:** 20 (Impact in GVN 19)

**Justification (3–5 sentences):**

In mature form, near-universal connectivity makes online communities, creator work, remote volunteering, and participation in global causes available regardless of location or income. It directly expands belonging and self-expression, while second-order effects shift bargaining power toward or away from platforms and can also scale always-on work norms and extremist recruitment. Because the challenger regime in this GVN relies on digital communities and globally shareable contribution, this is a linchpin: once hundreds of thousands use it weekly, it exceeds the 10-anchor and merits 20.

**Weak signals (9):**

- (+) [Sense of belonging] → rural and low-income participation rates on major community platforms approach urban levels (access gap closes)
- (+) [Meaningful work] → small-town freelancers, co-ops, or volunteers serve national/global clients routinely (place stops limiting purpose)
- (+) [Participation in a grand mission] → climate, science, or mutual-aid networks recruit persistent remote contributors (missions gain active members)
- (+) [Self-expression] → creator revenues and audiences spread beyond metropolitan hubs (recognition broadens)

- (+) [Local community] → municipalities or associations fund shared connectivity infrastructure as a civic utility (belonging gets a base layer)
- (+) [Serving others] → telecare, mentoring, or peer-support use rises among mobility-limited groups (participation barriers fall)
- (-) [Desire for comfort and stability] → employers normalize evening/weekend responsiveness after access gaps shrink (always-on norms harden)
- (-) [Potential for negative influences] → destructive online communities recruit newly connected populations measurably (belonging misdirected)
- (-) [Ownership/access] → a few operators control identity, traffic, or moderation choke points (gatekeeper power expands)

## ART 01.002 - Ultra-Low Latency Networks

**Score:** 10 (Impact in GVN 19)

### **Justification (3–5 sentences):**

By making shared digital spaces and remote cooperation feel immediate, this technology changes whether online work, co-presence, gaming, therapy, learning, and volunteering feel meaningful or thin. It can create richer remote communities and more comprehensive, feedback-rich work roles, but it also enables hyper-responsive behavioral optimization and tighter employer control. If low-latency presence becomes normal across major platforms, weekly life for hundreds of thousands shifts enough to justify 10.

### **Weak signals (9):**

- (+) [Sense of belonging] → clubs and teams switch from video calls to persistent shared spaces (co-presence feels real)
- (+) [Meaningful work] → remote craft, therapy, music, or training sessions are rated near in-person quality (distance loses penalty)
- (+) [Achievements & exceeding limits] → synchronized mixed-reality competitions and performances grow fast (new achievement arenas)
- (+) [Serving others] → edge-compute hubs appear in libraries, schools, or community centers (high-quality access localizes)
- (+) [Local/online community bridge] → hybrid events give remote participants equal speaking or acting roles (belonging hybridizes)
- (+) [Peer appreciation] → remote work metrics shift from attendance to real-time joint contribution (recognition becomes interactive)
- (-) [Societal pressure and conformity] → employers or platforms treat instant response as the norm (lag becomes deviance)
- (-) [Potential for negative influences] → ultra-responsive gambling, parasocial, or competitive systems show rising compulsive use (immersion exploits reflexes)

- (-) [Ownership/access] → premium edge zones produce clear quality tiers in participation (status follows infrastructure)

## ART 01.003 - Edge AI for Sensor Data

**Score:** 3 (Impact in GVN 19)

### **Justification (3–5 sentences):**

The main link is via measurement: this makes work, care, or local environments more continuously visible and easier to coordinate. That can support gamified volunteering, safer community stewardship, and feedback-rich roles, but it also normalizes hidden scoring and ambient surveillance. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

### **Weak signals (3):**

- (+) [Measurement & gamification of work] → volunteer or workplace platforms reward sensor-verified micro-contributions (contribution becomes legible)
- (+) [Local/community belonging] → municipalities or NGOs deploy resident-run sensing for care, safety, or stewardship (shared responsibility grows)
- (-) [Peer appreciation/status] → employers, landlords, or insurers start scoring behavior from passive sensing data (meaning becomes surveilled)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.004 - Quantum & High-Precision Sensing

**Score:** 1 (Impact in GVN 19)

### **Justification (3–5 sentences):**

The path is mostly via high-resolution self, health, or environmental tracking that can preserve participation and create new achievement cultures. The stronger downside is that attention, stress, or behavior becomes measurable enough for elite or coercive uses. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

### **Weak signals (3):**

- (+) [Achievements & exceeding limits] → high-precision self-tracking enters wellness, sport, or recovery communities (achievement culture intensifies)
- (+) [Serving others] → hospitals or civic services pilot precision sensing to anticipate problems before they isolate people (care becomes more anticipatory)
- (-) [Societal pressure and conformity] → organizations request precise fatigue, stress, or attention measurements (internal states become auditable)

Signal density: LOW (linkage weak; additional signals would be speculative).



## ART 01.005 - Micro/Nano Sensor Networks

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main link is via measurement: this makes work, care, or local environments more continuously visible and easier to coordinate. That can support gamified volunteering, safer community stewardship, and feedback-rich roles, but it also normalizes hidden scoring and ambient surveillance. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Measurement & gamification of work] → volunteer or workplace platforms reward sensor-verified micro-contributions (contribution becomes legible)
- (+) [Local/community belonging] → municipalities or NGOs deploy resident-run sensing for care, safety, or stewardship (shared responsibility grows)
- (-) [Peer appreciation/status] → employers, landlords, or insurers start scoring behavior from passive sensing data (meaning becomes surveilled)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.006 - Privacy-Preserving Pervasive Sensing

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

This makes continuous sensing compatible with trust, letting workplaces, communities, and homes measure contribution, care, and context without fully centralizing raw personal data. That supports gamified volunteering, safer remote collaboration, and more adaptive communities, while still risking subtle scoring and normalization of surveillance. If widely built into consumer and civic systems, it can materially reallocate tens of millions of person-hours between checking, coordinating, and participating, which fits 5.

**Weak signals (9):**

- (+) [Sense of belonging] → users actively choose on-device, federated, or policy-controlled data modes (trust becomes operational)
- (+) [Serving others] → hospitals, municipalities, and co-ops share models or analytics without centralizing raw records (collaboration unlocks sensitive domains)
- (+) [Meaningful work] → small organizations join shared learning networks while retaining local data control (capability diffuses without surrender)
- (+) [Participation in a grand mission] → climate, care, or research coalitions publish privacy-preserving collaboration charters and actually use them (mission networks scale safely)

- (+) [Community building] → member-governed data trusts or cooperative data rooms appear (collective control grows)
- (+) [Peer appreciation] → platforms disclose what personal signals stay local versus what is shared (recognition feels less extractive)
- (-) [Ownership/access] → dominant vendors turn “privacy-preserving” stacks into closed ecosystems (trust becomes branded dependency)
- (-) [Potential for negative influences] → regulators or journalists show that supposedly safe updates still leak group or personal traits (privacy theater exposed)
- (-) [Fear of change] → organizations delay collaboration because secure-compute overhead is too high or governance too complex (good intent stalls)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

**Score: 3 (Impact in GVN 19)**

### **Justification (3–5 sentences):**

The main link is trust in remote communities and long-lived digital work relations. Better communications security lowers fear of interception and identity theft, but most users experience it only when crises or attacks expose dependence. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

### **Weak signals (3):**

- (+) [Sense of belonging] → community platforms advertise long-term secure messaging or identity recovery as a key feature (trust becomes visible)
- (+) [Participation in a grand mission] → activist, civic, or mutual-aid networks migrate sensitive coordination to hardened channels (coordination feels safer)
- (-) [Fear of change] → security shocks force rushed upgrades by schools, co-ops, or associations (trust fragility is exposed)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 - Integrated Sensing and Communication (ISAC)

**Score: 3 (Impact in GVN 19)**

### **Justification (3–5 sentences):**

The main link is via measurement: this makes work, care, or local environments more continuously visible and easier to coordinate. That can support gamified volunteering, safer community stewardship, and feedback-rich roles, but it also normalizes hidden scoring and ambient surveillance. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

### **Weak signals (3):**

- (+) [Measurement & gamification of work] → volunteer or workplace platforms reward sensor-verified micro-contributions (contribution becomes legible)
- (+) [Local/community belonging] → municipalities or NGOs deploy resident-run sensing for care, safety, or stewardship (shared responsibility grows)
- (-) [Peer appreciation/status] → employers, landlords, or insurers start scoring behavior from passive sensing data (meaning becomes surveilled)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.011 - Quantum Computing Platforms

**Score:** 1 (Impact in GVN 19)

### **Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

### **Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

**Score:** 3 (Impact in GVN 19)

### **Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

### **Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)

- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

**Score:** 3 (Impact in GVN 19)

### **Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

### **Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

**Score:** 0 (Impact in GVN 19)

### **Justification (3–5 sentences):**

No clear mature-state pathway from this technology to existential meaning stands out beyond distant enabling effects. Any impact would likely be mediated through several other technologies or niche sectors before it reaches belonging, purpose, or meaningful work. That keeps it at 0 unless future weak signals show a direct community, identity, or work-meaning linkage.

### **Weak signals (3):**

- (+) [Watchpoint: self-expression] → developers position molecular systems as direct substrates for personal or community devices (linkage would become concrete)
- (+) [Watchpoint: meaningful work] → pilot applications appear in everyday health, learning, or communication tools rather than lab equipment (GVN path opens)
- (-) [Watchpoint: governance] → public debate shifts from niche molecular computation to mainstream identity or community uses (social relevance emerges)

Signal density: LOW (linkage weak; additional signals would be speculative).

### 3. Artificial Intelligence & Learning Systems

#### ART 03.015 - Causal Learning & Reasoning

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

Causal models can make community organizers, educators, and employers better at seeing which interventions actually increase belonging, motivation, or meaningful contribution. The second-order effect is stronger governance of digital communities and local programs, but also more targeted manipulation if platforms learn which actions most reliably steer identity and behavior. Used across public services, large employers, and platforms, it can materially improve or distort how meaning-related interventions are chosen, which fits 5.

**Weak signals (9):**

- (+) [Serving others] → community organizations deploy AI copilots for matching care, volunteering, mentoring, or dispute triage (coordination capacity rises)
- (+) [Meaningful work] → small employers, schools, or co-ops build or tune AI tools without specialist teams (agency diffuses downward)
- (+) [Peer appreciation] → contribution metrics shift from crude output counts to context-aware, causal, or intent-sensitive measures (recognition gets more nuanced)
- (+) [Sense of belonging] → users actively appeal, override, or inspect AI decisions inside communities and work platforms (contestability becomes normal)
- (+) [Participation in a grand mission] → multi-agent or automated systems run local climate, care, or innovation projects at community scale (collective action accelerates)
- (+) [Community building] → local AI councils, ethics boards, or evaluation commons emerge (governance capacity grows)
- (-) [Pursuit of achieved status] → complaints rise about subtle ranking, nudging, or emotion-based inference in major platforms (identity steering surfaces)
- (-) [Fear of change] → unions, schools, or civic groups demand human override rights after AI-governance controversies (legitimacy is contested)
- (-) [Ownership/access] → a few model providers control defaults, evaluation benchmarks, or agent platforms used by many communities (power recentralizes)

#### ART 03.016 - Federated & Privacy-Preserving Learning

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

This lets shared AI systems learn from personal and local data without forcing people to surrender their full histories, which is crucial for community, health, and work tools tied to identity. It widens access to localized AI support and can strengthen trust in purpose-oriented networks, but it also empowers large platforms to optimize influence while appearing privacy-respectful. That is a significant institutional shift rather than a full operating-model rewrite, so 5.

**Weak signals (9):**

- (+) [Sense of belonging] → users actively choose on-device, federated, or policy-controlled data modes (trust becomes operational)
- (+) [Serving others] → hospitals, municipalities, and co-ops share models or analytics without centralizing raw records (collaboration unlocks sensitive domains)
- (+) [Meaningful work] → small organizations join shared learning networks while retaining local data control (capability diffuses without surrender)
- (+) [Participation in a grand mission] → climate, care, or research coalitions publish privacy-preserving collaboration charters and actually use them (mission networks scale safely)
- (+) [Community building] → member-governed data trusts or cooperative data rooms appear (collective control grows)
- (+) [Peer appreciation] → platforms disclose what personal signals stay local versus what is shared (recognition feels less extractive)
- (-) [Ownership/access] → dominant vendors turn “privacy-preserving” stacks into closed ecosystems (trust becomes branded dependency)
- (-) [Potential for negative influences] → regulators or journalists show that supposedly safe updates still leak group or personal traits (privacy theater exposed)
- (-) [Fear of change] → organizations delay collaboration because secure-compute overhead is too high or governance too complex (good intent stalls)

**ART 03.017 - Trustworthy AI Systems**

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

If AI becomes auditable, reliable, and contestable enough for everyday work, education, community moderation, and public services, it changes whether people trust machine-mediated participation at all. The direct effect is broader use of AI for matching, support, and creation; the second-order effect is institutional dependence on AI rules and audit systems; the third-order effect is a new baseline for what counts as fair participation. Because it can reconfigure weekly life for large populations across work and community platforms, it fits 10.

**Weak signals (9):**



- (+) [Serving others] → community organizations deploy AI copilots for matching care, volunteering, mentoring, or dispute triage (coordination capacity rises)
- (+) [Meaningful work] → small employers, schools, or co-ops build or tune AI tools without specialist teams (agency diffuses downward)
- (+) [Peer appreciation] → contribution metrics shift from crude output counts to context-aware, causal, or intent-sensitive measures (recognition gets more nuanced)
- (+) [Sense of belonging] → users actively appeal, override, or inspect AI decisions inside communities and work platforms (contestability becomes normal)
- (+) [Participation in a grand mission] → multi-agent or automated systems run local climate, care, or innovation projects at community scale (collective action accelerates)
- (+) [Community building] → local AI councils, ethics boards, or evaluation commons emerge (governance capacity grows)
- (-) [Pursuit of achieved status] → complaints rise about subtle ranking, nudging, or emotion-based inference in major platforms (identity steering surfaces)
- (-) [Fear of change] → unions, schools, or civic groups demand human override rights after AI-governance controversies (legitimacy is contested)
- (-) [Ownership/access] → a few model providers control defaults, evaluation benchmarks, or agent platforms used by many communities (power recentralizes)

## ART 03.018 - Automated Machine Learning (AutoML)

**Score:** 5 (Impact in GVN 19)

### **Justification (3–5 sentences):**

AutoML lowers the skill threshold for building tools that shape belonging, work, and local coordination. That can let community organizations and small firms create fit-for-purpose systems, but it also multiplies low-quality or manipulative optimization applied to identity, status, and labor. The likely effect is significant because it broadens who can operationalize AI in meaning-related domains, so 5.

### **Weak signals (9):**

- (+) [Serving others] → community organizations deploy AI copilots for matching care, volunteering, mentoring, or dispute triage (coordination capacity rises)
- (+) [Meaningful work] → small employers, schools, or co-ops build or tune AI tools without specialist teams (agency diffuses downward)
- (+) [Peer appreciation] → contribution metrics shift from crude output counts to context-aware, causal, or intent-sensitive measures (recognition gets more nuanced)
- (+) [Sense of belonging] → users actively appeal, override, or inspect AI decisions inside communities and work platforms (contestability becomes normal)
- (+) [Participation in a grand mission] → multi-agent or automated systems run local climate, care, or innovation projects at community scale (collective action accelerates)

- (+) [Community building] → local AI councils, ethics boards, or evaluation commons emerge (governance capacity grows)
- (-) [Pursuit of achieved status] → complaints rise about subtle ranking, nudging, or emotion-based inference in major platforms (identity steering surfaces)
- (-) [Fear of change] → unions, schools, or civic groups demand human override rights after AI-governance controversies (legitimacy is contested)
- (-) [Ownership/access] → a few model providers control defaults, evaluation benchmarks, or agent platforms used by many communities (power recentralizes)

## ART 03.019 - Collaborative Multi-Agent AI

**Score:** 5 (Impact in GVN 19)

### **Justification (3–5 sentences):**

Distributed AI agents can coordinate community projects, digital commons, care logistics, local production, and civic missions at a scale that today exceeds human attention. This can turn grand narratives into actionable everyday participation, but it can also replace human roles, flatten status into machine-managed workflows, and concentrate control in whoever sets the agent rules. The likely impact is significant but not singularly decisive for this GVN, so 5.

### **Weak signals (9):**

- (+) [Serving others] → community organizations deploy AI copilots for matching care, volunteering, mentoring, or dispute triage (coordination capacity rises)
- (+) [Meaningful work] → small employers, schools, or co-ops build or tune AI tools without specialist teams (agency diffuses downward)
- (+) [Peer appreciation] → contribution metrics shift from crude output counts to context-aware, causal, or intent-sensitive measures (recognition gets more nuanced)
- (+) [Sense of belonging] → users actively appeal, override, or inspect AI decisions inside communities and work platforms (contestability becomes normal)
- (+) [Participation in a grand mission] → multi-agent or automated systems run local climate, care, or innovation projects at community scale (collective action accelerates)
- (+) [Community building] → local AI councils, ethics boards, or evaluation commons emerge (governance capacity grows)
- (-) [Pursuit of achieved status] → complaints rise about subtle ranking, nudging, or emotion-based inference in major platforms (identity steering surfaces)
- (-) [Fear of change] → unions, schools, or civic groups demand human override rights after AI-governance controversies (legitimacy is contested)
- (-) [Ownership/access] → a few model providers control defaults, evaluation benchmarks, or agent platforms used by many communities (power recentralizes)

## ART 03.020 - Quantum-Accelerated AI Systems

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
- (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
- (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.021 - AI-Driven Autonomous Scientific Discovery

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main linkage is through grand missions and knowledge work: more of the discovery process can be opened, accelerated, or coordinated. That can let more people contribute to collective problem-solving, but it can also devalue human judgment and intensify winner-take-all research reputations. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → citizen-science or problem-solving platforms use AI to open larger hypothesis spaces (missions widen)
- (+) [Achievements & recognition] → public research challenges begin crediting human–AI teams distinctly (new prestige metrics appear)
- (-) [Peer appreciation/status] → institutions overweight AI-generated output volume over mentorship or judgment (purpose gets hollowed)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 4. Human-Machine Interaction & Augmentation

## ART 04.022 - Immersive Augmented & Virtual Reality

Score: 20 (Impact in GVN 19)

Justification (3–5 sentences):

This technology directly matches the GVN's challenger regime: it makes distant people, projects, and communities feel co-present and gives achievements, missions, and social worlds a vivid stage. First-order it deepens belonging and self-expression; second- and third-order it creates new status systems, labor markets, and risks of escapism, manipulation, and extremist immersion. Because it is a core medium for the shift from place-bound meaning to hybrid local/online meaning, it is a 20.

Weak signals (9):

- (+) [Sense of belonging] → persistent mixed-reality clubs, faith groups, or hobby spaces retain members longer than text/video communities (presence deepens attachment)
- (+) [Self-expression] → people earn status from building worlds, performances, or avatars rather than only formal credentials (new status economies emerge)
- (+) [Meaningful work] → remote teamwork in shared 3D environments replaces screen-share workflows in selected sectors (work feels embodied)
- (+) [Participation in a grand mission] → large volunteer, science, or activism campaigns meet and rehearse in immersive spaces (missions gain ritual and cohesion)
- (+) [Local/online community bridge] → local festivals, classes, or clubs routinely extend into spatial online twins (community becomes hybrid)
- (+) [Serving others] → disabled, isolated, or caregiving users show higher participation in social and cultural life through immersive access (inclusion widens)
- (-) [Potential for negative influences] → immersive extremist, gambling, or status-driven communities show measurable recruitment and retention (belonging can radicalize)
- (-) [Desire for comfort and stability] → escapist time displacement from family, local ties, or offline duties becomes a public concern (meaning detaches from place)
- (-) [Ownership/access] → a few stores, identity layers, or asset standards dominate major immersive spaces (gatekeepers shape worlds)

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

BCI expands who can participate in creation, work, and community by reducing dependence on conventional speech and motor interfaces and by opening new forms of expression. It may especially transform meaning for disabled people and high-intensity digital workers, but it also creates strong risks of cognitive surveillance, coercive productivity norms, and enhancement inequality. That is significant in affected populations and institutions, but not yet a full society-wide operating model shift, so 5.

Weak signals (9):

- (+) [Self-realization] → people with severe motor or speech limits return to study, work, or creative communities using neural control (participation restored)
- (+) [Achievements & exceeding limits] → new BCI-native sports, arts, or collaboration formats emerge (new achievement fields appear)
- (+) [Meaningful work] → professions with heavy interface load adopt BCI for high-focus or hands-free tasks (interface friction drops)
- (+) [Sense of belonging] → peer communities form around shared neural-interface practices rather than diagnoses alone (identity reframes capability)
- (+) [Serving others] → public or insurer funding expands beyond medical rehabilitation into daily participation support (use becomes social, not niche)
- (+) [Peer appreciation] → reputation systems start recognizing BCI-enabled creation and labor on equal terms (ability bias decreases)
- (-) [Societal pressure and conformity] → employers or schools begin implying “optional” neural enhancement for performance (enhancement becomes expectation)
- (-) [Ownership/access] → premium neural interfaces create visible capability tiers in elite work or learning settings (meaning stratifies by hardware)
- (-) [Security/dual-use] → neural data breaches or coercion incidents trigger new regulation and public backlash (inner life feels vulnerable)

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
  - (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
  - (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

Richer touch, force, and embodiment make remote presence, craft, care, training, and play feel consequential rather than abstract. This strengthens belonging in distributed teams and communities and makes digital work more comprehensive, while also enabling deeper behavioral capture and more addictive mediated environments. If widely paired with telepresence, games, and learning, the impact on meaningful participation is large enough for 5.

Weak signals (9):

- (+) [Sense of belonging] → remote touch-rich interactions become routine in therapy, companionship, or collaborative craft (distance feels less empty)
- (+) [Meaningful work] → teleoperation and remote service roles use fine-grained feedback instead of rough video control (care and craft become viable)
- (+) [Achievements & exceeding limits] → skill communities benchmark force, touch, or embodied performance remotely (new mastery cultures form)
- (+) [Serving others] → rehabilitation and training programs adopt rich feedback to keep more people participating (learning becomes embodied)
- (+) [Local/online community bridge] → distributed teams use shared tactile cues in performances, games, or making (coordination feels mutual)
- (+) [Peer appreciation] → remote artisans or caregivers receive ratings tied to felt quality, not only speed (recognition tracks embodied skill)
- (-) [Pursuit of achieved status] → addictive or manipulative sensory reward loops become a design controversy (embodiment can be exploited)
- (-) [Ownership/access] → premium haptic rigs separate elite and ordinary participants in remote creation spaces (capability stratifies)
- (-) [Privacy/dual-use] → debates rise over recording and replaying intimate tactile interaction data (contact becomes datafied)

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 10 (Impact in GVN 19)

Justification (3–5 sentences):

When machines infer intent, emotion, and social context, digital systems stop being blunt tools and start acting like social environments. That can dramatically lower participation barriers, personalize support, and make communities and work feel more seen, but it also enables manipulation, conformity pressure, and automated status sorting at a finer grain. Because it can restructure everyday interaction across major platforms and workplaces, it fits 10.

Weak signals (9):

- (+) [Serving others] → community organizations deploy AI copilots for matching care, volunteering, mentoring, or dispute triage (coordination capacity rises)
- (+) [Meaningful work] → small employers, schools, or co-ops build or tune AI tools without specialist teams (agency diffuses downward)

- (+) [Peer appreciation] → contribution metrics shift from crude output counts to context-aware, causal, or intent-sensitive measures (recognition gets more nuanced)
- (+) [Sense of belonging] → users actively appeal, override, or inspect AI decisions inside communities and work platforms (contestability becomes normal)
- (+) [Participation in a grand mission] → multi-agent or automated systems run local climate, care, or innovation projects at community scale (collective action accelerates)
- (+) [Community building] → local AI councils, ethics boards, or evaluation commons emerge (governance capacity grows)
- (-) [Pursuit of achieved status] → complaints rise about subtle ranking, nudging, or emotion-based inference in major platforms (identity steering surfaces)
- (-) [Fear of change] → unions, schools, or civic groups demand human override rights after AI-governance controversies (legitimacy is contested)
- (-) [Ownership/access] → a few model providers control defaults, evaluation benchmarks, or agent platforms used by many communities (power recentralizes)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
  - (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
  - (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.



Weak signals (3):

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
  - (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
  - (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

Autonomous transport changes where people can live, how much time is reclaimed from commuting, and who can access work, friends, and voluntary communities. Second-order effects are large: mobility jobs and local service economies shift, while children, elders, and people with disabilities gain or lose autonomy depending on access. The effect on existential meaning is significant rather than foundational, so 5.

Weak signals (9):

- (+) [Meaningful work] → human roles shift from repetitive execution toward coaching, care, exception handling, or local stewardship (drudgery leaves center stage)
- (+) [Serving others] → mobility, care, or public-service access expands for groups previously constrained by time or physical ability (participation widens)
- (+) [Local community] → neighborhoods or firms redesign routines around more available transport, delivery, or service capacity (daily coordination changes)
- (+) [Participation in a grand mission] → communities use autonomous systems for resilience, safety, or climate tasks at scales small teams could not manage (agency scales)
- (+) [Peer appreciation] → new status markers emerge around managing, training, or integrating autonomous systems responsibly (recognition shifts)
- (+) [Work and professional identity] → unions, schools, or employers create retraining pipelines into relational or supervisory roles (identity is renegotiated)
- (-) [Pursuit of achieved status] → owners of robot fleets or autonomy infrastructure capture outsized income and bargaining power (meaning decouples from labor)
- (-) [Fear of losing stability] → workers protest loss of entry-level or route-based occupations that once anchored identity (status disruption becomes visible)

- (-) [Public trust/security] → collisions, bias incidents, or machine-first urban design trigger legitimacy conflicts (autonomy can alienate people)

## ART 05.030 - Drone Swarms & Aerial Robots

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main path is indirect: hazardous or physically awkward tasks move to remote or autonomous systems, changing which human roles remain. This can expand what small teams can do for their communities, but it can also hollow out entry-level field roles and distance people from embodied contribution. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Serving others] → hazardous inspection, repair, or response tasks shift from people to supervised machines (human burden drops)
  - (+) [Achievements & exceeding limits] → local clubs, firms, or civic services use robotic tools to expand what small teams can do (agency scales)
  - (-) [Work identity] → organizations remove field or manual entry roles and keep humans as exception handlers only (purpose thins out)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 10 (Impact in GVN 19)

Justification (3–5 sentences):

General-purpose robots would directly challenge the dominant regime's link between human worth and many forms of paid, embodied work. They could remove drudgery and expand time for care, community, and self-directed projects, but they could also hollow out status, bargaining power, and everyday usefulness for large groups if ownership stays concentrated. Because this can transform how work-based meaning is organized across society, it fits 10.

Weak signals (9):

- (+) [Meaningful work] → human roles shift from repetitive execution toward coaching, care, exception handling, or local stewardship (drudgery leaves center stage)
- (+) [Serving others] → mobility, care, or public-service access expands for groups previously constrained by time or physical ability (participation widens)
- (+) [Local community] → neighborhoods or firms redesign routines around more available transport, delivery, or service capacity (daily coordination changes)
- (+) [Participation in a grand mission] → communities use autonomous systems for resilience, safety, or climate tasks at scales small teams could not manage (agency scales)
- (+) [Peer appreciation] → new status markers emerge around managing, training, or integrating autonomous systems responsibly (recognition shifts)

- (+) [Work and professional identity] → unions, schools, or employers create retraining pipelines into relational or supervisory roles (identity is renegotiated)
- (-) [Pursuit of achieved status] → owners of robot fleets or autonomy infrastructure capture outsized income and bargaining power (meaning decouples from labor)
- (-) [Fear of losing stability] → workers protest loss of entry-level or route-based occupations that once anchored identity (status disruption becomes visible)
- (-) [Public trust/security] → collisions, bias incidents, or machine-first urban design trigger legitimacy conflicts (autonomy can alienate people)

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main path is indirect: hazardous or physically awkward tasks move to remote or autonomous systems, changing which human roles remain. This can expand what small teams can do for their communities, but it can also hollow out entry-level field roles and distance people from embodied contribution. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Serving others] → hazardous inspection, repair, or response tasks shift from people to supervised machines (human burden drops)
- (+) [Achievements & exceeding limits] → local clubs, firms, or civic services use robotic tools to expand what small teams can do (agency scales)
- (-) [Work identity] → organizations remove field or manual entry roles and keep humans as exception handlers only (purpose thins out)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main path is indirect: hazardous or physically awkward tasks move to remote or autonomous systems, changing which human roles remain. This can expand what small teams can do for their communities, but it can also hollow out entry-level field roles and distance people from embodied contribution. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Serving others] → hazardous inspection, repair, or response tasks shift from people to supervised machines (human burden drops)
- (+) [Achievements & exceeding limits] → local clubs, firms, or civic services use robotic tools to expand what small teams can do (agency scales)

- (-) [Work identity] → organizations remove field or manual entry roles and keep humans as exception handlers only (purpose thins out)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

When public and workplace environments are redesigned for robot fleets, autonomy stops being occasional and becomes an organizing principle of everyday logistics and service work. That can free humans into more relational or creative roles, yet it can also make spaces feel machine-first and reduce informal human discretion. The indirect but system-wide effect on work meaning and public belonging is large enough for 5.

Weak signals (9):

- (+) [Meaningful work] → human roles shift from repetitive execution toward coaching, care, exception handling, or local stewardship (drudgery leaves center stage)
- (+) [Serving others] → mobility, care, or public-service access expands for groups previously constrained by time or physical ability (participation widens)
- (+) [Local community] → neighborhoods or firms redesign routines around more available transport, delivery, or service capacity (daily coordination changes)
- (+) [Participation in a grand mission] → communities use autonomous systems for resilience, safety, or climate tasks at scales small teams could not manage (agency scales)
- (+) [Peer appreciation] → new status markers emerge around managing, training, or integrating autonomous systems responsibly (recognition shifts)
- (+) [Work and professional identity] → unions, schools, or employers create retraining pipelines into relational or supervisory roles (identity is renegotiated)
- (-) [Pursuit of achieved status] → owners of robot fleets or autonomy infrastructure capture outsized income and bargaining power (meaning decouples from labor)
- (-) [Fear of losing stability] → workers protest loss of entry-level or route-based occupations that once anchored identity (status disruption becomes visible)
- (-) [Public trust/security] → collisions, bias incidents, or machine-first urban design trigger legitimacy conflicts (autonomy can alienate people)

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main path is indirect: hazardous or physically awkward tasks move to remote or autonomous systems, changing which human roles remain. This can expand what small teams can do for their communities, but it can also hollow out entry-level field roles and distance people from embodied contribution. That makes it worth monitoring for this GVN, yet below the threshold for a material

society-wide shift, so 1.

Weak signals (3):

- (+) [Serving others] → hazardous inspection, repair, or response tasks shift from people to supervised machines (human burden drops)
  - (+) [Achievements & exceeding limits] → local clubs, firms, or civic services use robotic tools to expand what small teams can do (agency scales)
  - (-) [Work identity] → organizations remove field or manual entry roles and keep humans as exception handlers only (purpose thins out)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### **ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation**

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main path is indirect: hazardous or physically awkward tasks move to remote or autonomous systems, changing which human roles remain. This can expand what small teams can do for their communities, but it can also hollow out entry-level field roles and distance people from embodied contribution. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Serving others] → hazardous inspection, repair, or response tasks shift from people to supervised machines (human burden drops)
  - (+) [Achievements & exceeding limits] → local clubs, firms, or civic services use robotic tools to expand what small teams can do (agency scales)
  - (-) [Work identity] → organizations remove field or manual entry roles and keep humans as exception handlers only (purpose thins out)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **6. Additive, Agile & Digital Manufacturing**

### **ART 06.037 - Multi-Material & Hybrid 3D Printing**

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is shorter distance between design intent, production, and local use. That can support maker culture and responsive local supply, but it can also move discretion into software and reduce hands-on autonomy. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Self-expression] → maker spaces or local firms offer personalized products with far shorter iteration cycles (creation feels immediate)
- (+) [Serving others] → communities source niche parts locally during disruptions (local usefulness rises)
- (-) [Work and professional identity] → design and production decisions concentrate in software platforms (craft becomes abstract)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is shorter distance between design intent, production, and local use. That can support maker culture and responsive local supply, but it can also move discretion into software and reduce hands-on autonomy. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Self-expression] → maker spaces or local firms offer personalized products with far shorter iteration cycles (creation feels immediate)
- (+) [Serving others] → communities source niche parts locally during disruptions (local usefulness rises)
- (-) [Work and professional identity] → design and production decisions concentrate in software platforms (craft becomes abstract)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.039 - Reconfigurable & Agile Factories

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

Agile factories can relocalize production, support small-batch creation, and shorten the distance between design intent and physical outcome. That can make industrial work more varied and community-serving, but it can also intensify software control and reduce demand for stable craft roles if workers do not share governance. The shift is significant for meaningful work and local mission formation, which supports a 5.

Weak signals (9):

- (+) [Meaningful work] → local firms take on more custom, mission-driven production rather than repetitive volume-only work (purpose gets closer to output)
- (+) [Self-expression] → maker communities and small businesses offer fast customization with visible user co-design (creation feels personal)
- (+) [Serving others] → hospitals, repair networks, or municipalities source niche parts locally during disruptions (local usefulness rises)

- (+) [Participation in a grand mission] → factories publicly frame output around circularity, resilience, or community service rather than only margin (industrial purpose becomes visible)
- (+) [Sense of belonging] → workers gain dashboards showing where their work ends up and who benefits (impact becomes legible)
- (+) [Community building] → local industrial clusters share modules, material loops, or repair ecosystems (place-based cooperation deepens)
- (-) [Work and professional identity] → software recipes and remote control reduce hands-on autonomy for operators (craft can thin out)
- (-) [Ownership/access] → firms with capital for modular plants or circular data systems dominate local markets (new concentration risk)
- (-) [Peer appreciation/status] → sustainability and customization metrics become new ranking systems that can exclude smaller actors (virtue/status competition rises)

## ART 06.040 - Circular & Sustainable Manufacturing

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

This technology makes industrial work easier to frame as stewardship rather than extraction, linking everyday production to repair, reuse, and climate missions. It can generate new community identities around local material cycles and reduce guilt or alienation around consumption, while also creating new monitoring burdens and green-status competition. Because it materially reshapes how industrial contribution is valued, it fits 5.

Weak signals (9):

- (+) [Meaningful work] → local firms take on more custom, mission-driven production rather than repetitive volume-only work (purpose gets closer to output)
- (+) [Self-expression] → maker communities and small businesses offer fast customization with visible user co-design (creation feels personal)
- (+) [Serving others] → hospitals, repair networks, or municipalities source niche parts locally during disruptions (local usefulness rises)
- (+) [Participation in a grand mission] → factories publicly frame output around circularity, resilience, or community service rather than only margin (industrial purpose becomes visible)
- (+) [Sense of belonging] → workers gain dashboards showing where their work ends up and who benefits (impact becomes legible)
- (+) [Community building] → local industrial clusters share modules, material loops, or repair ecosystems (place-based cooperation deepens)
- (-) [Work and professional identity] → software recipes and remote control reduce hands-on autonomy for operators (craft can thin out)



- (-) [Ownership/access] → firms with capital for modular plants or circular data systems dominate local markets (new concentration risk)
- (-) [Peer appreciation/status] → sustainability and customization metrics become new ranking systems that can exclude smaller actors (virtue/status competition rises)

## ART 06.041 - Bio-fabrication technologies

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
  - (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
  - (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is shorter distance between design intent, production, and local use. That can support maker culture and responsive local supply, but it can also move discretion into software and reduce hands-on autonomy. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Self-expression] → maker spaces or local firms offer personalized products with far shorter iteration cycles (creation feels immediate)
  - (+) [Serving others] → communities source niche parts locally during disruptions (local usefulness rises)
  - (-) [Work and professional identity] → design and production decisions concentrate in software platforms (craft becomes abstract)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is shorter distance between design intent, production, and local use. That can support maker culture and responsive local supply, but it can also move discretion into software and reduce hands-on autonomy. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Self-expression] → maker spaces or local firms offer personalized products with far shorter iteration cycles (creation feels immediate)
  - (+) [Serving others] → communities source niche parts locally during disruptions (local usefulness rises)
  - (-) [Work and professional identity] → design and production decisions concentrate in software platforms (craft becomes abstract)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
  - (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
  - (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.045 - Room-Temperature Superconductors

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.046 - Self-Healing & Smart Polymers

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
  - (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
  - (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
  - (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
  - (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
  - (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
  - (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)

- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength**

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
- (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
- (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling**

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
  - (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
  - (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as water infrastructure for resilience and lower service burdens. It can stabilize participation where water insecurity or emergency provision matter, but in this GVN the linkage is usually indirect and place-specific. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link advanced water supply to resilience and ecological stewardship (purpose framing spreads)
  - (+) [Serving others] → critical facilities adopt lower-energy water systems to reduce outage or shortage risk (basic participation stabilizes)
  - (-) [Local belonging] → pricing, siting, or ownership conflicts split communities around water infrastructure (resource politics intensify)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

This matters mainly by making AI, immersive media, or personal devices cheaper, smaller, or more locally capable. That can widen access to supportive tools, but it can also deepen platform concentration and always-on surveillance when advanced hardware is unevenly distributed. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift,

so 1.

Weak signals (3):

- (+) [Self-expression tools] → smaller or cheaper devices gain always-on AI, storage, or immersive capability (advanced tools diffuse)
  - (+) [Meaningful work] → local services run more intelligence on-device rather than in distant clouds (autonomy from platforms rises)
  - (-) [Ownership/access] → premium hardware tiers create clear quality gaps in participation (capability stratifies)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.



Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.058 - Thin-film solar cells

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

Light, flexible solar moves energy generation from distant specialist assets into buildings, vehicles, and everyday surfaces, making participation in the energy transition more visible and local. That can strengthen community autonomy and climate-purpose narratives, but it can also shift responsibility and status competition onto households and small organizations. The impact on this GVN is significant, especially through local mission-building and energy self-determination, so 5.

Weak signals (9):

- (+) [Local community] → schools, housing blocks, or villages treat energy assets as shared civic infrastructure (belonging gets a practical base)
- (+) [Participation in a grand mission] → residents join visible climate and resilience projects through everyday energy choices (purpose becomes tangible)

- (+) [Serving others] → resilience hubs keep care, communications, and community services running during disruptions (community stays functional)
- (+) [Meaningful work] → local maintenance, governance, and retrofit roles grow around distributed energy assets (new stewardship roles appear)
- (+) [Peer appreciation] → households or groups receive recognition for reliability, sharing, or energy-positive behavior (contribution becomes visible)
- (+) [Community building] → cooperatives or neighborhood associations negotiate energy rules and benefits directly (agency localizes)
- (-) [Equality] → affluent sites become energy-secure faster than poorer ones (resilience gap widens)
- (-) [Desire for comfort and stability] → households feel moral pressure to optimize constantly for status or savings (energy becomes performative)
- (-) [Ownership/access] → platform utilities or installers capture most data and value from “local” energy systems (localism becomes dependent)

## ART 08.059 - Bionic Leaf Technology

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.061 - Solid-State Batteries

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
  - (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
  - (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)

- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

Score: 3 (Impact in GVN 19)

Justification (3–5 sentences):

The main effect is as enabling infrastructure for resilience, affordability, and climate-purpose narratives. It can support meaningful local stewardship and reduce service fragility, but it often stays backgrounded and can also polarize communities over siting, ownership, or fairness. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

Weak signals (3):

- (+) [Participation in a grand mission] → public narratives link the technology to climate resilience or energy sovereignty (purpose framing spreads)
- (+) [Serving others] → critical services adopt it to reduce outages or energy burden (reliable participation grows)
- (-) [Local belonging] → siting, pricing, or ownership conflicts split communities (infrastructure becomes identity conflict)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

Score: 5 (Impact in GVN 19)

Justification (3–5 sentences):

Microgrids turn energy from a background utility into a local coordination project with visible governance, mutual dependence, and crisis meaning. They can anchor community resilience hubs and give people tangible roles in stewardship, while also creating new exclusions if affluent districts become more self-sufficient than others. That is a significant, institution-shaping effect on belonging and purposeful local action, so 5.

Weak signals (9):

- (+) [Local community] → schools, housing blocks, or villages treat energy assets as shared civic infrastructure (belonging gets a practical base)
- (+) [Participation in a grand mission] → residents join visible climate and resilience projects through everyday energy choices (purpose becomes tangible)
- (+) [Serving others] → resilience hubs keep care, communications, and community services running during disruptions (community stays functional)
- (+) [Meaningful work] → local maintenance, governance, and retrofit roles grow around distributed energy assets (new stewardship roles appear)
- (+) [Peer appreciation] → households or groups receive recognition for reliability, sharing, or energy-positive behavior (contribution becomes visible)
- (+) [Community building] → cooperatives or neighborhood associations negotiate energy rules and benefits directly (agency localizes)

- (-) [Equality] → affluent sites become energy-secure faster than poorer ones (resilience gap widens)
- (-) [Desire for comfort and stability] → households feel moral pressure to optimize constantly for status or savings (energy becomes performative)
- (-) [Ownership/access] → platform utilities or installers capture most data and value from “local” energy systems (localism becomes dependent)

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

More precise editing shifts identity, disability, prevention, and reproduction from fate toward design. It can preserve participation and reduce lifelong burdens, but it also risks new hierarchies of enhancement, parental pressure, and conflicts over what kinds of lives are seen as acceptable or meaningful. Because it significantly changes life-course possibilities and value conflicts without becoming a universal everyday interface, it fits 5.

**Weak signals (9):**

- (+) [Self-realization] → people with once-lifelong risks or conditions stay in work, study, or care roles longer (participation capacity grows)
- (+) [Sense of belonging] → communities form around proactive prevention or tailored treatment rather than only crisis response (identity shifts from coping to shaping)
- (+) [Serving others] → family care burdens fall when conditions are detected earlier or prevented (care time is reallocated)
- (+) [Peer appreciation] → schools and employers adapt expectations as more people contribute consistently after treatment or prevention (capability stereotypes weaken)
- (+) [Participation in a grand mission] → public campaigns frame the tools as ending inherited disease or failed trial-and-error care (mission identity broadens)
- (+) [Meaningful work] → patient-generated data and tailored care plans become normal in career planning and role design (life planning becomes more personalized)
- (-) [Pursuit of achieved status] → enhancement or premium prevention packages become visible prestige goods (health becomes a status ladder)
- (-) [Societal pressure and conformity] → non-use of available prevention or screening starts being judged as irresponsible (optimization pressure rises)
- (-) [Equality/governance] → insurers, employers, or schools use genomic risk data to sort access or expectations (life chances become bio-ranked)

## ART 09.068 - mRNA Therapies & Vaccines

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
- (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
- (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main pathway is through ethical, ecological, or local-production missions built around living systems. That can create new purpose narratives and resilient supply, but it can also trigger moral backlash, containment worries, and uneven access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → food or biotech projects recruit citizens around climate, welfare, or local production goals (purpose framing spreads)
- (+) [Serving others] → local facilities adopt monitored bio-based production for resilience or ethical sourcing (new usefulness appears)
- (-) [Identity conflict] → visible backlash forms around “synthetic” organisms, food, or ecosystem interventions (belonging fragments)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.



**Weak signals (3):**

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
- (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
- (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)  
Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 09.071 - Synthetic Biology & Designer Microbes****Score:** 3 (Impact in GVN 19)**Justification (3–5 sentences):**

The main pathway is through ethical, ecological, or local-production missions built around living systems. That can create new purpose narratives and resilient supply, but it can also trigger moral backlash, containment worries, and uneven access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → food or biotech projects recruit citizens around climate, welfare, or local production goals (purpose framing spreads)
- (+) [Serving others] → local facilities adopt monitored bio-based production for resilience or ethical sourcing (new usefulness appears)
- (-) [Identity conflict] → visible backlash forms around “synthetic” organisms, food, or ecosystem interventions (belonging fragments)  
Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 09.072 - Microbiome Engineering****Score:** 3 (Impact in GVN 19)**Justification (3–5 sentences):**

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
- (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)

- (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

Earlier and more individualized diagnosis can keep more people able to work, care, learn, and participate in communities that give life meaning. Its second-order effects include new data-driven health identities, insurance and employment sorting risks, and shifts in how people plan life trajectories. That is significant at society scale, but not a complete reorganization of meaning itself, so 5.

**Weak signals (9):**

- (+) [Self-realization] → people with once-lifelong risks or conditions stay in work, study, or care roles longer (participation capacity grows)
- (+) [Sense of belonging] → communities form around proactive prevention or tailored treatment rather than only crisis response (identity shifts from coping to shaping)
- (+) [Serving others] → family care burdens fall when conditions are detected earlier or prevented (care time is reallocated)
- (+) [Peer appreciation] → schools and employers adapt expectations as more people contribute consistently after treatment or prevention (capability stereotypes weaken)
- (+) [Participation in a grand mission] → public campaigns frame the tools as ending inherited disease or failed trial-and-error care (mission identity broadens)
- (+) [Meaningful work] → patient-generated data and tailored care plans become normal in career planning and role design (life planning becomes more personalized)
- (-) [Pursuit of achieved status] → enhancement or premium prevention packages become visible prestige goods (health becomes a status ladder)
- (-) [Societal pressure and conformity] → non-use of available prevention or screening starts being judged as irresponsible (optimization pressure rises)
- (-) [Equality/governance] → insurers, employers, or schools use genomic risk data to sort access or expectations (life chances become bio-ranked)

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is preserving or restoring the ability of specific groups to participate in work, care, learning, or community. That can reduce exclusion and identity loss, but it can also create enhancement pressure, medicalized status sorting, or unequal access. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Self-realization] → people with once-limiting conditions stay longer in work, study, or volunteering (participation preserved)
- (+) [Sense of belonging] → condition-specific communities form around new therapies or assistive routines (shared identity forms)
- (-) [Pursuit of achieved status] → employers or insurers start implying treatment or enhancement uptake (care becomes obligation)  
Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 09.075 - Biological Aging & Longevity Barriers**

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

If healthy lifespan extends materially, the timing of education, work, family, retirement, ambition, and intergenerational belonging all change. This can expand time for reinvention and contribution, but it can also entrench wealth-based longevity gaps and destabilize status ladders built around age. Because it can reshape everyday life and life-course meaning for hundreds of thousands, it fits 10.

**Weak signals (9):**

- (+) [Self-realization] → midlife and later-life retraining, entrepreneurship, or artistic reinvention rates rise (life horizon expands)
- (+) [Meaningful work] → retirement ages, sabbatical patterns, and second-career pathways are renegotiated widely (work identity stretches)
- (+) [Sense of belonging] → multi-generational communities stabilize as older adults stay active longer (intergenerational roles deepen)
- (+) [Serving others] → family care burdens from frailty or chronic decline are delayed or reduced (relational capacity is preserved)
- (+) [Participation in a grand mission] → public narratives treat longevity as a collective scientific and civic project (mission identity broadens)
- (+) [Peer appreciation] → later-life contribution receives more visible recognition in work and community settings (capability stereotypes weaken)
- (-) [Pursuit of achieved status] → premium longevity regimens become elite identity markers (life extension stratifies status)
- (-) [Fear of losing stability] → pension, promotion, and inheritance conflicts intensify as life-course timing shifts (institutions lose fit)
- (-) [Equality/governance] → employers, insurers, or wealthy groups convert longevity access into durable advantage (age hierarchy becomes class hierarchy)

## ART 09.076 - Engineered Living Materials

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main linkage is through better devices, infrastructure durability, or climate-adaptation tools that can support community participation. Benefits can be real, but they are usually mediated through other systems and can remain locked into premium products or elite facilities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Meaningful work tools] → lighter, longer-lasting, or more capable devices enter community-facing sectors (access widens)
- (+) [Participation in a grand mission] → public procurement ties new materials to resilience or climate goals (industrial purpose becomes visible)
- (-) [Equality] → early benefits stay concentrated in premium products or elite facilities (meaning tech stratifies)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main linkage is through environmental stewardship and public risk governance rather than daily meaning directly. It can create powerful mission identities around pest control or conservation, but it can also trigger legitimacy crises about irreversibility and human control of nature. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Participation in a grand mission] → local conservation or public-health programs openly debate targeted releases (mission framing becomes concrete)
- (+) [Community building] → affected residents join long-term monitoring panels or consent processes (belonging enters governance)
- (-) [Identity conflict] → protests or legal challenges frame releases as illegitimate control of shared ecosystems (meaning polarizes)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

This could decouple parts of reproduction from pregnancy, redistributing risk, care roles, and norms around parenthood. It may widen who can form families and pursue work or public roles, while also inviting marketization, coercion, and new conflicts over what counts as natural or ethically legitimate kinship. The societal effect on belonging and identity is significant, so 5.

**Weak signals (9):**

- (+) [Sense of belonging] → people previously excluded from parenthood form families through new gestational options (family access widens)
- (+) [Meaningful work] → pregnancy-related career interruption patterns change measurably (life planning gains flexibility)
- (+) [Serving others] → high-risk pregnancies or neonatal situations move into more controlled, instrumented environments (care burden redistributes)
- (+) [Peer appreciation] → workplaces and public services update parenthood norms beyond maternal-body assumptions (family roles diversify)
- (+) [Participation in a grand mission] → reproductive justice or infertility communities frame the technology as a public mission (mission identity broadens)
- (+) [Community building] → new support, ethics, and parenthood communities form around gestational technologies (kinship norms are renegotiated)
- (-) [Pursuit of achieved status] → premium embryo selection or gestational services become prestige consumption (reproduction stratifies)
- (-) [Societal pressure and conformity] → employers or states imply that technologically managed gestation is the safer or preferred norm (choice narrows)
- (-) [Equality/governance] → custody, embryo status, and parental-rights disputes expose legal mismatch (belonging becomes contested)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

This is a major alternative route to the same social shift as global broadband: persistent connectivity, shared awareness, and global participation from anywhere. It can pull remote populations into creator, learning, and mission networks while also widening surveillance, information warfare, and dependence on a few orbital operators. Because it can reshape weekly participation at large scale, but is not the only connectivity path, it fits 10.

**Weak signals (9):**

- (+) [Sense of belonging] → rural and low-income participation rates on major community platforms approach urban levels (access gap closes)
- (+) [Meaningful work] → small-town freelancers, co-ops, or volunteers serve national/global clients routinely (place stops limiting purpose)

- (+) [Participation in a grand mission] → climate, science, or mutual-aid networks recruit persistent remote contributors (missions gain active members)
- (+) [Self-expression] → creator revenues and audiences spread beyond metropolitan hubs (recognition broadens)
- (+) [Local community] → municipalities or associations fund shared connectivity infrastructure as a civic utility (belonging gets a base layer)
- (+) [Serving others] → telecare, mentoring, or peer-support use rises among mobility-limited groups (participation barriers fall)
- (-) [Desire for comfort and stability] → employers normalize evening/weekend responsiveness after access gaps shrink (always-on norms harden)
- (-) [Potential for negative influences] → destructive online communities recruit newly connected populations measurably (belonging misdirected)
- (-) [Ownership/access] → a few operators control identity, traffic, or moderation choke points (gatekeeper power expands)

## ART 10.080 - Space Resource Utilization (SRU)

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is symbolic and spillover-based: frontier capability can feed grand-mission identities and remote-operations practices. Most effects on belonging or meaningful work arrive only through other sectors, while frontier spending can also provoke backlash about local priorities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Participation in a grand mission] → frontier programs recruit schools, citizens, or local suppliers into visible missions (mission identity forms)
  - (+) [Achievements & status] → regions market themselves as part of frontier supply chains or habitats (prestige redirects)
  - (-) [Serving others] → budget debates frame frontier spending against local social needs (purpose conflict surfaces)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

**Score:** 1 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is symbolic and spillover-based: frontier capability can feed grand-mission identities and remote-operations practices. Most effects on belonging or meaningful work arrive only through other sectors, while frontier spending can also provoke backlash about local priorities. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

**Weak signals (3):**

- (+) [Participation in a grand mission] → frontier programs recruit schools, citizens, or local suppliers into visible missions (mission identity forms)
  - (+) [Achievements & status] → regions market themselves as part of frontier supply chains or habitats (prestige redirects)
  - (-) [Serving others] → budget debates frame frontier spending against local social needs (purpose conflict surfaces)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**ART 10.082 - High-Altitude Platforms & Balloons**

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main link is wider access to communication and observation in remote or disrupted areas. That can keep communities connected under stress, but the same systems can make belonging feel watched or externally controlled. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Sense of belonging] → temporary or remote connectivity keeps communities on shared platforms during disruptions (exclusion gap narrows)
  - (+) [Serving others] → civic agencies use the systems for schooling, telecare, or volunteer coordination (participation persists)
  - (-) [Security & dual-use] → public backlash grows when the same systems support persistent surveillance (belonging feels watched)
- Signal density: LOW (linkage weak; additional signals would be speculative).

**11. Digital Platforms & Collective-Intelligence Systems****ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)**

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

These networks can let communities, creators, and distributed teams coordinate value, identity, and rules without a single platform owner. That can support new forms of collective purpose and shared ownership, but also speculation, scams, plutocratic governance, and identity fragmentation. The impact on this GVN is significant because it changes the institutional terms on which people contribute and belong, so 5.

**Weak signals (9):**



- (+) [Meaningful work] → members, creators, or contributors receive auditable participation and payout records (contribution becomes legible)
- (+) [Community building] → groups use shared rules, credentials, or payment rails without a single dominant intermediary (governance capacity grows)
- (+) [Serving others] → mutual-aid, diaspora, or civic groups move value and proof of contribution with low friction (solidarity scales)
- (+) [Peer appreciation] → provenance, certification, or tamper-evident records reduce false claims about work and authorship (recognition becomes more trusted)
- (+) [Participation in a grand mission] → communities coordinate funding, voting, or accountability around collective goals more transparently (missions become governable)
- (+) [Sense of belonging] → members visibly influence platform rules, moderation, or payout formulas (audience becomes constituency)
- (-) [Ownership/access] → wealthier actors, early insiders, or technical elites dominate rule-setting and visibility (voice concentrates)
- (-) [Potential for negative influences] → scams, Sybil attacks, or forged credibility episodes trigger trust collapses (institutions can be gamed)
- (-) [Societal pressure and conformity] → ever-finer reputation and payment traces make social and work identities harder to reset (past locks in future)

## ART 11.084 - Platform Cooperatives & Fair Work

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

This directly targets one of the GVN's core tensions: whether digitally mediated work gives people purpose and belonging, or reduces them to externally ranked piecework. Co-owned platforms can make contribution more legible, locally accountable, and tied to community benefit, while failure modes include clique capture and slower scaling. Because it can substantially rewrite how meaningful work is organized, it fits 10.

**Weak signals (9):**

- (+) [Meaningful work] → members, creators, or contributors receive auditable participation and payout records (contribution becomes legible)
- (+) [Community building] → groups use shared rules, credentials, or payment rails without a single dominant intermediary (governance capacity grows)
- (+) [Serving others] → mutual-aid, diaspora, or civic groups move value and proof of contribution with low friction (solidarity scales)
- (+) [Peer appreciation] → provenance, certification, or tamper-evident records reduce false claims about work and authorship (recognition becomes more trusted)
- (+) [Participation in a grand mission] → communities coordinate funding, voting, or accountability around collective goals more transparently (missions become governable)

- (+) [Sense of belonging] → members visibly influence platform rules, moderation, or payout formulas (audience becomes constituency)
- (-) [Ownership/access] → wealthier actors, early insiders, or technical elites dominate rule-setting and visibility (voice concentrates)
- (-) [Potential for negative influences] → scams, Sybil attacks, or forged credibility episodes trigger trust collapses (institutions can be gamed)
- (-) [Societal pressure and conformity] → ever-finer reputation and payment traces make social and work identities harder to reset (past locks in future)

## ART 11.085 - Open Data Sharing Marketplaces

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is lower coordination friction between people or organizations that do not fully trust each other. That can widen participation in collective decisions, data use, or foresight, but it can also privilege actors with more data, liquidity, or interpretive power. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → cross-organization challenges or forecast systems open to smaller actors (coordination broadens)
  - (+) [Community building] → shared dashboards or marketplaces make contributions visible across institutions (cooperation becomes legible)
  - (-) [Ownership/access] → well-capitalized actors dominate data liquidity, attention, or rule interpretation (voice concentrates)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 - Secure & Resilient Social Platforms

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

If people cannot trust that their communities, identities, and conversations will survive manipulation, shutdowns, or surveillance, digital belonging remains brittle. Secure, portable, resilient platforms can stabilize mission-driven and intimate communities alike, but they can also shelter harmful enclaves and complicate moderation. Because they shape the viability of online belonging at scale, they fit 10.

**Weak signals (9):**

- (+) [Sense of belonging] → users move identities, contacts, and community history across platforms without major loss (belonging becomes portable)
- (+) [Self-expression] → creators carry audiences, assets, or moderation settings between services (recognition stops being platform-locked)

- (+) [Meaningful work] → workers and volunteers keep verified reputation when leaving an employer or platform (exit becomes less costly)
- (+) [Community building] → groups choose hosting and governance models without abandoning members (infrastructure becomes contestable)
- (+) [Participation in a grand mission] → cross-platform coalitions organize around shared causes without rebuilding their social graph each time (collective action becomes durable)
- (+) [Serving others] → privacy and safety settings travel with the person across tools and worlds (vulnerable users stay engaged)
- (-) [Potential for negative influences] → harmful actors port harassment, manipulation, or extremist identity across services more easily (abuse becomes portable)
- (-) [Ownership/access] → identity-wallet or protocol providers become new bottlenecks despite formal openness (control recentralizes differently)
- (-) [Peer appreciation/status] → cross-platform reputation scores harden social ranking and exclusion (status becomes harder to escape)

## ART 11.087 - Collective Open Innovation Networks

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

These networks turn participation in science, invention, and problem-solving into a more accessible social field, not just an elite institutional career. They can give many more people visible roles in grand missions and collaborative achievement, but they can also intensify reputation competition and extract unpaid creativity. The potential to reorganize meaningful contribution across work and civic life justifies 10.

**Weak signals (9):**

- (+) [Self-realization] → people stack portable credentials or project contributions into new career paths without gatekeeper institutions (growth becomes more self-directed)
- (+) [Participation in a grand mission] → open challenges recruit citizens, freelancers, and students into solving public problems (missions widen participation)
- (+) [Peer appreciation] → reputations increasingly reflect demonstrated skill or successful contributions rather than pedigree alone (status criteria shift)
- (+) [Meaningful work] → employers, co-ops, or civic networks hire from live skills and challenge records (entry barriers fall)
- (+) [Community building] → learning and innovation communities persist around shared projects, not just courses or firms (belonging forms around doing)
- (+) [Serving others] → local institutions use networked learning to retrain workers into community-serving roles faster (transition capacity grows)
- (-) [Pursuit of achieved status] → leaderboards, constant assessment, or challenge rankings intensify performative achievement (growth turns metric-heavy)

- (-) [Ownership/access] → dominant platforms control the credential graph, challenge visibility, or benchmark definitions (gatekeepers reappear)
- (-) [Fear of losing stability] → incumbents dispute quality, fairness, or labor impacts of alternative credential pathways (transition legitimacy is fought)

## ART 11.088 - Scalable Decentralized Governance

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

When communities can deliberate, vote, budget, and audit rules at scale, belonging becomes more than audience membership. This can deepen agency in online and local groups, but it can also exhaust participants, reward procedural gaming, and shift power to those who master governance interfaces. The institutional effect is significant but not by itself a linchpin, so 5.

**Weak signals (9):**

- (+) [Meaningful work] → members, creators, or contributors receive auditable participation and payout records (contribution becomes legible)
- (+) [Community building] → groups use shared rules, credentials, or payment rails without a single dominant intermediary (governance capacity grows)
- (+) [Serving others] → mutual-aid, diaspora, or civic groups move value and proof of contribution with low friction (solidarity scales)
- (+) [Peer appreciation] → provenance, certification, or tamper-evident records reduce false claims about work and authorship (recognition becomes more trusted)
- (+) [Participation in a grand mission] → communities coordinate funding, voting, or accountability around collective goals more transparently (missions become governable)
- (+) [Sense of belonging] → members visibly influence platform rules, moderation, or payout formulas (audience becomes constituency)
- (-) [Ownership/access] → wealthier actors, early insiders, or technical elites dominate rule-setting and visibility (voice concentrates)
- (-) [Potential for negative influences] → scams, Sybil attacks, or forged credibility episodes trigger trust collapses (institutions can be gamed)
- (-) [Societal pressure and conformity] → ever-finer reputation and payment traces make social and work identities harder to reset (past locks in future)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

This technology rewires how people gain status, competence, and access to meaningful roles by making learning continuous, portable, and less tied to incumbent gatekeepers. It can widen self-realization and community entry, while also hardening metricized achievement cultures and new credential hierarchies. Because it can change weekly life for large populations and reshape the meaning of education and work, it fits 10.

**Weak signals (9):**

- (+) [Self-realization] → people stack portable credentials or project contributions into new career paths without gatekeeper institutions (growth becomes more self-directed)
- (+) [Participation in a grand mission] → open challenges recruit citizens, freelancers, and students into solving public problems (missions widen participation)
- (+) [Peer appreciation] → reputations increasingly reflect demonstrated skill or successful contributions rather than pedigree alone (status criteria shift)
- (+) [Meaningful work] → employers, co-ops, or civic networks hire from live skills and challenge records (entry barriers fall)
- (+) [Community building] → learning and innovation communities persist around shared projects, not just courses or firms (belonging forms around doing)
- (+) [Serving others] → local institutions use networked learning to retrain workers into community-serving roles faster (transition capacity grows)
- (-) [Pursuit of achieved status] → leaderboards, constant assessment, or challenge rankings intensify performative achievement (growth turns metric-heavy)
- (-) [Ownership/access] → dominant platforms control the credential graph, challenge visibility, or benchmark definitions (gatekeepers reappear)
- (-) [Fear of losing stability] → incumbents dispute quality, fairness, or labor impacts of alternative credential pathways (transition legitimacy is fought)

**ART 11.090 - Prediction-Market Forecasting Platforms**

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is lower coordination friction between people or organizations that do not fully trust each other. That can widen participation in collective decisions, data use, or foresight, but it can also privilege actors with more data, liquidity, or interpretive power. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → cross-organization challenges or forecast systems open to smaller actors (coordination broadens)
  - (+) [Community building] → shared dashboards or marketplaces make contributions visible across institutions (cooperation becomes legible)
  - (-) [Ownership/access] → well-capitalized actors dominate data liquidity, attention, or rule interpretation (voice concentrates)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is to make complex systems more legible, comparable, and interoperable across organizations. That can lower entry barriers and improve trust, but it can also shift power to certifiers, standard-setters, and large integrators. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Meaningful work] → smaller organizations join interoperable ecosystems without bespoke integrations (entry barriers fall)
  - (+) [Serving others] → certification, provenance, or asset data becomes machine-readable to public buyers and communities (trust improves)
  - (-) [Ownership/access] → a few standard-setters or certifiers gain new gatekeeping power (control recentralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 12.092 - Interoperable Digital Twin Ecosystems

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is to make complex systems more legible, comparable, and interoperable across organizations. That can lower entry barriers and improve trust, but it can also shift power to certifiers, standard-setters, and large integrators. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Meaningful work] → smaller organizations join interoperable ecosystems without bespoke integrations (entry barriers fall)
  - (+) [Serving others] → certification, provenance, or asset data becomes machine-readable to public buyers and communities (trust improves)
  - (-) [Ownership/access] → a few standard-setters or certifiers gain new gatekeeping power (control recentralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 12.093 - Global Supply Chain Traceability Networks

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is to make complex systems more legible, comparable, and interoperable across organizations. That can lower entry barriers and improve trust, but it can also shift power to

certifiers, standard-setters, and large integrators. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Meaningful work] → smaller organizations join interoperable ecosystems without bespoke integrations (entry barriers fall)
  - (+) [Serving others] → certification, provenance, or asset data becomes machine-readable to public buyers and communities (trust improves)
  - (-) [Ownership/access] → a few standard-setters or certifiers gain new gatekeeping power (control recentralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.094 - Personal Data Portability & Trust Frameworks

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

When identity, history, and preference data can move with the person, people are less trapped inside single employers or platforms for recognition and belonging. That strengthens autonomy and cross-community participation, but it also creates new markets for profiling and new burdens of self-management. Because it changes who controls the raw material of digital meaning systems, it fits 10.

**Weak signals (9):**

- (+) [Sense of belonging] → users move identities, contacts, and community history across platforms without major loss (belonging becomes portable)
- (+) [Self-expression] → creators carry audiences, assets, or moderation settings between services (recognition stops being platform-locked)
- (+) [Meaningful work] → workers and volunteers keep verified reputation when leaving an employer or platform (exit becomes less costly)
- (+) [Community building] → groups choose hosting and governance models without abandoning members (infrastructure becomes contestable)
- (+) [Participation in a grand mission] → cross-platform coalitions organize around shared causes without rebuilding their social graph each time (collective action becomes durable)
- (+) [Serving others] → privacy and safety settings travel with the person across tools and worlds (vulnerable users stay engaged)
- (-) [Potential for negative influences] → harmful actors port harassment, manipulation, or extremist identity across services more easily (abuse becomes portable)
- (-) [Ownership/access] → identity-wallet or protocol providers become new bottlenecks despite formal openness (control recentralizes differently)
- (-) [Peer appreciation/status] → cross-platform reputation scores harden social ranking and exclusion (status becomes harder to escape)



## ART 12.095 - Interoperable Digital Currency Payment Networks

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

Frictionless movement of value across platforms and jurisdictions matters for creator livelihoods, mutual aid, diasporic communities, and cross-border mission work. It can help people turn contribution into sustainable income, but it can also accelerate extraction, fraud, and platformized financial dependency. The effect on meaningful participation is significant though still mostly institutional, so 5.

**Weak signals (9):**

- (+) [Meaningful work] → members, creators, or contributors receive auditable participation and payout records (contribution becomes legible)
- (+) [Community building] → groups use shared rules, credentials, or payment rails without a single dominant intermediary (governance capacity grows)
- (+) [Serving others] → mutual-aid, diaspora, or civic groups move value and proof of contribution with low friction (solidarity scales)
- (+) [Peer appreciation] → provenance, certification, or tamper-evident records reduce false claims about work and authorship (recognition becomes more trusted)
- (+) [Participation in a grand mission] → communities coordinate funding, voting, or accountability around collective goals more transparently (missions become governable)
- (+) [Sense of belonging] → members visibly influence platform rules, moderation, or payout formulas (audience becomes constituency)
- (-) [Ownership/access] → wealthier actors, early insiders, or technical elites dominate rule-setting and visibility (voice concentrates)
- (-) [Potential for negative influences] → scams, Sybil attacks, or forged credibility episodes trigger trust collapses (institutions can be gamed)
- (-) [Societal pressure and conformity] → ever-finer reputation and payment traces make social and work identities harder to reset (past locks in future)

## ART 12.096 - Machine-Readable Regulation (Rules as Code)

**Score:** 3 (Impact in GVN 19)

**Justification (3–5 sentences):**

The main effect is lower coordination friction between people or organizations that do not fully trust each other. That can widen participation in collective decisions, data use, or foresight, but it can also privilege actors with more data, liquidity, or interpretive power. That is enough to affect a material value related to meaning, but usually not enough to change the operating model by itself, so 3.

**Weak signals (3):**

- (+) [Participation in a grand mission] → cross-organization challenges or forecast systems open to smaller actors (coordination broadens)

- (+) [Community building] → shared dashboards or marketplaces make contributions visible across institutions (cooperation becomes legible)
- (-) [Ownership/access] → well-capitalized actors dominate data liquidity, attention, or rule interpretation (voice concentrates)  
Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.097 - Open Metaverse Interoperability Protocols

**Score:** 10 (Impact in GVN 19)

**Justification (3–5 sentences):**

If immersive spaces become major sites of work, community, and identity, interoperability determines whether people can carry relationships, reputations, and creations across worlds. It supports durable belonging and lowers lock-in, while also enabling portable harassment and new status economies. Because it governs whether immersive meaning systems remain open or feudal, it fits 10.

**Weak signals (9):**

- (+) [Sense of belonging] → users move identities, contacts, and community history across platforms without major loss (belonging becomes portable)
- (+) [Self-expression] → creators carry audiences, assets, or moderation settings between services (recognition stops being platform-locked)
- (+) [Meaningful work] → workers and volunteers keep verified reputation when leaving an employer or platform (exit becomes less costly)
- (+) [Community building] → groups choose hosting and governance models without abandoning members (infrastructure becomes contestable)
- (+) [Participation in a grand mission] → cross-platform coalitions organize around shared causes without rebuilding their social graph each time (collective action becomes durable)
- (+) [Serving others] → privacy and safety settings travel with the person across tools and worlds (vulnerable users stay engaged)
- (-) [Potential for negative influences] → harmful actors port harassment, manipulation, or extremist identity across services more easily (abuse becomes portable)
- (-) [Ownership/access] → identity-wallet or protocol providers become new bottlenecks despite formal openness (control recentralizes differently)
- (-) [Peer appreciation/status] → cross-platform reputation scores harden social ranking and exclusion (status becomes harder to escape)

## ART 12.098 - Content Authenticity Infrastructure

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

In digital meaning systems, recognition only matters if people can trust provenance of achievements, messages, and evidence. Authenticity infrastructure can protect creators, communities, and civic action from deepfakes and false attribution, though it can also privilege

credentialed actors and normalize surveillance of creation tools. That makes it a significant but supporting institutional technology, so 5.

**Weak signals (9):**

- (+) [Peer appreciation] → major platforms and employers begin privileging provenance-backed portfolios and media (recognition becomes verifiable)
- (+) [Sense of belonging] → communities rely on provenance checks to trust shared memories, events, and testimonies (group reality stabilizes)
- (+) [Meaningful work] → creators, journalists, and civic groups use attached provenance to defend authorship and labor claims (credit sticks to contributors)
- (+) [Participation in a grand mission] → activist and public-interest campaigns publish verified media chains as default practice (coordination trusts evidence)
- (+) [Community building] → browsers, messengers, or social tools show provenance summaries in ordinary user flows (verification becomes habitual)
- (+) [Serving others] → schools and community organizations teach provenance literacy alongside media literacy (trust becomes teachable)
- (-) [Ownership/access] → uncertified creators or informal communities lose visibility because they lack credentialed tools (credibility recentralizes)
- (-) [Potential for negative influences] → manipulated media without provenance still spreads faster than verified content in some networks (authenticity gap persists)
- (-) [Societal pressure and conformity] → always-on provenance expectations reduce anonymous whistleblowing or vulnerable self-expression (safety can shrink)

## ART 12.099 - Privacy-Preserving Collaboration Protocols

**Score:** 5 (Impact in GVN 19)

**Justification (3–5 sentences):**

These protocols let groups act on shared problems without surrendering all their sensitive data, which matters for community care, local coordination, and mission-driven collaboration. They can widen who participates in high-trust projects, but they also favor well-resourced actors able to set the rules and compute budgets. The GVN effect is significant via governance and participation, so 5.

**Weak signals (9):**

- (+) [Sense of belonging] → users actively choose on-device, federated, or policy-controlled data modes (trust becomes operational)
- (+) [Serving others] → hospitals, municipalities, and co-ops share models or analytics without centralizing raw records (collaboration unlocks sensitive domains)
- (+) [Meaningful work] → small organizations join shared learning networks while retaining local data control (capability diffuses without surrender)

- (+) [Participation in a grand mission] → climate, care, or research coalitions publish privacy-preserving collaboration charters and actually use them (mission networks scale safely)
- (+) [Community building] → member-governed data trusts or cooperative data rooms appear (collective control grows)
- (+) [Peer appreciation] → platforms disclose what personal signals stay local versus what is shared (recognition feels less extractive)
- (-) [Ownership/access] → dominant vendors turn “privacy-preserving” stacks into closed ecosystems (trust becomes branded dependency)
- (-) [Potential for negative influences] → regulators or journalists show that supposedly safe updates still leak group or personal traits (privacy theater exposed)
- (-) [Fear of change] → organizations delay collaboration because secure-compute overhead is too high or governance too complex (good intent stalls)

## **ART 12.100 — Manufacturing-specific standards, conformance testing & certification infrastructure**

**Score:** 1 (Impact in GVN 19)

### **Justification (3–5 sentences):**

The main effect is to make complex systems more legible, comparable, and interoperable across organizations. That can lower entry barriers and improve trust, but it can also shift power to certifiers, standard-setters, and large integrators. That makes it worth monitoring for this GVN, yet below the threshold for a material society-wide shift, so 1.

### **Weak signals (3):**

- (+) [Meaningful work] → smaller organizations join interoperable ecosystems without bespoke integrations (entry barriers fall)
  - (+) [Serving others] → certification, provenance, or asset data becomes machine-readable to public buyers and communities (trust improves)
  - (-) [Ownership/access] → a few standard-setters or certifiers gain new gatekeeping power (control recentralizes)
- Signal density: LOW (linkage weak; additional signals would be speculative).

## **GVN 20: Power Structures ART Impact**

### **1. Sensing, Measurement & Connectivity**

#### **ART 01.001 - Global Broadband Connectivity**

**Score:** 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, universal high-quality connectivity lets organizations, public bodies, unions, cooperatives, and citizen groups deliberate and coordinate continuously across distance instead of relying on geography-bound, office-bound decision processes. Second-order, it weakens the default advantage of geographically anchored authorities and large incumbents, while strengthening whoever controls the connectivity, cloud, and identity stack. Third-order, once remote participation, platform cooperatives, and sector-specific digital administrations become normal, expectations of openness, responsiveness, and comparability change in everyday civic and organizational life. That is a transformative change in how this GVN operates, affecting hundreds of thousands of people weekly.

Weak signals (9):

- (+) [Equality / geography-based authority] → participation in remote municipal, workplace, and member votes rises outside core cities (distance barrier weakens)
- (+) [Platform cooperatives] → member-owned service platforms operate nationally without regional offices (network governance scales)
- (+) [Openness] → public hearings default to livestreamed, archived, multilingual formats (decision visibility expands)
- (+) [Choice and competition] → users begin switching between digital service providers across administrative boundaries (interchangeability becomes real)
- (+) [Productivity] → travel-heavy expert review and board routines are replaced by remote workflows (coordination costs fall)
- (-) [Structural power / elite groups] → a few broadband operators bundle access, identity, cloud, and moderation services (new gatekeepers emerge)
- (-) [Equality] → participation statistics show persistent quality gaps by income or rurality (new exclusion layer)
- (-) [Security] → network outages or jamming disrupt formal decision deadlines (connectivity becomes a choke point)
- (-) [Control mechanisms] → emergency powers increasingly include traffic prioritization or shutdown clauses (infrastructure control politicizes)

## ART 01.002 - Ultra-Low Latency Networks

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, bounded-latency networks make remote supervision, shared virtual workspaces, and time-sensitive joint decisions feel reliable enough for more than basic communication. Second-order, they advantage actors that can afford edge infrastructure and privileged network quality, which can improve productivity while increasing dependence on telecom and cloud intermediaries. Third-order, they normalize expectations of immediate response and richer remote presence, materially shifting a related value of cooperativeness without by themselves remaking governance. That fits the 3-anchor better than 5.

Weak signals (6):

- (+) [Productivity] → public and large-firm control rooms move routine coordination into real-time remote environments (delay costs shrink)
- (+) [Cooperativeness] → arbitration, crisis response, and negotiation platforms start offering latency guarantees (shared timing matters)
- (+) [Subject-based administration] → sector-specific services procure local edge nodes for time-critical workflows (coordination decentralizes)
- (-) [Structural power / vendors] → premium network classes are sold mainly to large organizations (capability skews upward)
- (-) [Equality] → smaller municipalities or associations report poorer performance in high-bandwidth decision tools (access gap persists)
- (-) [Security] → brief latency spikes or edge outages become reportable causes of decision failure (timing becomes infrastructure risk)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.003 - Edge AI for Sensor Data

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, edge AI can move judgment closer to the source of events, allowing organizations and administrations to automate anomaly detection, triage, and local rule enforcement without waiting for centralized experts. Second-order, this changes bargaining power between frontline staff, managers, vendors, regulators, and affected communities because thresholds, alerts, and exceptions become software-defined. Third-order, once edge summaries rather than human narratives become the default input to oversight, appeals, audits, and accountability routines adapt around machine interpretation. That is large enough to plausibly land in the €100M–1B / 50–500M person-hour range across a 5.5M society.

Weak signals (8):

- (+) [Productivity] → public assets and large organizations cut routine site visits after deploying local anomaly detection (inspection workload drops)
- (+) [Decision quality] → dashboards begin showing machine-generated incident summaries instead of raw sensor streams (judgment moves outward)
- (+) [Privacy / openness] → tenders require on-device filtering before any central upload (data minimization gains legitimacy)
- (+) [Subsidiarity] → smaller units get local decision authority because edge systems handle first-pass assessment (local autonomy rises)
- (-) [Equality] → appeal rates climb where edge alerts disproportionately hit certain groups or sites (threshold bias matters)
- (-) [Structural power / vendors] → model updates and threshold tuning remain controlled by a few suppliers (governance externalizes)
- (-) [Cooperativeness] → workers and residents contest machine-triggered sanctions or escalations (legitimacy frays)
- (-) [Security] → spoofing or adversarial examples cause wrongful flags in operational environments (machine trust weakens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.004 - Quantum & High-Precision Sensing

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, more precise measurement can improve evidence quality in specific oversight and infrastructure contexts. Second-order, the main effect on this GVN comes through who controls unusually trusted measurement systems and whether those measurements become authoritative in disputes. Third-order feedbacks are limited unless these sensors become embedded in core governance workflows rather than specialist niches. That makes the impact concrete but limited.

Weak signals (4):

- (+) [Decision quality] → regulators begin accepting ultra-high-precision sensor evidence in complex infrastructure cases (evidence threshold rises)
- (+) [Productivity] → rare high-cost inspections are replaced by continuous precision monitoring in critical assets (expert bottleneck eases)
- (-) [Structural power / expert agencies] → a small number of national labs or vendors become default arbiters of “true” measurements (authority centralizes)
- (-) [Equality] → smaller actors challenge inability to access equivalent measurement capacity in disputes (evidence asymmetry grows)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.005 - Micro/Nano Sensor Networks

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, dense cheap sensor networks can make organizations, workplaces, and public environments continuously legible, which directly changes how decisions are made, supervised, and contested. Second-order, they redistribute power toward whoever controls deployment, access rights, analytics, and interpretation, while also enabling community-run counter-monitoring and transparency. Third-order, pervasive fine-grained measurement can harden continuous scoring and compliance cultures or, alternatively, support far more participatory evidence-sharing. That scale of monitoring and counter-monitoring is significant for this GVN.

Weak signals (9):

- (+) [Productivity] → facility, transport, and public-space management shifts from periodic checks to always-on sensing (oversight becomes continuous)
- (+) [Openness] → sensor-fed dashboards are shared with staff, tenants, or members rather than only managers (information asymmetry narrows)
- (+) [Comparativeness] → organizations benchmark branches or administrations using live condition data (performance becomes comparable)
- (+) [Choice and competition] → independent community or union sensing networks appear alongside official systems (counter-evidence emerges)



- (-) [Structural power / management elites] → access to full-resolution sensor feeds stays restricted to central administrators (control concentrates)
- (-) [Equality] → surveillance complaints cluster in low-power workplaces, schools, or neighborhoods (monitoring lands unevenly)
- (-) [Cooperativeness] → routine decisions increasingly rely on machine visibility rather than negotiated testimony (trust shifts to sensors)
- (-) [Security] → sensor spoofing or tampering becomes a recognized governance risk (data integrity matters)
- (-) [Normativity] → insurers, auditors, or regulators start requiring dense sensing as a condition of legitimacy (non-instrumented actors lose standing)

## ART 01.006 - Privacy-Preserving Pervasive Sensing

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this ART resolves one of the main blockers to data-rich administration and organizational coordination: the conflict between continuous sensing and social legitimacy. Second-order, it can widen participation in automated oversight, decentralized administration, and shared evidence systems without forcing raw-data centralization, but it can also produce a false sense of safety if privacy claims are uncheckable. Third-order, once trusted local sensing becomes acceptable, whole governance models based on crowdsourced evidence, AI-assisted rule implementation, and stakeholder-specific service layers become much more deployable. That is transformative for this GVN because it changes both the feasible scope and the legitimacy of digital decision-making.

Weak signals (9):

- (+) [Openness / privacy] → procurement requires verifiable on-device anonymization or aggregation by default (trust barrier falls)
- (+) [Equality] → unions, tenant groups, or citizen panels approve sensing pilots that they previously opposed (acceptability improves)
- (+) [Subject-based administration] → cross-organization services share protected outputs without pooling raw personal data (coordination expands)
- (+) [Choice and competition] → privacy guarantees become a differentiator between digital administrations or platforms (switching becomes safer)
- (+) [Control mechanisms] → compliance checks use privacy-preserving summaries instead of full recordings (automation becomes more legitimate)
- (+) [Comparativeness] → independent auditors begin certifying privacy budgets, secure enclaves, or local-processing claims (verification institutionalizes)
- (-) [Structural power / vendors] → only a few vendors can credibly implement and certify the privacy stack (trust centralizes)
- (-) [Security] → highly publicized re-identification or leakage incidents trigger backlash against “privacy-preserving” claims (legitimacy can snap)
- (-) [Equality] → higher-trust deployments arrive first in affluent sectors while lower-power groups still face raw surveillance (protection stratifies)

## ART 01.007 - Quantum-Resilient and Secure Communication Networks

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, secure long-lived communications are an enabling layer for digital voting, inter-organizational governance, remote administration, and automated control in contested environments. Second-order, they lower the fear of interception and manipulation that otherwise favors centralized, closed, or face-to-face decision systems, but they also raise the importance of certified vendors and state-grade security infrastructures. Third-order, once communication integrity becomes more reliable, smaller actors can participate in high-stakes coordination that previously required proximity or institutional backing. That is a significant enabler of the challenger regime, though not a sole linchpin.

Weak signals (8):

- (+) [Openness / security] → public networks and critical organizational systems begin post-quantum migration programs (long-lived trust is prioritized)
- (+) [Choice and competition] → smaller administrations join shared secure coordination networks previously limited to large incumbents (entry barrier falls)
- (+) [Cooperativeness] → distributed governance tools advertise end-to-end integrity guarantees for voting and deliberation (high-stakes use widens)
- (+) [Productivity] → cross-border or cross-sector collaboration speeds up where security review once delayed data exchange (coordination friction falls)
- (-) [Structural power / certified vendors] → a narrow set of approved suppliers dominate secure network upgrades (dependency rises)
- (-) [Normativity] → compliance burdens around certified hardware make informal or community-run systems harder to sustain (participation narrows)
- (-) [Security] → downgrade attacks or migration failures become reportable incidents in governance systems (transition risk becomes visible)
- (-) [Equality] → resource-poor organizations lag in secure upgrades and lose eligibility for sensitive collaboration (security gap hardens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 01.008 - Integrated Sensing and Communication (ISAC)

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, ISAC can turn communication networks themselves into ambient sensing systems, which improves situational awareness for coordination-heavy organizations and administrations. Second-order, it creates new power around whoever controls access points, buildings, and network policies, and it raises acute privacy questions because observation becomes bundled with connectivity. Third-order, when every dense network also senses, organizations may drift toward more continuous monitoring and faster intervention expectations. That is material, but still more supportive than foundational.

Weak signals (6):

- (+) [Productivity] → telecom or campus networks add radar-like monitoring functions for traffic, occupancy, or safety (communications become oversight tools)
- (+) [Control mechanisms] → municipal or organizational control rooms begin using network-derived movement data in routine decisions (ambient evidence expands)
- (+) [Openness] → building owners negotiate shared access to ISAC-derived situational data (new information layer forms)
- (-) [Privacy] → regulatory hearings treat communications coverage plans as de facto sensing deployments (bundling becomes politically visible)
- (-) [Structural power / infrastructure owners] → landlord or telecom control over indoor signal surfaces becomes leverage in service negotiations (coverage equals power)
- (-) [Security] → spoofing, covert tracking, or covert sensing incidents trigger new policy boundaries (dual-use risk surfaces)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 2. Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 - Compute-in-Memory & Neuromorphic Chips

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, these chips lower the cost and energy burden of embedding AI into local devices, which materially expands where automated sensing, assistance, and decision support can operate. Second-order, they reduce dependence on centralized data centers for some governance functions, but the benefit is filtered through whoever controls chip supply, toolchains, and software standards. Third-order, more capable local devices can normalize software-mediated oversight and assistance in places that currently lack the bandwidth or budget for constant cloud support. That is a material but indirect effect for this GVN.

Weak signals (5):

- (+) [Subsidiarity] → public-service and workplace devices begin running richer local AI without cloud dependence (local autonomy increases)
- (+) [Privacy] → procurement shifts toward on-device inference for sensitive coordination tasks (central data pooling shrinks)
- (+) [Productivity] → low-power always-on assistants appear in frontline organizational workflows (expert bottlenecks ease)
- (-) [Structural power / chip ecosystems] → a few hardware-software stacks dominate approved deployments (dependency deepens)

- (-) [Equality] → smaller actors adopt older, less auditable chips and fall behind in local automation quality (capability gap widens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 02.010 - Novel transistor technologies and materials beyond silicon CMOS**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better general-purpose computing efficiency strengthens many digital systems used in administration and coordination, but it does not by itself change how power is organized. Second-order, the main GVN effect comes through semiconductor supply concentration, cost curves, and who can deploy more computation close to users or sensors. Third-order governance effects are diffuse unless these devices specifically unlock new local autonomy or pervasive control architectures. That keeps it at 1.

Weak signals (4):

- (+) [Productivity] → edge and mobile governance tools become substantially cheaper or more capable per watt (deployment becomes easier)
- (+) [Privacy] → more sensitive workloads move onto personal or local devices rather than shared clouds (control shifts outward)
- (-) [Structural power / chip supply] → advanced-node access remains concentrated in a few firms or jurisdictions (dependency persists)
- (-) [Equality] → organizations with privileged hardware access pull ahead in AI-enabled administration (compute inequality matters)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 02.011 - Quantum Computing Platforms**

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, quantum platforms could materially improve a narrow set of optimization, simulation, and cryptographic tasks relevant to policy design, scheduling, and large-scale coordination. Second-order, access is likely to be concentrated among states, large firms, and top-tier cloud providers, which may reinforce elite analytical advantage even while improving some public decisions. Third-order, if quantum-enhanced optimization becomes normal in budgeting, logistics, or strategic planning, smaller actors may increasingly depend on a few external compute intermediaries. That is material enough for a 3, but not a core governance transformation.

Weak signals (5):

- (+) [Decision quality] → public or major private bodies pilot quantum optimization for allocation and scheduling problems (advanced planning enters governance)
- (+) [Comparativeness] → policy or organizational simulations start advertising quantum-assisted scenario search (decision methods differentiate)
- (-) [Structural power / elite groups] → access is concentrated in a handful of state or cloud providers (analytical power centralizes)
- (-) [Security] → cryptography migration accelerates because strategic actors treat quantum capability as credible (trust assumptions shift)
- (-) [Choice and competition] → smaller actors consume optimization as a managed service rather than owning it (dependency grows)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.012 - Photonic and Optical Computing

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, optical computing mostly changes the cost and scale of data-heavy computation rather than the architecture of decision-making. Second-order, it may strengthen whoever operates large AI and simulation platforms, which matters for vendor concentration but not directly for this GVN's core bottleneck. Third-order effects remain indirect unless cheaper large-scale computation translates into a visibly new governance model. That keeps it at 1.

Weak signals (4):

- (+) [Productivity] → large-scale simulation and AI services become cheaper for public and organizational users (compute friction eases)
- (+) [Decision quality] → digital policy or organizational twins can run at much higher fidelity or frequency (scenario testing grows)
- (-) [Structural power / cloud platforms] → hyperscalers consolidate advantage through proprietary optical stacks (platform power thickens)
- (-) [Equality] → smaller actors still access capability only through subscription platforms (ownership gap remains)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.013 - Next-Gen Memory & Storage

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better storage and memory can make large audit trails, simulations, and historical data retention easier for organizations and administrations. Second-order, the power effect comes mainly through who can cheaply preserve, query, and govern vast records. Third-order changes are limited unless persistent, low-cost storage becomes a decisive basis for new accountability or surveillance institutions. That is worth watching but not material enough for 3.

Weak signals (4):

- (+) [Openness] → organizations retain much longer machine-readable decision histories at low cost (auditability deepens)
- (+) [Productivity] → loading, querying, and comparing large administrative datasets becomes routine (analysis speeds up)
- (-) [Privacy] → retention periods quietly expand because storage costs stop constraining collection (surveillance memory lengthens)
- (-) [Structural power / data platforms] → archival and query capability remains bundled with a few cloud vendors (data dependence persists)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 02.014 - Molecular Computing

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, molecular computing has no clear direct role in organizing joint decision-making within organizations or administrations. Second-order effects on ownership, bargaining power, or accountability are too indirect for this GVN unless the technology becomes embedded in mainstream governance or sensing platforms. Third-order feedback loops are therefore weak at present. For this GVN it is mainly a watchpoint.

Weak signals (4):

- (+) [Decision infrastructures] → molecular computing appears inside routine public or organizational analytics tools (linkage would strengthen)
- (+) [Control mechanisms] → chemical or biological environments begin hosting automated rule-execution layers (governance coupling emerges)
- (-) [Structural power / specialist labs] → capability remains confined to specialist biocomputing environments (linkage stays weak)
- (-) [Regulation] → no meaningful policy or procurement frameworks connect it to administrative use (relevance remains distant)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 3. Artificial Intelligence & Learning Systems

### ART 03.015 - Causal Learning & Reasoning

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, causal learning directly improves the quality of joint decisions by helping organizations and administrations compare interventions, attribute outcomes, and test trade-offs rather than merely extrapolating patterns. Second-order, it can democratize expertise if smaller actors gain access to policy-quality causal tools, but it can also centralize power in whichever vendors or expert bodies define the causal model and its assumptions. Third-order, once “show the causal pathway” becomes normal in budgeting, regulation, strategy, and service design, both accountability and the competitive comparison of alternative administrative models intensify. That is a transformative shift in how this GVN’s goal is pursued.

Weak signals (9):

- (+) [Decision quality] → major decisions begin to include counterfactual or intervention analyses as standard attachments (reasoning deepens)
- (+) [Comparativeness] → administrations openly compare policy pathways using shared causal models (alternatives become legible)
- (+) [Openness] → stakeholders can inspect assumptions behind simulations instead of only outcomes (contestations become informed)
- (+) [Subsidiarity] → smaller municipalities, unions, or cooperatives adopt causal decision-support tools once reserved for central experts (expertise spreads)
- (+) [Productivity] → failed interventions are traced faster to specific levers rather than vague explanations (learning cycles shorten)
- (-) [Structural power / expert vendors] → a few vendors become default providers of policy-grade causal models (assumption power centralizes)
- (-) [Equality] → model assumptions systematically underrepresent weakly measured groups or local contexts (formal bias deepens)
- (-) [Normativity] → “the model says so” begins substituting for political deliberation in contested choices (technicization expands)
- (-) [Security / manipulation] → actors game input variables or causal assumptions to steer formally justified outcomes (model politics hardens)

## ART 03.016 - Federated & Privacy-Preserving Learning

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this ART lets organizations and administrations learn from fragmented sensitive data without pooling it, which is directly aligned with more open, distributed, and interoperable decision systems. Second-order, it reduces the advantage of actors that only win by hoarding raw data, while creating new leverage around orchestration servers, secure hardware, and standards. Third-order, it enables sector-specific administrations, co-ops, and smaller institutions to participate in shared intelligence systems without surrendering control of their records. That is transformative for this GVN because it changes who can join high-quality data-driven governance.

Weak signals (9):

- (+) [Choice and competition] → smaller organizations join shared models without handing over raw data (entry barrier falls)



- (+) [Openness / privacy] → compute-to-data clauses replace raw-data transfer clauses in public tenders (governance architecture shifts)
- (+) [Subsidiarity] → local units keep control of records while still contributing to network-wide decision tools (local authority preserved)
- (+) [Equality] → previously excluded actors gain access to shared forecasting or risk models (knowledge concentration softens)
- (+) [Productivity] → legal and compliance review time for cross-organization analytics drops markedly (coordination friction falls)
- (-) [Structural power / orchestrators] → a small number of model coordinators or secure-hardware providers dominate the stack (new bottleneck appears)
- (-) [Security] → leakage attacks or update inversion incidents become public governance concerns (trust can reverse quickly)
- (-) [Comparativeness] → model performance varies by participant size or data quality, creating uneven benefit capture (network gains distribute unevenly)
- (-) [Normativity] → participation in federated systems becomes a de facto requirement for legitimacy or funding (soft coercion emerges)

## ART 03.017 - Trustworthy AI Systems

Score: 20 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this is a linchpin for the challenger regime because large parts of AI-assisted administration, platform governance, crowdsourced rule implementation, and auditable delegation simply do not scale without predictable, inspectable, contestable AI. Second-order, it reorganizes accountability, procurement, and bargaining power by making controllability, auditability, and fairness part of the core operating model rather than after-the-fact compliance. Third-order, once trustworthy AI becomes the accepted basis for decisions across organizations and administrations, it compounds with data portability, machine-readable regulation, and decentralized governance to create durable path dependence. Because it is foundational rather than merely helpful to the main transformation, 20 is justified.

Weak signals (10):

- (+) [Openness] → public and enterprise AI systems publish audit logs, model cards, and appeal routes by default (black boxes weaken)
- (+) [Equality] → fairness, contestability, and override rights become mandatory procurement criteria (values move into design)
- (+) [Control mechanisms] → regulators accept AI automation only when behavior is provably bounded and traceable (trust becomes conditional)
- (+) [Productivity] → oversight staff shift from manual checking to exception handling and assurance review (supervision reorganizes)
- (+) [Comparativeness] → certified trustworthy-AI providers are benchmarked against opaque alternatives in public decisions (quality becomes visible)
- (+) [Choice and competition] → smaller administrations adopt advanced AI because assurance tooling lowers deployment risk (capability diffuses)
- (-) [Structural power / assurance vendors] → certification and monitoring markets consolidate around a few trusted intermediaries (trust centralizes)

- (-) [Normativity] → formally “aligned” AI is used to freeze contested norms into infrastructure (politics hides in assurance)
- (-) [Equality] → audit-compliant systems still show uneven burdens or false positives across weaker groups (fairness gap persists)
- (-) [Security] → adversarial failures, poisoned training, or silent drift trigger governance moratoria and redesigns (confidence remains fragile)

## ART 03.018 - Automated Machine Learning (AutoML)

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, AutoML materially lowers the skill barrier for building predictive and decision tools, so many more organizations can automate parts of coordination, evaluation, and service design. Second-order, it redistributes power by widening access to model building while also increasing the risk that low-capacity actors deploy poorly governed systems they do not fully understand. Third-order, rapid model proliferation can lock organizations into software-mediated management faster than oversight practices mature. That is a significant effect on the GVN, though not as foundational as trustworthy or causal AI.

Weak signals (8):

- (+) [Choice and competition] → small organizations and municipalities launch their own decision-support models without specialist teams (capability spreads)
- (+) [Productivity] → model development cycles shrink from months to days in routine governance tasks (iteration accelerates)
- (+) [Comparativeness] → organizations test multiple policy or workflow models in parallel before choosing one (experimentation broadens)
- (-) [Decision quality] → rollback rates and model incident reports rise as non-experts deploy weakly specified systems (fragility shows)
- (-) [Structural power / platform vendors] → model factories are bundled into a few cloud or enterprise suites (tool dependence deepens)
- (-) [Equality] → weaker actors rely on defaults that encode external values or assumptions (hidden governance imports)
- (-) [Openness] → documentation quality worsens because model creation becomes faster than internal scrutiny (traceability thins)
- (-) [Control mechanisms] → oversight teams report being unable to review proliferating models at the same pace (governance lags)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 03.019 - Collaborative Multi-Agent AI

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, multi-agent AI maps directly onto distributed decision-making because software agents can represent stakeholders, coordinate tasks, negotiate constraints, and maintain shared situational

awareness across organizations. Second-order, it can either democratize capacity—by giving many actors usable digital representatives—or intensify concentration if dominant platforms own the agent protocols, simulation spaces, and shared memory layers. Third-order, once agent-mediated coordination becomes normal, human institutions may shift from direct execution toward supervising, validating, and contesting agent behavior. That is transformative for how the GVN goal is realized.

Weak signals (9):

- (+) [Cooperativeness] → budgeting, scheduling, and service allocation begin using negotiating software agents rather than linear workflows (coordination architecture shifts)
- (+) [Subsidiarity] → local actors deploy their own agents that can still interoperate in larger governance systems (distributed representation grows)
- (+) [Productivity] → many small routine coordination tasks disappear into agent-to-agent handling (attention bottleneck eases)
- (+) [Openness] → agent protocols, role definitions, and decision traces become standard artifacts in governance systems (machine coordination becomes inspectable)
- (+) [Choice and competition] → marketplaces emerge for agents serving workers, residents, members, or small organizations (representation diversifies)
- (-) [Structural power / orchestration platforms] → a few companies control the shared memory, identity, or coordination layer (meta-governance centralizes)
- (-) [Equality] → resource-rich actors field better-trained agents that outperform weaker participants in negotiations (representation inequality grows)
- (-) [Security] → collusion, spoofing, or cascading agent failures become reportable governance incidents (machine politics emerges)
- (-) [Normativity] → institutions start accepting agent-optimized outcomes as “neutral” despite contested objectives (politics gets hidden)

## ART 03.020 - Quantum-Accelerated AI Systems

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, quantum-accelerated AI could improve a subset of complex search and optimization tasks used in governance or organizational planning. Second-order, the main effect is likely to be concentration of high-end analytical power in a few providers rather than broad restructuring of decision processes. Third-order feedbacks remain limited unless these systems become routine, cheap, and widely embedded in everyday administration. That keeps the linkage concrete but small.

Weak signals (4):

- (+) [Decision quality] → elite institutions advertise quantum-assisted planning or optimization in specific governance domains (advanced analytics enters practice)
- (+) [Structural power / large providers] → access remains concentrated in premium compute services rather than broad tooling (capability centralizes)
- (-) [Equality] → smaller actors cannot match optimization quality used by central authorities or major firms (analytical gap widens)

- (-) [Security] → policy-grade AI procurement begins to require special handling for quantum resources and outputs (complexity increases)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 03.021 - AI-Driven Autonomous Scientific Discovery**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, autonomous discovery primarily changes R&D throughput rather than decision-making architecture inside organizations and administrations. Second-order, it may strengthen the agenda-setting power of institutions that can run policy-relevant research engines or generate evidence faster than rivals. Third-order effects on this GVN stay limited unless autonomous discovery becomes a direct input to routine governance or organizational bargaining. That keeps the score at 1.

Weak signals (4):

- (+) [Decision quality] → policy labs and large organizations begin using autonomous discovery tools to generate intervention options (evidence production accelerates)
- (+) [Productivity] → research-backed regulatory or organizational updates happen more frequently with less human analytic effort (knowledge cycles shorten)
- (-) [Structural power / elite institutions] → evidence generation concentrates in actors with privileged compute and data access (agenda control rises)
- (-) [Openness] → stakeholders struggle to inspect or contest machine-generated evidence pipelines (legitimacy risk appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **4. Human-Machine Interaction & Augmentation**

### **ART 04.022 - Immersive Augmented & Virtual Reality**

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, immersive systems can materially improve remote deliberation, training, inspection, and shared understanding of complex situations, which supports more distributed joint decision-making. Second-order, they can reduce the advantage of physical co-location while creating new dependencies on platform-controlled meeting spaces, content layers, and moderation systems. Third-order, once major negotiations, consultations, and organizational routines happen in spatial

digital environments, visibility, persuasion, and access are reorganized around interface design. That is significant for this GVN, though not a keystone.

Weak signals (8):

- (+) [Cooperativeness] → complex planning, hearings, and board reviews move into shared 3D environments (remote presence becomes credible)
- (+) [Equality] → participation grows among remote or mobility-limited stakeholders in high-value decision processes (access broadens)
- (+) [Decision quality] → digital twins and spatial overlays are used before major organizational or public decisions (context becomes clearer)
- (+) [Productivity] → training and procedural alignment costs drop in dispersed organizations (coordination improves)
- (-) [Structural power / platform owners] → a few providers control identity, venue rules, and interaction analytics in immersive governance spaces (new intermediaries dominate)
- (-) [Equality] → device cost and bandwidth quality sort who can participate effectively (presence gap persists)
- (-) [Security] → impersonation, harassment, or recording abuse in virtual deliberation spaces becomes a governance issue (trust becomes interface-dependent)
- (-) [Normativity] → interface design subtly shapes turn-taking, persuasion, and perceived legitimacy (space design influences power)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.023 - Brain-Computer Interfaces (BCI)

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, BCIs can materially widen participation for some people and enable faster, more direct human-system interaction in high-cognitive-load settings. Second-order, they also create a new layer of power around neural data, attention monitoring, and employer or platform influence over mental states and interface design. Third-order, if BCIs enter knowledge work or administrative environments, norms around consent, performance, and cognitive privacy could shift meaningfully. That is material, but still below the threshold of broad operating-model transformation.

Weak signals (6):

- (+) [Equality] → accessibility-oriented BCIs begin to be accepted in mainstream work, governance, or education settings (participation widens)
- (+) [Productivity] → specialized decision environments adopt hands-free neural control or attention switching tools (interaction speeds up)
- (+) [Cooperativeness] → team coordination software starts integrating cognitive-state channels or workload indicators (mental states enter workflows)
- (-) [Privacy] → neural data governance rules emerge for workplaces and public-service interfaces (new sensitive data class)
- (-) [Structural power / employers] → employers test cognitive monitoring for fatigue, focus, or compliance (mental surveillance risk rises)

- (-) [Equality] → enhanced users in elite sectors gain an interaction advantage unavailable to most others (augmentation gap opens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.024 - Advanced Prosthetics & Exoskeletons

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, these technologies mainly affect inclusion in work and physical participation, which is relevant but peripheral to this GVN's core decision bottleneck. Second-order, the power effects come through labor inclusion, occupational standards, and reimbursement rather than through a direct redesign of governance. Third-order changes remain limited unless assisted physical participation becomes a major criterion of who can access organizational roles. That keeps the impact concrete but modest.

Weak signals (4):

- (+) [Equality] → more people with mobility limitations enter roles previously excluded by physical demands (participation broadens)
- (+) [Productivity] → safety rules and work design adapt around assisted physical labor in public and private organizations (task access expands)
- (-) [Equality] → access depends heavily on employer, insurer, or public reimbursement support (benefits stratify)
- (-) [Structural power / employers] → employers begin expecting augmented performance in demanding roles (support can become pressure)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.025 - Haptic and Multi-Sensory Feedback Systems

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, richer feedback improves remote handling, training, and some forms of telepresence, but it remains a supporting rather than defining element of power structures. Second-order, it matters mainly where mediated physical action shapes organizational authority or inclusion. Third-order effects are limited unless high-fidelity remote embodiment becomes central to routine governance or service work. That keeps the impact at 1.

Weak signals (4):

- (+) [Cooperativeness] → remote guidance and training systems begin using force and tactile feedback in routine operations (embodied coordination improves)
- (+) [Equality] → more participants can perform mediated physical tasks without full on-site presence (access broadens modestly)

- (-) [Structural power / platform vendors] → specialized haptic ecosystems become locked into proprietary workflows (dependency rises)
- (-) [Productivity] → adoption remains confined to niche high-value tasks rather than broad decision environments (linkage stays narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.026 - AI Understanding of Human Intent & Context

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this ART directly reshapes joint decision-making because interfaces stop waiting for explicit commands and start inferring needs, attention, status, emotion, and likely intent. Second-order, that can lower friction and widen participation, but it also gives enormous power to whoever defines the behavioral model, controls nudges, or monitors engagement and emotional compliance. Third-order, once organizations and administrations rely on anticipatory interfaces, norms of persuasion, accessibility, accountability, and manipulation all shift together. That is transformative for this GVN because it changes the microphysics of coordination itself.

Weak signals (9):

- (+) [Productivity] → meeting assistants begin reordering agendas, prompts, and follow-ups based on inferred attention and intent (interfaces become anticipatory)
- (+) [Equality] → tools adapt communication mode to accessibility needs, language, or social context without manual setup (participation becomes smoother)
- (+) [Cooperativeness] → collaboration platforms mediate turn-taking, escalation, and clarification using inferred social dynamics (friction drops)
- (+) [Decision quality] → organizational and public-service systems use context to route issues to better-matched people or procedures (fit improves)
- (+) [Choice and competition] → “understands my context” becomes a basis for switching between digital services (interface quality matters politically)
- (-) [Structural power / platform owners] → a few providers monopolize the behavioral models behind context inference (interpretive power centralizes)
- (-) [Privacy] → complaints rise over emotion, attention, and presence tracking in work and service environments (behavioral surveillance normalizes)
- (-) [Normativity] → nudging, moderation, and ranking quietly become personalized and hard to contest (influence becomes opaque)
- (-) [Equality] → system errors cluster around cultural, neurodivergent, or low-data users (misrecognition redistributes voice)

## ART 04.027 - Brain-to-Brain Interfaces

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, BBIs could materially alter a narrow set of coordination tasks by increasing the bandwidth of shared attention, tacit transfer, or synchronized action. Second-order, they raise



unusually strong questions about consent, cognitive privacy, and elite advantage if high-bandwidth collective cognition is available only to select groups. Third-order, the technology could shift norms of team coordination and authority in specialized settings, but not yet broadly across this GVN. That supports a 3 rather than a higher score.

Weak signals (5):

- (+) [Cooperativeness] → specialized teams test shared-attention or neural cueing systems for joint work (coordination bandwidth rises)
- (+) [Equality] → assistive communication uses appear for people excluded from speech- or text-heavy settings (new participation route opens)
- (-) [Privacy] → regulators define new consent boundaries for neural transmission between people (cognitive rights become explicit)
- (-) [Structural power / elite groups] → early use concentrates in military, high-end medical, or elite organizational environments (augmentation stratifies)
- (-) [Normativity] → institutions begin treating shared neural cueing as a performance enhancer rather than a sensitive exception (social pressure risk grows)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 04.028 - Memory Prostheses

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, memory prostheses mainly affect continuity of participation and performance for some individuals rather than the structure of decision-making itself. Second-order, the key power issues concern cognitive data control, access inequality, and the possibility of elite augmentation. Third-order impacts stay modest unless memory enhancement becomes widespread in leadership, administration, or credentialing. That keeps the score at 1.

Weak signals (4):

- (+) [Equality] → memory-support implants are accepted as accommodation tools in work and governance settings (participation continuity improves)
- (+) [Productivity] → high-stakes roles begin using implanted memory support for procedure retention or interruption recovery (cognitive support enters workflows)
- (-) [Structural power / elite groups] → enhancement uses appear first in top-tier professions or leadership tracks (cognitive advantage stratifies)
- (-) [Privacy] → rules emerge over ownership and disclosure of prosthetic memory data (new governance issue appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 5. Robotics & Physical Autonomy

### ART 05.029 - Self-Driving Vehicles

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, autonomous vehicles change how services, inspections, logistics, and mobility-heavy decision processes are organized, especially where human availability and travel time currently constrain coordination. Second-order, they affect labor bargaining, platform control, municipal transport authority, and who can provide mobility as a governed service. Third-order, the routine delegability of movement can shift expectations of responsiveness and centralized fleet management without fundamentally rewriting this GVN. That makes the impact material but not transformative.

Weak signals (6):

- (+) [Productivity] → public and large private fleets automate routine transport for inspections, services, and logistics (travel bottleneck eases)
- (+) [Equality] → mobility access improves for groups poorly served by current transport systems (service reach widens)
- (+) [Choice and competition] → new autonomous mobility cooperatives or municipal fleets challenge incumbent operators (provider landscape shifts)
- (-) [Structural power / platforms] → a few fleet software providers control routing, pricing, and service terms (mobility governance centralizes)
- (-) [Equality] → driver displacement becomes a bargaining flashpoint in unions and local politics (labor power shifts)
- (-) [Security] → remote takeover or safety incidents trigger governance restrictions on autonomous fleet use (trust becomes conditional)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 05.030 - Drone Swarms & Aerial Robots

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, aerial swarms materially change who can monitor, map, inspect, and rapidly intervene across dispersed spaces, which affects both public authority and organizational control. Second-order, they redistribute power toward actors that can deploy persistent airborne awareness, but they also enable community or cooperative oversight capabilities that were previously too expensive. Third-order, routine aerial presence can normalize faster response and broader surveillance, while making airspace governance, transparency, and accountability much more salient. That is a significant shift in this GVN.

Weak signals (8):

- (+) [Control mechanisms] → municipal, corporate, or civic actors deploy coordinated aerial monitoring for routine oversight (presence scales cheaply)
- (+) [Productivity] → large-area inspections and mapping move from periodic human teams to persistent swarms (coordination speed jumps)
- (+) [Choice and competition] → small operators or cooperatives enter service markets once fleet coordination software becomes accessible (capability diffuses)
- (+) [Openness] → public dashboards begin showing drone-based evidence in planning, compliance, or environmental disputes (new visibility layer)
- (-) [Structural power / public authority] → police, border, or infrastructure operators gain persistent aerial reach over everyday spaces (surveillance leverage rises)
- (-) [Equality] → low-power communities experience more intensive overhead monitoring than affluent areas (airspace burden stratifies)
- (-) [Security] → spoofing, jamming, or swarm collisions become policy-relevant incidents (control fragility becomes visible)
- (-) [Normativity] → emergency or safety exceptions expand routine airborne monitoring beyond original limits (mission creep appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.031 - Humanoid and General-Purpose Robots

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, general-purpose robots can take over repetitive physical service, inspection, and support tasks in human-built environments, materially changing who must be physically present to keep organizations functioning. Second-order, they alter bargaining power in labor markets, service provision, procurement, and remote expert oversight, while reinforcing whichever firms own the behavior libraries and fleet-control platforms. Third-order, once robots become normal organizational actors, authority shifts toward those who specify goals, exceptions, and safety envelopes rather than those who execute tasks. That is a significant effect on this GVN.

Weak signals (8):

- (+) [Productivity] → routine support tasks in public facilities, logistics, and maintenance move to robots in human spaces (presence requirement drops)
- (+) [Subsidiarity] → remote experts supervise robots across many dispersed sites (specialist authority stretches further)
- (+) [Equality] → organizations can offer some services in places previously short of staff (service reach broadens)
- (+) [Choice and competition] → smaller firms access shared robotic behavior libraries instead of building bespoke systems (entry barriers fall)
- (-) [Structural power / vendors] → a few robot operating systems dominate fleets and task updates (control centralizes)
- (-) [Equality] → lower-wage frontline roles shrink faster than governance and ownership arrangements adapt (labor asymmetry rises)
- (-) [Security] → misuse, sabotage, or unsafe behavior in public-facing robots leads to new accountability rules (delegation is contested)

- (-) [Cooperativeness] → worker-management relations harden around robot deployment decisions (task allocation becomes political)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.032 - Soft Robotics & Bio-Inspired Machines

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, soft robots mainly extend automation into fragile or awkward physical tasks rather than directly reorganizing decision-making. Second-order, they matter to this GVN chiefly through labor substitution and safer remote intervention in hard-to-reach environments. Third-order effects on power structures stay narrow unless these systems become central to public authority or service delivery. That keeps the impact limited.

Weak signals (4):

- (+) [Productivity] → fragile-handling or confined-space tasks shift from humans to softer autonomous systems (task feasibility grows)
- (+) [Safety] → hazardous maintenance or inspection roles reduce human exposure in public and industrial settings (authority can act at distance)
- (-) [Structural power / vendors] → task libraries and maintenance expertise concentrate in specialist providers (capability stays narrow)
- (-) [Equality] → adoption benefits accrue mainly in capital-rich sectors rather than broad governance contexts (distribution stays uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.033 - Fully Autonomous Drones, Robots & Underwater Vehicles

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, fully autonomous platforms materially extend the reach of organizations and authorities into remote, dangerous, or inaccessible environments. Second-order, they strengthen actors able to maintain persistent machine presence across infrastructure, borders, oceans, and hard-to-staff areas, while also lowering entry barriers for some specialized monitoring and service providers. Third-order, they can normalize governance at a distance, with accountability shifting from operators in the field to those specifying missions, thresholds, and exceptions. That is significant for this GVN.

Weak signals (8):

- (+) [Control mechanisms] → infrastructure, environmental, and territorial oversight increasingly runs through persistent autonomous platforms (presence detaches from staffing)
- (+) [Productivity] → response times fall where travel and human deployment were major bottlenecks (reach improves)

- (+) [Subsidiarity] → local actors contract autonomous services instead of waiting for central expert teams (operational autonomy expands)
- (+) [Openness] → machine-collected evidence becomes part of planning, inspection, or enforcement records (remote observation gains standing)
- (-) [Structural power / public authority] → states and large firms gain stronger remote control over difficult spaces (distance power rises)
- (-) [Equality] → communities affected by remote monitoring or intervention have limited capacity to contest machine presence (voice imbalance persists)
- (-) [Security] → communication loss, spoofing, or mission drift events become politically salient (autonomy risk becomes visible)
- (-) [Normativity] → routine unsupervised operation expands beyond originally exceptional use cases (operational creep sets in)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.034 - Supportive Infrastructure for Autonomy

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, autonomy-support infrastructure makes environments legible and governable for machines, which materially changes how organizations design space, traffic, access, and coordination. Second-order, it shifts power toward landlords, municipalities, infrastructure owners, and standards setters who decide whose robots can operate and under what terms. Third-order, once public and organizational environments are retrofitted for machine-native coordination, exclusion and path dependence increase because human and nonstandard actors must adapt to the robot layer. That supports a 3.

Weak signals (6):

- (+) [Control mechanisms] → buildings, campuses, and public sites add robot-readable markers, docking nodes, or access protocols (space becomes machine-governed)
- (+) [Productivity] → simpler, cheaper robots become viable in retrofitted environments (capability spreads through infrastructure)
- (+) [Normativity] → procurement and construction standards begin to require “autonomy-ready” features (design assumptions shift)
- (-) [Structural power / infrastructure owners] → landlords or municipalities gain leverage by controlling robot access layers (space control deepens)
- (-) [Equality] → non-retrofitted or low-income areas are excluded from autonomy benefits (infrastructure divide grows)
- (-) [Choice and competition] → proprietary infrastructure standards lock in favored robot ecosystems (interchangeability weakens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.035 - Optical/Microwave Power Beaming for Persistent Robotics

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, power beaming mainly extends robot endurance, which matters for persistent monitoring and response but not directly for decision architecture. Second-order, the main GVN effect is stronger continuous presence by whoever owns beam infrastructure and exclusion rules. Third-order governance implications remain limited unless such persistence becomes common in public authority, logistics, or service provision. That keeps the score at 1.

Weak signals (4):

- (+) [Control mechanisms] → long-duration aerial or remote robotic patrols become feasible without frequent servicing (presence hardens)
- (+) [Productivity] → high-downtime monitoring tasks gain much longer machine duty cycles (coverage improves)
- (-) [Structural power / infrastructure owners] → beam transmitters and exclusion zones are controlled by a small set of operators (energy equals authority)
- (-) [Security] → beam alignment or safety failures trigger strong regulatory restrictions (persistent use remains contested)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 05.036 - Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, dry-adhesion systems improve some climbing and handling tasks, but they do not clearly alter how joint decision-making or authority is organized. Second-order effects on labor or access remain narrow and application-specific. Third-order impacts on this GVN are therefore weak unless the technology becomes embedded in major inspection, policing, or public-service architectures. It is mainly a watchpoint.

Weak signals (4):

- (+) [Public authority] → climbing or attachment capabilities appear in mainstream inspection or security robots used by public bodies (linkage would strengthen)
- (+) [Productivity] → routine overhead or vertical-surface maintenance shifts to automated systems at scale (organizational relevance would rise)
- (-) [Decision structures] → adoption stays limited to specialized industrial maintenance (linkage remains narrow)
- (-) [Regulation] → there is little policy attention to governance implications beyond narrow safety rules (power-structure relevance stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 6. Additive, Agile & Digital Manufacturing

### ART 06.037 - Multi-Material & Hybrid 3D Printing

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, hybrid 3D printing can shorten supply chains and enable more local, customized production, which slightly reduces dependence on centralized procurement hierarchies. Second-order, it changes bargaining power between local producers, major suppliers, and certification bodies, especially where public or cooperative actors can fabricate what they need faster. Third-order, if distributed production becomes routine, organizations may shift authority toward design libraries, standards, and quality assurance rather than large integrated manufacturers. That is material but not central for this GVN.

Weak signals (6):

- (+) [Choice and competition] → municipalities, co-ops, or mid-size firms fabricate specialized components in-house or locally (supplier dependence falls)
- (+) [Productivity] → lead times for repairs or custom public-service equipment drop sharply (coordination improves)
- (+) [Subsidiarity] → local actors adopt shared design libraries to meet sector-specific needs (design power decentralizes)
- (-) [Structural power / IP owners] → design files and certified material recipes remain tightly controlled by a few licensors (value shifts upstream)
- (-) [Normativity] → certification bottlenecks slow local experimentation despite technical feasibility (rules favor incumbents)
- (-) [Equality] → advanced fabrication remains concentrated in better-funded regions or organizations (capacity spreads unevenly)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 06.038 - Digital Twin & Simulation-Driven Production

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, production twins improve visibility, prediction, and coordination in organizations that manage complex assets and processes. Second-order, they redistribute leverage toward those who own the models, operating data, and scenario frameworks used to justify decisions. Third-order, repeated use can shift authority from tacit local judgment toward model-mediated management, but



mainly within industrial and operational domains rather than this GVN's core institutional redesign. That supports a 3.

Weak signals (5):

- (+) [Decision quality] → production changes are routinely simulated before approval (model-based decision norms rise)
- (+) [Productivity] → remote experts supervise more facilities through shared twin environments (specialist reach expands)
- (+) [Comparativeness] → performance comparisons across sites rely on common twin metrics rather than local reporting (standardized evaluation grows)
- (-) [Structural power / software vendors] → a few twin platforms control asset models and interoperability terms (operational authority centralizes)
- (-) [Cooperativeness] → frontline expertise is discounted when it conflicts with the simulated baseline (model authority hardens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 06.039 - Reconfigurable & Agile Factories**

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, reconfigurable factories make production more modular and adaptable, which can reduce dependence on large-scale fixed hierarchies and improve local responsiveness. Second-order, they shift power toward actors that control modules, recipes, and orchestration software, while potentially enabling smaller or regional production networks. Third-order, if agile production spreads, some economic power may move away from scale-monopolized incumbents toward those who can coordinate flexible capacity. That is material, but still indirect for this GVN.

Weak signals (5):

- (+) [Choice and competition] → smaller manufacturers enter markets once changeover costs fall sharply (entry becomes easier)
- (+) [Subsidiarity] → regional or sector-specific production cells are coordinated without large centralized plants (local capability rises)
- (+) [Productivity] → product or policy-driven procurement shifts faster into physical output (responsiveness improves)
- (-) [Structural power / module vendors] → control over standard modules and recipes concentrates with a few suppliers (platformization risk appears)
- (-) [Equality] → benefits accrue first to already digitized firms and regions (industrial divergence persists)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.040 - Circular & Sustainable Manufacturing

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, circular manufacturing can make production more local, traceable, and less dependent on long linear supply chains, which modestly changes the power geometry of provision. Second-order, it creates new influence for those who manage material passports, recycling rights, and local feedstock streams, while weakening some incumbent raw-material advantages. Third-order, if circular flows become standardized, procurement and industrial policy may shift toward local recirculation networks and platform-coordinated material commons. That is a material but indirect GVN impact.

Weak signals (6):

- (+) [Openness] → product passports and recycled-content records become standard in procurement and compliance (material transparency rises)
- (+) [Choice and competition] → local recirculation networks or co-ops win contracts previously tied to long supply chains (local bargaining grows)
- (+) [Productivity] → waste handling and material recovery become integrated into routine production planning (coordination improves)
- (-) [Structural power / standards owners] → passport schemas and certification channels are dominated by a few software or audit providers (control recentralizes)
- (-) [Equality] → cleaner circular infrastructure appears first in affluent regions or sectors (benefits stratify)
- (-) [Normativity] → complex reporting burdens make compliance easier for large incumbents than small producers (regulation can entrench scale)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.041 - Bio-fabrication technologies

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, bio-fabrication mostly affects health and specialty bioproduction capacity rather than decision architecture. Second-order, it may alter who controls critical biological supply chains and access to specialized therapies or materials. Third-order power effects on this GVN remain limited unless distributed bio-fabrication becomes a broad governance issue. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → localized tissue or biological product fabrication reduces dependence on central facilities (supply autonomy rises modestly)
- (+) [Equality] → public or regional facilities seek bio-fabrication capacity for access reasons (service geography matters)

- (-) [Structural power / specialist providers] → capability remains concentrated in highly regulated, capital-intensive centers (control stays narrow)
- (-) [Normativity] → oversight and certification burdens block small or cooperative entrants (institutional gatekeeping persists)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.042 - 4D Printed & Programmable Materials

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, programmable materials mainly change product function and maintenance rather than governance or decision structures. Second-order impacts on this GVN are too indirect unless such materials become core to adaptive public infrastructure or automated rule-enforcement environments. Third-order effects are therefore weak. This is mainly a watchpoint.

Weak signals (4):

- (+) [Public infrastructure] → adaptive materials are integrated into widely governed public assets rather than niche products (linkage would strengthen)
- (+) [Control mechanisms] → self-reconfiguring materials begin to affect access, safety, or compliance rules in shared spaces (governance coupling would rise)
- (-) [Decision structures] → uses remain confined to engineering optimization without institutional redesign (linkage stays weak)
- (-) [Regulation] → no major governance or procurement frameworks emerge around these materials (relevance remains peripheral)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 06.043 - Volumetric Additive Manufacturing

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, faster small-batch fabrication can improve responsiveness in specific organizational supply chains. Second-order, it modestly shifts leverage toward actors that can produce custom parts locally rather than wait for centralized procurement. Third-order governance effects remain limited unless such distributed fabrication becomes widespread in public or platform-coordinated provisioning. That keeps the impact at 1.

Weak signals (4):

- (+) [Productivity] → critical spare parts for public and organizational systems are produced on demand locally (response time shrinks)
- (+) [Choice and competition] → smaller fabrication providers gain contracts because fast customized output is viable (entry expands modestly)

- (-) [Structural power / materials and machine vendors] → feedstocks and calibration remain locked to proprietary ecosystems (dependency persists)
- (-) [Normativity] → certification lags prevent broad institutional use despite speed gains (rules cap impact)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 7. Advanced Materials & Nano-engineering

### ART 07.044 - Metamaterials for Novel Optics & Connectivity

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, metamaterials materially affect signal steering, coverage control, and sensing quality, which can change who gets reliable connectivity and who can observe whom in shared spaces. Second-order, they create new leverage for building owners, telecom operators, and security actors because wave behavior becomes a configurable governance variable. Third-order, if signal environments are actively shaped by infrastructure owners, access and privacy may increasingly depend on physical surface control rather than only spectrum licenses. That is material for this GVN.

Weak signals (6):

- (+) [Choice and competition] → buildings and campuses start buying programmable surfaces to improve or redirect connectivity (coverage control localizes)
- (+) [Productivity] → hard-to-serve spaces gain reliable communications without major new active infrastructure (access improves)
- (+) [Privacy] → organizations market spaces with controlled signal leakage or selective shielding (wave control becomes a governance feature)
- (-) [Structural power / property owners] → landlords gain leverage by controlling indoor signal performance through surfaces (property power deepens)
- (-) [Security] → disputes emerge over covert sensing or signal steering in shared buildings (dual-use concerns appear)
- (-) [Equality] → premium sites get much better managed connectivity conditions than ordinary public environments (quality stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

### ART 07.045 - Room-Temperature Superconductors

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, cheaper high-performance power and compute infrastructures could support more resilient digital systems, but the governance effect is indirect. Second-order, the main relevance is whether lower-loss energy and magnetics strengthen centralized mega-infrastructures or empower more local autonomy. Third-order impacts on this GVN remain diffuse unless superconducting performance becomes a direct basis for new administrative or platform control systems. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → major digital or energy infrastructures gain much lower losses and better uptime (support conditions improve)
- (+) [Choice and competition] → some local systems become viable because power-density or efficiency constraints fall (autonomy could widen)
- (-) [Structural power / infrastructure owners] → gains are captured mainly by very large grid, data-center, or transport operators (centralization risk)
- (-) [Equality] → benefits appear first in capital-intensive sectors rather than everyday institutional settings (diffusion remains narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.046 - Self-Healing & Smart Polymers**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, self-healing materials mainly improve infrastructure uptime and maintenance patterns. Second-order, they can modestly shift power by reducing dependence on frequent inspection and repair labor or by extending asset life in hard-to-access places. Third-order effects on this GVN are limited unless maintenance resilience becomes a major differentiator in governance capacity. That keeps the impact modest.

Weak signals (4):

- (+) [Productivity] → infrastructure operators extend inspection intervals due to self-healing components (manual burden falls)
- (+) [Safety] → failure rates drop in hard-to-access assets that support public or organizational continuity (resilience improves)
- (-) [Structural power / materials suppliers] → specialized formulations remain controlled by a few vendors (dependency persists)
- (-) [Equality] → premium resilient materials appear first in well-funded networks and facilities (resilience stratifies)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.047 - Nano-Catalysts & Advanced Coatings

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better coatings and catalysts mostly improve efficiency, maintenance, and reliability in technical systems. Second-order, that can matter for who controls durable infrastructure or low-cost transformation processes, but the GVN linkage is indirect. Third-order changes are weak unless such materials clearly reshape supply or service power. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → public or large organizational assets extend service intervals due to durable coatings (maintenance friction falls)
- (+) [Safety] → critical systems show lower corrosion, fouling, or contamination-related downtime (reliability improves)
- (-) [Structural power / specialty suppliers] → high-performance coatings become strategic proprietary inputs (materials leverage increases)
- (-) [Choice and competition] → smaller operators cannot access premium formulations or application capacity (advantage concentrates)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.048 - High-Entropy Alloys & Advanced Metals

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, stronger or more heat-tolerant metals do not clearly change how joint decision-making or authority is organized. Second-order benefits mostly stay inside engineering performance and maintenance economics. Third-order impacts on this GVN are therefore too weak to score above 0. It is a distant watchpoint.

Weak signals (3):

- (+) [Public authority] → HEAs become decisive in infrastructure or defense assets that shift strategic control patterns (linkage would strengthen)
- (+) [Productivity] → maintenance or failure reduction in critical public systems becomes large enough to affect governance capacity (relevance would rise)
- (-) [Decision structures] → use stays within materials engineering without institutional redesign (linkage remains weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 07.049 - Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better CO<sub>2</sub> capture media mainly influence industrial decarbonization capacity. Second-order, they can affect climate governance, permitting, and industrial bargaining, but not directly the organization of joint decision-making. Third-order power effects remain limited unless CO<sub>2</sub> removal becomes a major basis for local authority, funding, or legitimacy. That keeps the score at 1.

Weak signals (4):

- (+) [Public authority] → local or regional plans begin tying industrial permits or incentives to capture-media deployment (governance coupling appears)
- (+) [Comparativeness] → organizations use verifiable capture performance as a reputational or procurement differentiator (legitimacy factor grows)
- (-) [Structural power / large emitters] → only large incumbents can finance capture upgrades and shape rules (decarbonization power concentrates)
- (-) [Equality] → communities contest hosting burden without proportional decision power or benefit-sharing (distributional conflict appears)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.050 - Graphene and Nanotube Composites for Lightweight Strength**

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, lighter stronger composites mainly change engineering performance and maintenance. Second-order effects on supply chains and asset design do not clearly reach this GVN's core decision architecture. Third-order impacts are therefore too indirect to score above 0 here. It is mainly a watchpoint.

Weak signals (3):

- (+) [Infrastructure power] → composite adoption becomes decisive in assets that change control over mobility, energy, or sensing networks (linkage would strengthen)
- (+) [Productivity] → maintenance or uptime gains in public-critical assets become large enough to alter governance capacity (relevance would rise)
- (-) [Decision structures] → adoption remains an engineering optimization rather than institutional redesign (linkage stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.051 - Smart Thermal Materials for Energy-Efficient Heating & Cooling**

Score: 1 (Impact in GVN 20)



Justification (3–5 sentences):

First-order, better thermal control can improve resilience and lower operating costs in buildings and infrastructure. Second-order, it modestly affects who can afford energy resilience and how much organizations depend on centralized utility conditions. Third-order effects on power structures remain limited unless thermal autonomy becomes a major basis for local institutional independence. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → public facilities and housing reduce energy volatility through passive thermal control upgrades (operational resilience improves)
- (+) [Equality] → more buildings can maintain usable conditions during energy stress or price spikes (participation continuity improves)
- (-) [Equality] → affluent buildings adopt advanced thermal materials much earlier than ordinary housing (resilience gap grows)
- (-) [Structural power / materials vendors] → premium thermal modules are locked to specialized suppliers and certification channels (dependency persists)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.052 - Rare-Earth-Free Magnets for Sustainable Motors**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, alternative magnets mainly change supply security for motors and devices. Second-order, they can modestly reduce geopolitical dependency and supply concentration in infrastructures that support digital administration and autonomy. Third-order effects on this GVN remain indirect. That keeps the score at 1.

Weak signals (4):

- (+) [Choice and competition] → motor supply diversifies away from rare-earth bottlenecks (dependency risk softens)
- (+) [Productivity] → resilient component availability improves public fleet and equipment planning (supply predictability grows)
- (-) [Structural power / materials supply] → substitute magnet supply chains form new concentrations around other critical processes (bottleneck shifts)
- (-) [Equality] → cost benefits reach large fleet operators before smaller organizations (adoption remains uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.053 - Nano-Engineered Membranes for Low-Energy Desalination**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, cheaper desalination can improve water security, which matters indirectly for local resilience and governance. Second-order, it may change who controls water infrastructure and how much water scarcity shapes bargaining and administrative conflict. Third-order, the impact on this GVN remains limited unless water governance becomes a central institutional redesign issue in the target society. That keeps it at 1.

Weak signals (4):

- (+) [Public authority] → local desalination becomes economically viable enough to enter regional planning (water autonomy rises modestly)
- (+) [Productivity] → lower maintenance and energy use improve continuity of critical water services (resilience strengthens)
- (-) [Structural power / infrastructure owners] → water control still concentrates in large utilities and contractors (authority stays centralized)
- (-) [Equality] → improved water autonomy appears first where capital and coastal access are strongest (distribution remains uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.054 - Ultra-Wide-Bandgap (UWBG) Power Semiconductors**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better power electronics improve the efficiency and compactness of electrified infrastructures that support digital systems. Second-order, the main GVN effect comes through infrastructure cost, resilience, and which firms control advanced modules. Third-order effects on authority or participation are indirect. That keeps the impact limited.

Weak signals (4):

- (+) [Productivity] → critical power conversion systems in grids, data centers, or transport become smaller and more reliable (support layer improves)
- (+) [Choice and competition] → some local energy or autonomy systems become viable because converter losses and size fall (autonomy modestly expands)
- (-) [Structural power / component vendors] → high-performance modules remain dominated by a few suppliers (dependency persists)
- (-) [Equality] → early gains concentrate in capital-rich infrastructures rather than broad institutional use (benefits diffuse slowly)

Signal density: LOW (linkage weak; additional signals would be speculative).

## **ART 07.055 - Solid Hydrogen Storage Materials for Safe, Dense Fuel**

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, safer hydrogen storage mainly changes energy logistics and some remote operations. Second-order, it can alter regional energy bargaining and resilience, but not directly how decisions are made inside organizations or administrations. Third-order effects remain indirect unless hydrogen becomes a core everyday infrastructure layer in the target society. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → remote facilities or fleets use safer hydrogen modules to reduce servicing constraints (operational autonomy grows modestly)
- (+) [Public authority] → local energy plans begin treating hydrogen storage as a realistic resilience option (governance relevance rises)
- (-) [Structural power / industrial suppliers] → safe storage remains controlled by specialist vendors and large operators (entry stays narrow)
- (-) [Equality] → deployment first benefits industrial clusters rather than everyday communities (distribution remains uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 8. Energy Generation, Storage & Conversion

### ART 08.056 - Fusion Energy Reactors

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, reliable high-density fusion power would materially change the energy base under organizations, administrations, and digital infrastructures. Second-order, it could strongly reinforce state-capital coordination and large technical bureaucracies, while reducing some dependence on imported fuels and intermittent balancing. Third-order, the resulting concentration or abundance of energy could reshape bargaining power and planning horizons across society, but mainly through the resource base rather than direct governance architecture. That is significant, though not a keystone for this GVN.

Weak signals (8):

- (+) [Structural power / state-industry alliances] → fusion sites are governed through major public-private institutional arrangements (energy authority recentralizes)
- (+) [Productivity] → long-horizon infrastructure and compute planning begins assuming abundant firm low-carbon power (planning envelope widens)
- (+) [Choice and competition] → some regions market fusion-linked industrial autonomy or service reliability (resource advantage becomes political)

- (+) [Public authority] → siting, benefit-sharing, and safety oversight become major governance questions (new governance layer forms)
- (-) [Equality] → fusion benefits accrue first to high-capital regions and industrial clusters (distribution skews upward)
- (-) [Structural power / expert elites] → operational control stays with narrow technical and regulatory elites (participation remains limited)
- (-) [Normativity] → abundance narratives are used to justify delaying institutional reform elsewhere (resource optimism crowds out change)
- (-) [Security] → fusion asset protection and supply-chain sensitivity increase central-security influence over energy governance (strategic control rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.057 - Small Modular Fission Reactors (SMRs)

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, SMRs can materially improve local access to firm energy and heat, which affects institutional resilience and the autonomy of some regions or sectors. Second-order, they strengthen actors that can navigate licensing, security, and financing, and they may create new bargaining relationships between central states, municipalities, and industrial users. Third-order, energy reliability may increase local decision freedom while simultaneously deepening dependence on nuclear-grade governance and vendor ecosystems. That is significant for this GVN.

Weak signals (8):

- (+) [Public authority] → municipalities or industrial clusters negotiate direct roles in SMR siting and heat/power governance (local energy authority rises)
- (+) [Productivity] → essential services plan around SMR-backed continuity rather than external grid uncertainty (reliability changes coordination)
- (+) [Choice and competition] → smaller-scale nuclear projects become a policy option for regions previously excluded from large reactors (energy options widen)
- (-) [Structural power / regulatory elites] → licensing and security requirements keep control in a narrow institutional circle (governance centralizes)
- (-) [Equality] → communities with less bargaining power host risk without equal benefit-sharing (distributional conflict emerges)
- (-) [Normativity] → long-term vendor service contracts limit actual local autonomy after deployment (formal local control may be shallow)
- (-) [Security] → cyber and physical security regimes expand around reactor-adjacent institutions (exceptional governance hardens)
- (-) [Choice and competition] → few reactor vendors dominate national or regional procurement (vendor dependence deepens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.058 - Thin-film solar cells

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, thin-film solar can turn many more surfaces into generation assets, materially broadening who can produce and govern energy. Second-order, it supports more distributed ownership models—households, housing companies, municipalities, cooperatives—while also inviting platform control over aggregation, financing, and data. Third-order, more pervasive local generation can shift power away from purely centralized utilities and toward multi-actor energy governance. That is significant for this GVN because control over energy directly affects organizational and civic autonomy.

Weak signals (8):

- (+) [Choice and competition] → building-integrated solar appears in public housing, offices, and municipal assets as standard practice (generation decentralizes)
- (+) [Subsidiarity] → local bodies gain revenue or autonomy through surface-based generation under their own control (local bargaining improves)
- (+) [Productivity] → distributed energy cuts outage and price-shock vulnerability for organizational operations (planning gets easier)
- (+) [Openness] → energy output and sharing rules become visible at site or community level (local governance becomes tangible)
- (-) [Structural power / aggregators] → a few financiers or software platforms manage fleets of distributed assets (control recentralizes digitally)
- (-) [Equality] → owners of roofs, facades, and capital capture disproportionate benefits (asset-based inequality widens)
- (-) [Normativity] → grid rules lag behind distributed generation and favor incumbents (institutional friction persists)
- (-) [Cooperativeness] → landlord-tenant conflicts rise over who controls or benefits from integrated generation surfaces (local disputes intensify)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.059 - Bionic Leaf Technology

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, bionic leaf systems mainly change local molecule production rather than decision-making structures. Second-order, they could modestly widen local energy or chemical autonomy where centralized supply is a bottleneck. Third-order effects on this GVN remain indirect unless they become a widespread basis of local governance or industrial bargaining. That keeps the score at 1.

Weak signals (4):

- (+) [Subsidiarity] → distributed molecule production pilots appear in municipal or cooperative infrastructure contexts (local autonomy could grow)
- (+) [Productivity] → remote or small-scale users reduce dependence on centralized fuel or chemical deliveries (coordination burden falls)
- (-) [Structural power / specialist vendors] → capability remains tied to high-complexity suppliers and maintenance contracts (control stays narrow)
- (-) [Equality] → adoption appears first in premium or strategic sites rather than broad everyday settings (diffusion remains limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.060 - Grid-Scale Energy Storage

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, long-duration storage materially changes who can guarantee reliable electricity, when, and under what rules, which directly affects organizational continuity and local resilience. Second-order, it shifts bargaining power among utilities, grid operators, communities, and large asset owners, especially where storage enables more distributed generation or resilience contracts. Third-order, the ability to buffer volatility can make local energy governance more viable but may also deepen algorithmic control by dispatch platforms. That is significant for this GVN.

Weak signals (8):

- (+) [Choice and competition] → non-utility actors such as municipalities, campuses, or co-ops own meaningful storage assets (energy bargaining diversifies)
- (+) [Productivity] → public and organizational continuity plans rely less on diesel backup and more on stored electricity (resilience model changes)
- (+) [Subsidiarity] → local energy governance begins deciding charging, discharge, and priority rules (control localizes)
- (+) [Openness] → outage recovery and peak-shaving performance become visible public metrics (energy decisions become more legible)
- (-) [Structural power / dispatch platforms] → algorithmic optimization software controls revenue and operating strategy for many assets (digital gatekeeping rises)
- (-) [Equality] → affluent sites secure resilience first while vulnerable areas remain exposed to outages (resilience stratifies)
- (-) [Normativity] → market rules reward large sophisticated operators more than community or public owners (institutional bias persists)
- (-) [Security] → cyber or fire incidents at large storage sites trigger tighter central control over deployments (exception governance expands)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.061 - Solid-State Batteries

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, safer denser batteries materially expand what can be electrified and stored in buildings, fleets, and devices used by organizations and administrations. Second-order, they change insurance, siting, and operational rules for local energy and mobility assets, while also shifting power to whoever controls pack standards and recycling loops. Third-order, they support distributed resilience more than today's batteries but do not by themselves redesign governance. That supports a 3.

Weak signals (6):

- (+) [Productivity] → public facilities and fleets adopt more on-site storage because fire and cooling burdens fall (deployment barrier drops)
- (+) [Choice and competition] → smaller actors can use safer batteries in buildings and mobile assets without specialized infrastructure (entry widens)
- (+) [Equality] → backup and off-grid capability becomes more practical in ordinary institutional settings (resilience broadens modestly)
- (-) [Structural power / battery ecosystems] → pack management, firmware, and recycling remain locked to a few major suppliers (dependency persists)
- (-) [Normativity] → insurers and code bodies rewrite rules around indoor storage and fleet electrification (institutional terms shift)
- (-) [Equality] → higher-quality storage reaches wealthy sites earlier, widening resilience gaps (distribution remains uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.062 - Green Hydrogen & Power-to-X

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, power-to-X changes how regions and organizations can store energy, secure feedstocks, and buffer volatility. Second-order, it affects industrial bargaining, regional development, water allocation, and who governs new energy-molecule infrastructures. Third-order, the technology could shift some power away from fossil incumbents while creating new platform-like intermediaries around certification and balancing, but the direct effect on decision structures is still limited. That fits a 3.

Weak signals (6):

- (+) [Choice and competition] → regions or industrial clusters use power-to-X to gain more autonomy over energy and feedstocks (strategic options widen)
- (+) [Productivity] → energy-intensive organizations hedge price and availability volatility through molecule production/storage (planning improves)
- (+) [Openness] → certification of origin and carbon content becomes part of contract and procurement decisions (traceable legitimacy grows)
- (-) [Structural power / large developers] → infrastructure ownership concentrates in capital-rich consortia (new energy elites form)



- (-) [Equality] → water and land conflicts emerge where production is sited without broad local benefit-sharing (distributional politics sharpen)
- (-) [Normativity] → complex safety and certification rules lock out smaller cooperative entrants (institutional barrier rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.063 - High-Efficiency Wind Turbines

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better wind systems improve local and regional energy provision, which affects institutional resilience and long-run bargaining. Second-order, ownership models—community, municipal, utility, or corporate—matter greatly for whether the power impact decentralizes or recentralizes local authority. Third-order, wind expansion can sharpen conflict over siting, benefit-sharing, and planning legitimacy without directly remaking decision structures. That is material but indirect.

Weak signals (6):

- (+) [Choice and competition] → community and municipal ownership models gain visible market share in new wind projects (energy governance diversifies)
- (+) [Productivity] → improved output and reliability reduce energy uncertainty for local institutions and organizations (planning stabilizes)
- (+) [Openness] → real-time performance and community-benefit dashboards become part of project governance (accountability grows)
- (-) [Structural power / large developers] → project pipelines and data remain concentrated in major energy firms (control centralizes)
- (-) [Equality] → communities hosting assets contest unequal distribution of benefits and burdens (local bargaining intensifies)
- (-) [Normativity] → planning processes become battlegrounds over who gets to decide energy landscapes (legitimacy becomes contested)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.064 - Wireless & Space-Based Power Transfer

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, wireless power mainly changes access in hard-to-connect environments rather than mainstream decision structures. Second-order, it could strengthen whoever controls beam infrastructure, orbital assets, or local rectenna sites. Third-order effects on this GVN remain limited unless power beaming becomes a major public utility layer. That keeps the score at 1.

Weak signals (4):

- (+) [Public authority] → remote public-service or emergency sites use wireless power links in place of difficult grid extensions (access improves modestly)
- (+) [Productivity] → temporary operations reduce dependence on fuel logistics or heavy cabling (deployment friction falls)
- (-) [Structural power / infrastructure owners] → beam-routing and receiving rights are tightly centralized (access becomes discretionary)
- (-) [Security] → mispointing, interference, or sovereignty concerns trigger strong governance constraints (scalability becomes political)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.065 - Advanced geothermal technology

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, advanced geothermal can provide firm local heat and power, materially improving institutional resilience and energy autonomy in places that adopt it. Second-order, it changes bargaining power between municipalities, utilities, industrial heat users, landowners, and drilling specialists. Third-order, reliable local thermal energy can support more decentralized planning and reduce dependence on fuel logistics, but it does not itself redesign decision-making. That supports a 3.

Weak signals (6):

- (+) [Subsidiarity] → municipalities or regional entities co-own deep heat and power projects (local energy authority expands)
- (+) [Productivity] → critical services plan around stable geothermal heat rather than volatile external supply (operational certainty rises)
- (+) [Choice and competition] → more regions become candidates for firm local energy rather than only traditional geothermal sites (option space widens)
- (-) [Structural power / drilling and service firms] → specialist contractors dominate project execution and performance data (capability centralizes)
- (-) [Equality] → benefits favor geology-rich or capital-rich areas first (territorial inequality persists)
- (-) [Normativity] → induced seismicity and subsurface-risk controversies reshape local consent politics (legitimacy becomes central)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 08.066 - Resilient microgrids

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, resilient microgrids make local energy governance a practical daily responsibility for campuses, municipalities, housing entities, and organizations rather than only distant utilities. Second-order, they materially shift bargaining power over continuity, outage recovery, and priority

setting, while also creating new dependencies on control software and asset ownership models. Third-order, local energy coordination can strengthen subsidiarity and cooperative governance, but also widen inequality if resilience is captured first by affluent districts or closed campuses. That is a significant effect on this GVN.

Weak signals (8):

- (+) [Subsidiarity] → municipalities, housing companies, campuses, or co-ops run island-capable local grids (local authority becomes operational)
- (+) [Productivity] → continuity of public and organizational services improves during wider grid disturbances (decision capacity hardens)
- (+) [Choice and competition] → local actors negotiate energy rules and dispatch priorities rather than only buying passive supply (governance broadens)
- (+) [Openness] → local grid status and outage-recovery metrics become visible to members or residents (accountability improves)
- (-) [Equality] → affluent districts adopt resilience first, leaving weaker communities more exposed (energy security stratifies)
- (-) [Structural power / software vendors] → microgrid control platforms dominate dispatch logic and market access (digital gatekeeping rises)
- (-) [Cooperativeness] → disputes emerge over who gets priority during islanded operation (scarcity politics localize)
- (-) [Normativity] → utility and interconnection rules limit truly local control even where technical capability exists (formal autonomy may lag)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 9. Bio-engineering & Life-Science Technologies

### ART 09.067 - Next-Generation Gene Editing

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, better gene editing materially affects public health, agriculture, and bioindustrial governance, all of which influence how power and legitimacy are allocated. Second-order, it sharpens issues of consent, access, biosecurity, and who gets to define acceptable human, ecological, or agricultural modification. Third-order, once precise editing becomes governable at scale, new institutions of approval, monitoring, and compensation can reshape elite advantage and public trust. That is significant for this GVN.

Weak signals (8):

- (+) [Public authority] → durable public deliberation bodies or ethics panels gain real influence over editing deployment (governance formalizes)
- (+) [Equality] → access, reimbursement, and anti-discrimination rules become central to editing policy (distribution becomes explicit)
- (+) [Decision quality] → regulatory decisions use more structured evidence and post-deployment monitoring for edits (oversight matures)
- (+) [Choice and competition] → smaller national or regional systems seek editing capacity to avoid external dependence (bio-sovereignty rises)
- (-) [Structural power / elite groups] → high-end therapeutic or enhancement uses cluster among wealthy institutions and households (biological advantage stratifies)
- (-) [Security] → biosecurity controls intensify around dual-use editing capabilities (exception governance expands)
- (-) [Normativity] → edited outcomes become embedded in insurance, education, or employment expectations (social pressure grows)
- (-) [Cooperativeness] → ecological or agricultural editing decisions trigger cross-border or rural-urban legitimacy conflicts (consent becomes contested)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.068 - mRNA Therapies & Vaccines

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, mRNA platforms materially improve the speed and adaptability of health interventions, which matters for public authority, crisis response, and institutional trust. Second-order, they shift power toward actors with agile manufacturing, regulatory agility, and trusted communication channels, while also enabling more regional production if capabilities diffuse. Third-order, recurrent rapid updates can change public expectations of state responsiveness and evidence use, but the effect on broader power structures remains indirect. That supports a 3.

Weak signals (6):

- (+) [Productivity] → regional or public-interest manufacturing nodes produce updated mRNA products quickly (central bottlenecks ease)
- (+) [Public authority] → health systems build standing rapid-response governance and distribution routines around the platform (responsiveness institutionalizes)
- (+) [Openness] → product updates and evidence communication become more frequent and machine-readable (trust workflow changes)
- (-) [Structural power / pharma platforms] → a few firms dominate delivery systems, manufacturing IP, or regulatory pathways (control concentrates)
- (-) [Equality] → access to updated therapies varies sharply by region or payer (response capacity stratifies)
- (-) [Cooperativeness] → trust and misinformation conflicts repeatedly disrupt deployment and legitimacy (social cohesion becomes fragile)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.069 - Cellular Agriculture & Cultured Meat

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, cellular agriculture can materially change who produces food and protein, how land is used, and which institutions set standards and subsidies. Second-order, it redistributes power between legacy agricultural actors, biomanufacturing firms, urban production sites, and potentially cooperative food networks. Third-order, food governance, labeling, and public procurement can become new arenas for bargaining over fairness, sustainability, and rural representation. That is material for this GVN, though not transformative.

Weak signals (6):

- (+) [Choice and competition] → public procurement trials include cultivated or fermentation-based proteins from new providers (market structure shifts)
- (+) [Productivity] → controlled production reduces weather- and disease-related volatility in institutional food supply (predictability rises)
- (+) [Openness] → traceability and process data become part of legitimacy claims in food contracts (evidence-based governance grows)
- (-) [Structural power / incumbents] → large food and biotech firms dominate IP, media inputs, and distribution channels (control recentralizes)
- (-) [Equality] → rural and agricultural groups contest loss of influence over food-system governance (representation conflict rises)
- (-) [Normativity] → labeling and subsidy debates become proxy fights over which production models deserve legitimacy (policy conflict deepens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.070 - Organoids & Tissue Engineering

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, organoids improve testing and specialized therapy development more than decision structures themselves. Second-order, they can modestly shift power in research regulation, evidence generation, and access to advanced treatment. Third-order effects on the broad power-structure GVN remain limited. That keeps the score at 1.

Weak signals (4):

- (+) [Decision quality] → health regulators or major organizations rely more on organoid-based evidence in approvals or planning (evidence pipeline shifts)
- (+) [Productivity] → treatment or testing cycles shorten because living human-like models are easier to access (expert bottlenecks ease)
- (-) [Structural power / specialist labs] → capability remains concentrated in leading hospitals, labs, and firms (access stays narrow)

- (-) [Equality] → advanced use remains available mainly through elite care or research networks (benefits stratify)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.071 - Synthetic Biology & Designer Microbes

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, programmable microbes can localize production, sensing, and environmental control in ways that materially affect industrial and public-service dependence on centralized infrastructure. Second-order, they shift bargaining power toward actors that own microbial chassis, bioprocess standards, and containment governance, while also enabling smaller or regional production networks. Third-order, biosecurity and traceability institutions may grow around distributed biological manufacturing. That is material for this GVN.

Weak signals (6):

- (+) [Choice and competition] → regional or specialized production shifts to biomanufacturing using designer microbes (industrial entry diversifies)
- (+) [Subsidiarity] → local actors produce specific materials or chemicals without large centralized plants (production autonomy rises)
- (+) [Openness] → microbial process traceability and containment data become standard in contracts and oversight (governance formalizes)
- (-) [Structural power / IP owners] → chassis organisms, media, or control software are tightly proprietary (biological platform power grows)
- (-) [Security] → containment, dual-use, and sabotage concerns drive stronger centralized biosecurity control (exception governance expands)
- (-) [Equality] → high-compliance costs block smaller cooperative entrants from sharing benefits (entry remains uneven)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.072 - Microbiome Engineering

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, microbiome engineering mostly influences health and environmental management outcomes rather than decision architecture. Second-order, it may modestly affect who controls individualized interventions or ecosystem remediation strategies. Third-order impacts on broader power structures remain limited unless microbiome control becomes a routine lever in public administration or labor settings. That keeps the score at 1.

Weak signals (4):

- (+) [Public authority] → environmental or public-health programs begin using targeted microbiome interventions with standardized monitoring (governance relevance rises)
- (+) [Decision quality] → invisible microbial dynamics become measurable enough to affect routine institutional choices (evidence improves)
- (-) [Structural power / consumer-health platforms] → microbiome recommendations and data are controlled by a few service providers (interpretive power concentrates)
- (-) [Equality] → precision interventions reach affluent users long before mainstream systems (benefits stratify)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.073 - Precision Medicine & Genomic Diagnostics

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, genomic diagnostics materially change how health decisions are made, who gets what treatment, and how risk is classified across populations. Second-order, they redistribute power among patients, clinicians, insurers, employers, state health systems, and data intermediaries because biological information becomes more comparable and portable. Third-order, large-scale genomic stratification can improve decision quality while also hardening new forms of sorting and inequality if rights and access lag. That is significant for this GVN.

Weak signals (8):

- (+) [Decision quality] → treatment, screening, or prevention pathways routinely branch on genomic diagnostics (biological evidence gains authority)
- (+) [Openness] → patients receive portable, machine-readable genomic summaries usable across providers (data-mediated agency rises)
- (+) [Choice and competition] → more providers compete on integrating genomic guidance into care and prevention (service models differentiate)
- (+) [Productivity] → fewer trial-and-error pathways reduce repeated visits and conflicting recommendations (coordination improves)
- (-) [Structural power / data platforms] → genomic interpretation and reference datasets concentrate in a few actors (meaning-making centralizes)
- (-) [Equality] → variant interpretation works better for some populations than others (biological justice gap persists)
- (-) [Normativity] → insurers, employers, or institutions seek more influence over genomic risk categories (sorting pressure rises)
- (-) [Privacy] → genomic data breaches or misuse trigger major trust conflicts around health governance (consent becomes fragile)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.074 - Organs-on-Chips & Bio-Computational Hybrids

Score: 1 (Impact in GVN 20)



Justification (3–5 sentences):

First-order, these systems mainly improve experimentation and specialized biological monitoring. Second-order, they may shift regulatory evidence standards and the location of high-value testing capacity. Third-order, the broad effect on organizational power structures stays limited unless such systems become routine in everyday governance decisions. That keeps the impact modest.

Weak signals (4):

- (+) [Decision quality] → regulators or major organizations accept chip-based biological evidence in more decisions (evidence authority broadens)
- (+) [Productivity] → testing and approval cycles shorten because high-fidelity proxies replace slower methods (feedback loops tighten)
- (-) [Structural power / specialized providers] → leading labs and platform vendors dominate validated chip ecosystems (capacity centralizes)
- (-) [Equality] → access to chip-based testing and hybrid systems stays highly uneven (benefit distribution remains narrow)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.075 - Biological Aging & Longevity Barriers

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, if aging can be materially slowed or partially reversed, the distribution of capability, dependency, labor participation, leadership tenure, and care burdens changes across society. Second-order, access inequality could sharply reinforce elite power, wealth accumulation, and intergenerational asymmetry, while broad access could reduce age-based exclusion and dependency. Third-order, retirement norms, welfare financing, organizational hierarchies, and political representation could all be re-negotiated around longer healthy life. That is transformative for this GVN even though the pathway runs through demographic and institutional feedback rather than software governance alone.

Weak signals (9):

- (+) [Equality] → healthy-life extension becomes a visible policy objective rather than only a luxury therapy niche (distribution enters politics)
- (+) [Productivity] → organizations redesign career paths and retraining around longer periods of high capability (hierarchies stretch)
- (+) [Choice and competition] → older adults remain more active in entrepreneurship, civic roles, or workplace governance (participation base widens)
- (+) [Public authority] → pension, retirement, and care systems begin formal redesign around changed healthy-life assumptions (institutional ripple begins)
- (-) [Structural power / elite groups] → executive, investor, or political tenure lengthens disproportionately among wealthy groups (power entrenchment risk rises)
- (-) [Equality] → biological aging gaps between income groups become a major justice issue (longevity becomes stratified)

- (-) [Cooperativeness] → intergenerational conflicts intensify over jobs, assets, benefits, and representation (social bargaining sharpens)
- (-) [Normativity] → longer healthy life becomes a tacit expectation in work and public roles (non-users can be penalized)
- (-) [Security / bio-governance] → states or insurers seek stronger monitoring of aging biomarkers and treatment compliance (biological surveillance expands)

## ART 09.076 - Engineered Living Materials

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, engineered living materials mainly influence maintenance, carbon handling, and asset life. Second-order, they can slightly change who controls long-lived infrastructure and how much ongoing inspection is needed. Third-order power effects remain limited unless such materials become central in public infrastructure governance. That keeps the score at 1.

Weak signals (4):

- (+) [Productivity] → public infrastructure pilots show reduced repair cycles due to self-healing living materials (maintenance burden falls)
- (+) [Openness] → embedded condition signals make asset degradation more visible to multiple stakeholders (evidence improves)
- (-) [Structural power / specialist suppliers] → living-material recipes and maintenance know-how remain narrowly controlled (control stays concentrated)
- (-) [Normativity] → biosafety and certification burdens keep deployment restricted to a few high-capacity operators (adoption stays limited)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.077 - Gene Drive Pest Control

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, gene drives materially affect who can control ecological threats and how long interventions persist without ongoing labor. Second-order, they create strong governance issues around consent, reversibility, liability, and cross-border authority because releases can outgrow the jurisdiction that approved them. Third-order, they may shift power toward actors able to define acceptable ecological futures and monitoring regimes. That is material for this GVN.

Weak signals (6):

- (+) [Public authority] → multi-stakeholder governance panels are created for any contemplated field release (consent architecture formalizes)
- (+) [Decision quality] → long-term ecological monitoring and reversal planning become standard preconditions for deployment (oversight deepens)

- (+) [Choice and competition] → affected communities demand real veto or benefit-sharing rights before releases (power is negotiated)
- (-) [Structural power / state and biotech actors] → release authority is concentrated in a small expert-regulatory nexus (decision centralization risk)
- (-) [Cooperativeness] → neighboring jurisdictions or groups contest being affected by others' approvals (cross-border legitimacy conflict grows)
- (-) [Security] → biosecurity and sabotage concerns drive more centralized control over gene-drive research and deployment (exception governance expands)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 09.078 - Artificial Wombs & Synthetic Embryos

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, these technologies directly alter reproduction, gestation, family formation, and developmental oversight, which are foundational social institutions tied to power, equality, and participation. Second-order, they redistribute authority among parents, clinicians, states, employers, insurers, and reproductive-service providers, while also reshaping gendered burdens and reproductive bargaining. Third-order, family law, labor norms, care policy, and moral legitimacy conflicts can all reorganize around who can reproduce, under what terms, and with which rights. That is transformative for this GVN.

Weak signals (9):

- (+) [Equality] → policy debates frame gestation support as an equality and participation issue rather than only a medical niche (institutional stakes rise)
- (+) [Public authority] → family law, parental rights, and developmental oversight are revised for extra-body gestation contexts (core institutions adapt)
- (+) [Choice and competition] → new reproductive service models challenge geography-bound specialist centers (service provision diversifies)
- (+) [Productivity] → employers and welfare systems revisit parental leave, risk allocation, and work continuity assumptions (labor norms shift)
- (+) [Decision quality] → developmental monitoring data becomes central in formal reproductive decisions (hidden processes become governable)
- (-) [Structural power / providers and states] → reproductive capacity and developmental data concentrate in tightly regulated providers (control centralizes)
- (-) [Equality] → affluent users access lower-risk or higher-control reproductive options first (reproductive inequality grows)
- (-) [Normativity] → strong political and cultural conflicts emerge over acceptable embryo-like constructs and gestational control (legitimacy battle deepens)
- (-) [Cooperativeness] → women's, disability, religious, and family-rights movements diverge over what counts as liberation or coercion (coalitions fragment)

## 10. Space & Aeronautical Engineering

### ART 10.079 - Satellite Mega-Constellations & Space Internet

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, mega-constellations directly expand connectivity, observation, and timing services beyond terrestrial bottlenecks, which changes who can participate in digital coordination and under what conditions. Second-order, they can weaken geography-bound infrastructure advantages while concentrating immense leverage in a small number of constellation operators and allied states. Third-order, if administrations, platforms, and civic coordination increasingly rely on orbital infrastructure, everyday power shifts toward whoever can grant, revoke, prioritize, or interpret those services. That is transformative for this GVN.

Weak signals (9):

- (+) [Equality / geography-based authority] → remote communities, mobile workforces, or crisis zones join digital decision processes through satellite links (geography loses grip)
- (+) [Productivity] → public services and organizations use orbital connectivity as routine continuity infrastructure (coordination resilience rises)
- (+) [Openness] → satellite imagery and network data enter public-facing evidence and planning systems more frequently (visibility broadens)
- (+) [Choice and competition] → actors can bypass weak terrestrial incumbents using independent satellite-linked service layers (administrative alternatives strengthen)
- (+) [Comparativeness] → near-real-time Earth observation is used to compare conditions and claims across jurisdictions (monitoring scales)
- (-) [Structural power / constellation operators] → a few firms become indispensable gateways for connectivity and observation (orbital gatekeeping emerges)
- (-) [Security] → jamming, state pressure, or service denial become politically salient risks to everyday coordination (sovereignty tension rises)
- (-) [Equality] → user-terminal costs or service quality gaps limit who fully benefits from orbital access (orbital divide persists)
- (-) [Normativity] → always-on observation expands expectations of remote oversight in work and governance (surveillance baseline rises)

### ART 10.080 - Space Resource Utilization (SRU)

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, SRU mainly changes long-term resource geopolitics rather than near-term organizational decision-making structures. Second-order, it could modestly affect bargaining power over critical materials and future industrial concentration. Third-order effects on this GVN remain speculative and indirect at the society scale used here. That keeps the score at 1.

Weak signals (4):

- (+) [Structural power / resource politics] → national or corporate strategies begin treating off-Earth materials as credible supply options (future bargaining shifts)
- (+) [Choice and competition] → critical-material security debates include SRU pathways in procurement and industrial policy (relevance grows)
- (-) [Equality] → ownership claims and access debates concentrate in a few states and firms (new frontier concentration emerges)
- (-) [Decision structures] → no practical spillover reaches everyday organizations or administrations (linkage stays weak)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.081 - Closed-Loop Life Support System

Score: 0 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, closed-loop life support is highly important for off-Earth habitation but has no clear direct role in this GVN's joint decision-making architecture. Second-order spillovers into terrestrial resilience are too indirect for this assessment. Third-order impacts on power structures are therefore weak. It remains a watchpoint only.

Weak signals (3):

- (+) [Resilience governance] → terrestrial critical facilities adopt life-support-style closed-loop systems as mainstream infrastructure (linkage would strengthen)
- (+) [Productivity] → closed-loop habitat logic becomes central in disaster, remote, or institutional planning (governance coupling would grow)
- (-) [Decision structures] → deployment stays confined to space and extreme-isolation contexts (linkage remains negligible)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 10.082 - High-Altitude Platforms & Balloons

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, HAPs materially improve temporary connectivity, regional sensing, and emergency coordination without needing permanent terrestrial build-out. Second-order, they redistribute power toward actors that can quickly deploy pseudo-satellite infrastructure over disrupted or underserved regions, while also creating airspace-governance and surveillance issues. Third-order, HAPs can make remote or contested spaces more governable from a distance, but usually as an overlay rather than a full redesign of authority. That supports a 3.

Weak signals (6):

- (+) [Equality / geography-based authority] → disaster or rural areas use HAPs to restore participation and service continuity quickly (distance barrier softens)
- (+) [Productivity] → temporary administrative, emergency, or organizational networks rely on HAP coverage rather than waiting for ground repair (response speed rises)
- (+) [Choice and competition] → regions gain alternatives to fixed terrestrial incumbents for coverage and sensing (service options widen)
- (-) [Structural power / operators] → a few aerospace-telecom players dominate deployment permissions and operating capability (airborne gatekeeping grows)
- (-) [Privacy] → persistent high-altitude observation triggers stronger concerns over remote oversight of populations (surveillance visibility rises)
- (-) [Security] → sovereignty, airspace, or sabotage disputes surround platform deployment in contested contexts (governance complexity grows)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 11. Digital Platforms & Collective-Intelligence Systems

### ART 11.083 - Decentralized Trust Networks (Web3 & Blockchain)

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, decentralized trust networks directly rework how records, commitments, identity, and automated rule execution can be coordinated across actors that do not fully trust a central intermediary. Second-order, they can reduce reconciliation and enable more contestable shared infrastructures, but they can also create new plutocratic or technical gatekeepers around validators, wallets, bridges, and governance tokens. Third-order, once shared ledgers and verifiable credentials enter everyday contracting, membership, and resource allocation, the boundary between hierarchy, market, and software-mediated coordination shifts materially. That is transformative for this GVN.

Weak signals (9):

- (+) [Openness] → public or organizational registries move to tamper-evident shared ledgers with auditable histories (record trust changes)
- (+) [Choice and competition] → participants carry portable credentials and memberships across services or administrations (switching friction falls)
- (+) [Platform cooperatives] → worker- or user-owned platforms manage payouts and rights through shared rule stacks (member governance gains tooling)
- (+) [Productivity] → reconciliation, escrow, and dispute-resolution time falls in multi-party workflows (coordination costs drop)
- (+) [Comparativeness] → resource flows and governance actions become more inspectable across organizations (accountability improves)

- (-) [Structural power / validators and infrastructure] → control concentrates in a few chains, custodians, or bridge operators (decentralization can recentralize)
- (-) [Equality] → token-weighted governance or wallet literacy skews influence toward better-resourced participants (voice stratifies)
- (-) [Security] → smart-contract exploits and bridge failures trigger visible governance losses (trust is technically fragile)
- (-) [Normativity] → software-executed rules harden contested assumptions into infrastructure (politics hides in code)

## ART 11.084 - Platform Cooperatives & Fair Work

Score: 20 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this ART is explicitly part of the challenger regime described in the GVN: member-managed digital platforms are a direct alternative to incumbent hierarchies and investor-controlled intermediaries. Second-order, they reorganize bargaining power over pricing, access, data rights, dispute resolution, and surplus distribution, making power inside digital coordination systems more contestable and more legible. Third-order, once platform-cooperative tooling becomes reusable and interoperable, many sectors can move from hierarchical coordination toward stakeholder-governed network administration. Because this is not just helpful but central to the GVN's envisioned transformation, 20 is justified.

Weak signals (10):

- (+) [Platform cooperatives] → worker- or user-owned digital marketplaces win visible contracts from municipalities, unions, or large organizations (alternative operating model legitimizes)
- (+) [Equality] → payout transparency, fee transparency, and member voting are built into mainstream platform interfaces (power becomes legible)
- (+) [Choice and competition] → workers and users begin switching from investor-owned platforms to member-owned alternatives at scale (governance switching becomes real)
- (+) [Cooperativeness] → dispute resolution, scheduling, and benefit pools are managed through member rule-setting rather than unilateral platform policy (joint action deepens)
- (+) [Openness] → algorithmic ranking and penalty rules become inspectable and amendable by members (opaque control weakens)
- (+) [Subsidiarity] → sector-specific or place-specific co-op instances federate while retaining local control (subject-based administration becomes practical)
- (-) [Structural power / voting blocs] → concentrated member blocs or capital-like tokens recreate elite influence inside co-ops (capture risk appears)
- (-) [Productivity] → participation fatigue or governance overload slows decisions in fast-moving markets (coordination costs can rise)
- (-) [Security] → identity fraud, coercive voting, or treasury abuse become visible governance threats (institutional trust remains work)
- (-) [Normativity] → regulators or buyers still default to incumbent platform assumptions, limiting co-op scaling (dominant regime resists)



## ART 11.085 - Open Data Sharing Marketplaces

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, data marketplaces materially improve access to fragmented information needed for better coordination, oversight, and comparison across organizations. Second-order, they change bargaining power around who can monetize, buy, or conditionally expose data, while potentially reducing dependence on one-off bilateral relationships. Third-order, once data exchange becomes routine and machine-readable, smaller actors can participate in evidence-based decision-making that previously required privileged access—though new intermediaries can still centralize control. That is significant for this GVN.

Weak signals (8):

- (+) [Openness] → datasets are listed with machine-readable access terms and quality indicators rather than shared ad hoc (exchange formalizes)
- (+) [Choice and competition] → small actors begin buying or selling data they previously could not mobilize institutionally (information market broadens)
- (+) [Productivity] → cross-organization analytics cycles speed up as access is granted through standard permissions (coordination friction drops)
- (+) [Comparativeness] → benchmarking across administrations, firms, or service providers increases because comparable data is easier to acquire (comparative governance strengthens)
- (-) [Structural power / marketplace operators] → a few exchanges or data brokers dominate discovery, pricing, and policy terms (information gatekeeping rises)
- (-) [Equality] → actors with richer legacy data capture most market value (data inequality monetizes)
- (-) [Privacy] → disputes over re-identification, consent, or secondary use become politically salient (trust remains fragile)
- (-) [Normativity] → ability to pay increasingly determines who gets visibility into socially useful information (knowledge access can stratify)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.086 - Secure & Resilient Social Platforms

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, resilient social platforms directly affect whether large groups can coordinate, deliberate, mobilize, and preserve collective memory without depending on fragile or manipulable central chokepoints. Second-order, they can rebalance power away from single platforms and toward federated communities, but they can also create new moderation, interoperability, and trust challenges. Third-order, when identity, reputation, and group continuity become portable and censorship-resistant, power structures around communication and social organization change substantially. That is transformative for this GVN.

Weak signals (9):

- (+) [Cooperativeness] → unions, civic groups, professional associations, or public-interest communities migrate from single-platform dependence to interoperable networks (coordination autonomy grows)
- (+) [Openness] → moderation logs, policy changes, and federation rules become inspectable by affected communities (governance visibility rises)
- (+) [Choice and competition] → people retain social ties and content portability when moving between services (exit becomes practical)
- (+) [Security] → communications persist through outages, censorship, or targeted blocking thanks to replication and relay diversity (continuity strengthens)
- (+) [Equality] → smaller organizations gain communications resilience without needing large proprietary infrastructures (access broadens)
- (-) [Structural power / node operators] → a few hosting, identity, or reputation providers still become de facto hubs (federation can concentrate)
- (-) [Normativity] → cross-node moderation disputes fragment shared publics and create governance fatigue (coordination cost can rise)
- (-) [Privacy] → key recovery and metadata protection remain hard for ordinary users (usability shapes who stays secure)
- (-) [Security] → extremist capture, harassment, or malicious mirroring lead to pressure for more centralized controls (resilience faces legitimacy tests)

## ART 11.087 - Collective Open Innovation Networks

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, open innovation networks materially improve how organizations find expertise, test alternatives, and coordinate invention without requiring co-location. Second-order, they weaken some elite gatekeeping over problem definition and participation while creating new influence around platform rules, reputation systems, and IP terms. Third-order, if policy and administrative innovation also move onto such networks, decision-making can become more comparative, crowdsourced, and evidence-traceable. That is significant for this GVN.

Weak signals (8):

- (+) [Comparativeness] → organizations and public bodies post open challenges with clear evaluation criteria instead of relying only on internal experts (alternatives become visible)
- (+) [Cooperativeness] → distributed teams repeatedly form around specific problems and leave reusable evidence trails (collective problem-solving scales)
- (+) [Productivity] → solution cycles shorten because parallel attempts and benchmarked validation become normal (exploration cost falls)
- (+) [Openness] → failed pathways and negative results are retained as searchable common knowledge (learning becomes cumulative)
- (-) [Structural power / platform owners] → reputation algorithms and challenge access are controlled by a few operators (agenda-setting recentralizes)
- (-) [Equality] → contributors without strong digital reputations struggle to be noticed despite capability (new gatekeeping forms)

- (-) [Normativity] → IP and confidentiality rules limit who can truly participate in high-value challenges (openness is partial)
- (-) [Productivity] → coordination overhead or contest design flaws waste effort in low-quality challenges (crowdsourcing can misfire)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.088 - Scalable Decentralized Governance

Score: 20 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this ART is a direct operating model for the challenger regime: it lets large groups make binding decisions, allocate resources, and update rules without relying entirely on centralized hierarchy. Second-order, it reconfigures accountability, membership, delegation, and auditability, shifting power from fixed authorities toward software-mediated, stakeholder-visible governance processes. Third-order, once interoperable decentralized governance becomes normal, subject-based administration, competing service bodies, and platform cooperatives become much more feasible and durable. Because it is a foundational mechanism for the GVN's core transformation, 20 is justified.

Weak signals (10):

- (+) [Subsidiarity] → sector-specific digital bodies govern budgets, rules, or memberships outside traditional geography-based structures (new institutional form appears)
- (+) [Openness] → proposals, delegations, votes, and treasury actions are visible and auditable to participants (decision process becomes legible)
- (+) [Choice and competition] → members switch between governance bodies or service associations without losing identity and standing (interchangeability rises)
- (+) [Cooperativeness] → delegation, liquid voting, or structured deliberation reduce coordination friction in large groups (scalability improves)
- (+) [Productivity] → funding, access rights, and routine governance changes execute faster through agreed rule stacks (operational lag falls)
- (+) [Comparativeness] → alternative governance designs are benchmarked against each other in real deployments (institutional experimentation scales)
- (-) [Structural power / wealthy blocs] → governance influence clusters among actors with more time, expertise, reputation, or tokens (capture risk is persistent)
- (-) [Normativity] → automated or codified governance locks in poor rules faster than social correction can keep up (bad rules scale too)
- (-) [Security] → identity fraud, voting coercion, or contract bugs trigger visible crises of legitimacy (technical failures become constitutional)
- (-) [Equality] → participation fatigue leaves active minorities in control while most members become passive (formal decentralization can mask oligarchy)

## ART 11.089 - Digital Learning Networks and Skill Credentialing

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, digital learning networks materially broaden access to expertise and verifiable competence, which matters in a GVN where better joint decision-making depends on wider participation and better-informed stakeholders. Second-order, they reduce dependence on a few institutions for gatekeeping credentials, while creating new platform power around assessment rules, identity, and reputation. Third-order, portable skill proof can make subject-based administration and platform-cooperative workforces easier to assemble and trust. That is significant for this GVN.

Weak signals (8):

- (+) [Equality] → public and large organizations accept portable digital credentials alongside traditional degrees (entry barriers soften)
- (+) [Productivity] → skill gaps in emerging governance and digital-coordination tasks are closed faster through AI-guided learning (adaptation accelerates)
- (+) [Choice and competition] → workers move between employers, co-ops, and administrations using wallet-based skill evidence (mobility increases)
- (+) [Cooperativeness] → shared training communities and peer assessment become part of sector governance ecosystems (knowledge commons deepen)
- (-) [Structural power / platform owners] → credential legitimacy depends on a few learning and assessment platforms (new gatekeepers emerge)
- (-) [Equality] → performance analytics and identity checks disadvantage some users or regions (assessment bias matters)
- (-) [Normativity] → employers begin requiring constant recredentialing and behavioral signals rather than broader judgment (human evaluation narrows)
- (-) [Security] → fraud, credential stuffing, or synthetic identity abuse become salient governance issues (trust layer must harden)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 11.090 - Prediction-Market Forecasting Platforms

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, prediction markets materially improve how groups aggregate dispersed judgment under uncertainty, which directly supports better joint decision-making. Second-order, they can reduce deference to hierarchy or loud voices by giving trackable weight to calibration and evidence, but they can also be gamed by those with better information, capital, or framing power. Third-order, if forecasts become routine governance inputs, organizations may reallocate authority toward measurable forecasting performance and away from status. That is significant for this GVN.

Weak signals (8):

- (+) [Decision quality] → major organizations and public bodies use forecast markets for planning, budgeting, or risk signals (collective uncertainty becomes measurable)
- (+) [Comparativeness] → forecast accuracy across teams, units, or service models is tracked publicly or internally (judgment becomes benchmarkable)

- (+) [Openness] → assumptions are decomposed into linked questions that stakeholders can inspect and challenge (reasoning becomes structured)
- (+) [Productivity] → slower consensus-building processes are shortened by live probability signals (coordination friction falls)
- (-) [Structural power / informed elites] → insiders or better-resourced actors dominate markets through information or liquidity advantages (voice stratifies)
- (-) [Normativity] → managers or authorities treat market prices as neutral truth in contested value questions (quantification overreaches)
- (-) [Security] → manipulation, question wording abuse, or settlement disputes undermine legitimacy (institutional trust can crack)
- (-) [Equality] → participation remains narrow unless design actively broadens who can forecast safely (collective intelligence can stay elite)

Signal density: LOW (linkage weak; additional signals would be speculative).

## 12. Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 - Universal IoT Interoperability Standards

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, universal IoT standards materially lower the cost of connecting many devices across organizational and administrative boundaries, which improves coordination and reduces custom integration bottlenecks. Second-order, they weaken some vendor lock-in and make distributed sensing and automation more contestable, while also creating new power around certification and standards-setting. Third-order, interoperable devices make data-rich decentralized administration more feasible because the sensing layer no longer belongs to one supplier at a time. That is significant for this GVN.

Weak signals (8):

- (+) [Choice and competition] → public and enterprise tenders require open interoperability rather than single-vendor stacks (switching becomes more realistic)
- (+) [Productivity] → integration time for new sensors and control devices drops sharply across mixed fleets (coordination friction falls)
- (+) [Openness] → device capabilities, permissions, and update histories become machine-readable to multiple stakeholders (legibility improves)
- (+) [Subsidiarity] → smaller actors plug into shared administrative or monitoring systems without bespoke integrations (entry broadens)
- (-) [Structural power / standards bodies and certifiers] → certification programs become a new gatekeeper layer (control can recentralize)
- (-) [Security] → vulnerabilities in common profiles or update chains affect many deployments at once (shared standards amplify failures)

- (-) [Equality] → legacy or low-cost devices are excluded from compliant ecosystems (older actors can be stranded)
- (-) [Normativity] → standard schemas encode dominant assumptions about what should be measured and controlled (politics enters infrastructure)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.092 - Interoperable Digital Twin Ecosystems

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, interoperable twins materially improve multi-party coordination because the same asset or process can be seen, simulated, and contested across organizations without rebuilding models. Second-order, they reduce some platform lock-in and make assumptions, uncertainty, and maintenance history more transportable, while creating new leverage for standards and access-control owners. Third-order, once shared simulations become common in planning and governance, arguments shift toward comparable model evidence rather than siloed claims. That is significant for this GVN.

Weak signals (8):

- (+) [Decision quality] → major interventions are tested in shared digital twins across agencies, suppliers, or departments (scenario coordination deepens)
- (+) [Openness] → assumptions, uncertainty bounds, and provenance become visible parts of asset or process models (model politics becomes inspectable)
- (+) [Choice and competition] → organizations switch tools without losing the twin's operational meaning (vendor dependence softens)
- (+) [Productivity] → duplicate modeling and translation work fall across complex multi-party projects (coordination cost drops)
- (-) [Structural power / platform vendors] → a few ecosystems dominate interoperability definitions in practice (soft lock-in persists)
- (-) [Normativity] → decisions overfit what the twin can represent while sidelining unmodeled interests (model bias shapes power)
- (-) [Equality] → actors with better instrumentation or modeling skills dominate shared twin interpretation (evidence asymmetry remains)
- (-) [Security] → compromised or drifting twins cause large coordination failures across multiple stakeholders (shared model risk rises)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.093 — Global Supply Chain Traceability Networks

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, traceability networks materially improve visibility across organizations, which changes procurement, compliance, and accountability decisions. Second-order, they redistribute power

between large buyers, suppliers, auditors, workers, and regulators because provenance becomes easier to demand and contest. Third-order, once real-time chain-of-custody information becomes routine, counterfeiting, hidden outsourcing, and opaque resource dependence become harder to sustain—but smaller actors can also be burdened by compliance. That is significant for this GVN.

Weak signals (8):

- (+) [Openness] → public and major private procurement starts requiring portable provenance records for products and materials (supply visibility becomes mandatory)
- (+) [Decision quality] → faster root-cause analysis shortens disputes and corrective action after quality or ethics failures (accountability improves)
- (+) [Choice and competition] → buyers can compare suppliers on verified handling and origin rather than only price (comparative governance strengthens)
- (+) [Control mechanisms] → sanctions, recalls, and compliance actions rely on shared digital custody histories (enforcement becomes data-driven)
- (-) [Structural power / large buyers and auditors] → compliance costs and data demands favor large incumbents over small suppliers (power can centralize)
- (-) [Equality] → weaker suppliers lack bargaining power over what must be disclosed or at what cost (visibility burden is uneven)
- (-) [Security] → tampering, false provenance, or identifier fraud become significant governance threats (trust infrastructure is contested)
- (-) [Normativity] → traceability regimes prioritize what large buyers care about, sidelining other stakeholder concerns (measurement politics deepens)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.094 — Personal Data Portability & Trust Frameworks

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, portable personal data and granular consent directly support the challenger regime's values of interchangeability, choice, and competition between service providers, platforms, and administrative bodies. Second-order, they reduce lock-in to incumbent intermediaries and can rebalance power toward individuals and communities, though only if wallet usability, trust, and standards are widely good enough. Third-order, once people can actually move identity, records, and permissions across organizations, whole governance ecosystems can become more open, contestable, and modular. That is transformative for this GVN.

Weak signals (9):

- (+) [Choice and competition] → users begin switching services without losing history, identity, or eligibility data (lock-in weakens)
- (+) [Interchangeability] → public and private services accept user-mediated data from multiple sources through common consent flows (provider pluralism grows)
- (+) [Openness] → consent receipts, access logs, and revocation states become visible to users by default (data power becomes legible)



- (+) [Equality] → repeated form-filling and verification burdens drop for citizens, workers, or members moving between institutions (friction falls)
- (+) [Platform cooperatives] → co-ops and smaller providers gain customers because onboarding no longer requires rebuilding data history (market access improves)
- (-) [Structural power / wallet and identity providers] → a few wallets or trust frameworks become de facto chokepoints (new intermediaries arise)
- (-) [Equality] → digital literacy and recovery failures leave some users unable to exercise portability in practice (formal rights outrun use)
- (-) [Security] → phishing, account takeover, or fraudulent consent events become central governance risks (control can be stolen)
- (-) [Normativity] → institutions request more data than needed because requesting becomes easier (over-collection can persist)

## ART 12.095 — Interoperable Digital Currency Payment Networks

Score: 5 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, interoperable payment networks materially reduce friction in moving value across organizations, platforms, and administrative domains. Second-order, they can weaken payment lock-in, support competing service bodies, and make cross-boundary coordination easier, while also creating new power around compliance, routing, and wallet infrastructure. Third-order, once settlement becomes smoother and more programmable, resource allocation and conditional payments can be embedded into more modular governance arrangements. That is significant for this GVN.

Weak signals (8):

- (+) [Choice and competition] → payments move seamlessly across CBDC, bank, crypto, and mobile-money rails (boundary friction falls)
- (+) [Platform cooperatives] → smaller platforms and associations can manage payouts and pooled funds without bespoke payment stacks (institutional entry improves)
- (+) [Productivity] → cross-organization reimbursements, grants, and micro-payments settle much faster (coordination lag shrinks)
- (+) [Subsidiarity] → local administrations or networks use programmable payments for targeted benefits or shared budgets (resource governance modularizes)
- (-) [Structural power / routing and compliance nodes] → a few intermediaries dominate path selection, screening, or wallet standards (new chokepoints emerge)
- (-) [Privacy] → disputes intensify over traceability, selective disclosure, and financial surveillance (payment trust becomes political)
- (-) [Equality] → low-connectivity or low-literacy users struggle with wallet recovery and multi-rail complexity (use remains uneven)
- (-) [Security] → outages, fraud, or routing exploits become visible governance failures (money infrastructure fragility matters)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.096 — Machine-Readable Regulation (Rules as Code)

Score: 20 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, machine-readable regulation is a core enabler of the GVN’s challenger regime because AI-assisted administration, competing service bodies, and transparent automated enforcement need rules that software can execute and stakeholders can inspect. Second-order, it reorganizes legal interpretation, compliance, procurement, and accountability by moving part of regulatory power from opaque institutional practice into versioned, testable infrastructure. Third-order, once laws and procedures become executable, governments and organizations can compare administrative models, update them faster, and automate more coordination—while also risking overformalization. Because it drastically increases the feasibility of the GVN’s main transformation, 20 is justified.

Weak signals (10):

- (+) [Openness] → authorities publish machine-readable rule packages alongside human-readable text (law becomes operationally inspectable)
- (+) [Productivity] → organizations update compliance logic much faster when rules change (adaptation lag falls)
- (+) [Comparativeness] → policy variants are simulated in sandboxes before adoption using the same executable rules (administrative experimentation scales)
- (+) [Choice and competition] → multiple service providers can implement the same rules consistently without bespoke interpretation monopolies (interchangeability improves)
- (+) [Control mechanisms] → decisions come with clause-level execution traces that can be appealed or audited (accountability becomes specific)
- (+) [Subsidiarity] → local or sector-specific variations are encoded transparently as policy profiles rather than hidden administrative practice (difference becomes legible)
- (-) [Structural power / rule-engine vendors] → a few software stacks become the de facto operating system for law (interpretive power recentralizes)
- (-) [Normativity] → only easily codified parts of law are automated, sidelining discretion and context where they still matter (overformalization risk grows)
- (-) [Equality] → groups with weaker representation get their realities encoded poorly into machine-readable definitions (bias can scale cleanly)
- (-) [Security] → buggy or malicious rule implementations can propagate quickly across many organizations (legal infrastructure becomes attack surface)

## ART 12.097 — Open Metaverse Interoperability Protocols

Score: 3 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, interoperability protocols can materially improve continuity of identity, assets, and participation across immersive environments used for work, training, and some public interaction. Second-order, they reduce dependence on single virtual-world operators while creating new standards power around identity, moderation, and asset semantics. Third-order, if immersive spaces become serious venues for coordination, these protocols influence who can move, assemble, and retain social capital across them. That is material but still secondary for this GVN.

Weak signals (6):

- (+) [Choice and competition] → users keep identity, contacts, and assets when moving between major immersive platforms (lock-in weakens)
- (+) [Cooperativeness] → organizations host interoperable virtual meetings, training, or consultation spaces across engines (participation continuity improves)
- (+) [Openness] → common moderation and rights metadata travel with content and users (governance becomes more portable)
- (-) [Structural power / standards setters] → a few large vendors still dominate de facto protocol interpretation (openness can be partial)
- (-) [Equality] → access remains shaped by hardware quality and bandwidth despite protocol openness (presence remains unequal)
- (-) [Security] → harassment, impersonation, or rights abuse across interconnected worlds become salient governance failures (social safety must scale)

Signal density: LOW (linkage weak; additional signals would be speculative).

## ART 12.098 — Content Authenticity Infrastructure

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, content authenticity infrastructure directly affects whether people and institutions can trust digital evidence, attribution, and provenance in decision-making. Second-order, it can reduce the advantage of manipulation, impersonation, and opaque synthetic media, while also creating new power around credential issuers, device certification, and accepted provenance standards. Third-order, once credibility becomes machine-checkable across platforms, media trust, organizational evidence, and public discourse all change in ways that affect everyday power. That is transformative for this GVN.

Weak signals (9):

- (+) [Openness] → public and organizational communications begin shipping with machine-checkable provenance by default (source trust changes)
- (+) [Decision quality] → procurement, compliance, journalism, and internal investigations start requiring authenticity credentials for sensitive media (evidence standards rise)
- (+) [Comparativeness] → platforms and users can rapidly distinguish attributable content from unprovenanced media (triage improves)
- (+) [Choice and competition] → smaller credible sources gain visibility because provenance substitutes for platform status (trust can decentralize)
- (+) [Control mechanisms] → administrative and legal workflows accept provenance summaries as part of formal records (credibility becomes operational)
- (-) [Structural power / certifiers and device makers] → a small set of hardware and software roots become arbiters of legitimacy (trust can centralize)
- (-) [Equality] → anonymous, citizen, or low-resource creators struggle if high-trust provenance depends on certified tools (voice can narrow)

- (-) [Normativity] → provenance is mistaken for truth, even when authentic content is misleading or selective (credibility can overreach)
- (-) [Security] → signing-key compromise, broken chains, or spoofed credentials trigger confidence crises (authenticity layer is attack surface)

## ART 12.099 — Privacy-Preserving Collaboration Protocols

Score: 10 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, privacy-preserving collaboration protocols directly enable joint analysis and decision support across organizational boundaries without requiring a single trusted central data holder. Second-order, they can widen participation in high-value coordination, lower legal friction, and reduce raw-data power hoarding, while also creating new dependence on cryptographic infrastructure and neutral compute layers. Third-order, once many parties can jointly reason over sensitive data without surrendering it, new forms of sectoral administration and cooperative governance become much more feasible. That is transformative for this GVN.

Weak signals (9):

- (+) [Cooperativeness] → agencies, firms, and civil-society actors begin running joint analytics without moving raw data (collaboration barrier falls)
- (+) [Choice and competition] → smaller actors join shared intelligence systems without ceding proprietary or personal records (entry broadens)
- (+) [Openness / privacy] → policy and contract templates increasingly specify approved outputs rather than raw-data transfer (governance architecture shifts)
- (+) [Decision quality] → fragmented evidence can be combined more frequently in planning, monitoring, and resource allocation (blind spots shrink)
- (+) [Subsidiarity] → local bodies keep custody of records while participating in broader governance calculations (local authority preserved)
- (-) [Structural power / neutral compute operators] → a few orchestration or secure-compute providers dominate trust relationships (new chokepoints emerge)
- (-) [Productivity] → latency and complexity still keep the most advanced use in well-resourced institutions first (capability gap persists)
- (-) [Equality] → actors lacking clean data or technical capacity gain less from the shared protocols (formal access may not equal benefit)
- (-) [Security] → leakage, collusion, or unsafe-output failures create visible legitimacy shocks (cryptographic trust must be maintained)

## ART 12.100 — Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

Score: 1 (Impact in GVN 20)

Justification (3–5 sentences):

First-order, this infrastructure mainly changes trust and scaling in advanced manufacturing rather than the core organization of joint decision-making. Second-order, it modestly affects who can enter

certified production networks and how quickly new local suppliers gain legitimacy. Third-order, the broader GVN impact remains limited unless certification infrastructure becomes a major template for other sectors' governance. That keeps the score at 1.

Weak signals (4):

- (+) [Choice and competition] → smaller producers enter public or high-assurance supply chains because conformance evidence is standardized (entry barrier lowers modestly)
- (+) [Productivity] → qualification cycles for new processes or suppliers shorten substantially (coordination friction falls)
- (-) [Structural power / certifiers] → accredited labs and standard owners dominate who counts as legitimate (gatekeeping persists)
- (-) [Equality] → audit and testing costs still favor large incumbents over small entrants (benefits distribute unevenly)

Signal density: LOW (linkage weak; additional signals would be speculative).

## Attachment 4. ART descriptions used in evidence gathering

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## Group 1 – Sensing, Measurement & Connectivity

### ART 01.001 Global Broadband Connectivity

Across the next two decades, multiple firms, public agencies, and research consortia are converging on a family of technologies aimed at delivering affordable, high-speed internet to essentially any point on the planet. Instead of relying on a single type of infrastructure, these “global broadband connectivity” systems integrate dense terrestrial 5G/6G deployments, low-Earth-orbit satellite constellations, and community-operated mesh networks. On the ground, next-generation wireless uses very high-frequency bands, including millimeter-wave and early terahertz ranges, combined with dense arrays of antennas and, in some environments, optical links such as Li-Fi, to massively expand wireless capacity where demand is concentrated. This mix of form factors balances coverage and cost: satellites bridge long distances and sparsely populated regions, while local mesh and short-range radios reuse inexpensive equipment and existing structures. Buildings, roadside fixtures, and other surfaces can be fitted with reconfigurable intelligent surfaces (RIS): thin, electronically tunable panels that subtly redirect and shape radio signals to improve coverage, reduce dead zones, and increase overall system efficiency without adding many active base stations. End users experience this as small, rugged terminals,

integrated antennas in everyday devices, or compact community access points that automatically select the best available path. The networks handle mobility, intermittent power, and variable weather by shifting traffic among satellites, ground stations, RIS-equipped structures, and peer nodes, using software-defined control and adaptive compression to keep latency and throughput within predictable ranges. Configuration and optimization are largely automated, updated remotely through standardized software interfaces. Technical constraints remain significant. High-capacity backhaul still requires energy-intensive ground stations and data hubs; user terminals and relays must balance performance with power consumption and environmental exposure; orbital congestion, spectrum and safety regulation, and security requirements shape how aggressively capacity can be expanded. Capital costs for a regional deployment are comparable to major transport infrastructure, while individual terminals and community nodes are in the range of current smartphones to small vehicles, depending on robustness and capacity. From a value-creation bottleneck perspective, this technology can ease constraints where unreliable or nonexistent connectivity limits what can be monitored, coordinated, or traded; where the scarcity of local expertise forces long delays for troubleshooting, training, or decision support; where data-heavy processes are infeasible because moving information is too slow or expensive; and where concentration of digital infrastructure in a few locations creates fragility, exclusion, or quality and safety risks for activities that depend on timely, synchronized information flows.

#### ART 01.002 Ultra Low Latency Networks

Over the next two decades, multiple infrastructure providers, device manufacturers, cloud platforms, and specialized research groups are converging on networking designs that drive end-to-end delays down to a few milliseconds. This push toward ultra-low latency builds on several factors: the spread of edge computing nodes closer to users and devices, more deterministic wireless and wired protocols, and tighter synchronization between communication and computation. The rationale is that many emerging digital and cyber-physical systems are limited not by raw bandwidth, but by how quickly they can sense, decide, and act across a network without noticeable lag or jitter. In practice, ultra-low latency networks combine densely distributed compute at the “edge,” specialized routing and scheduling that prioritize time-critical traffic, and hardware and software stacks that can guarantee bounded response times under realistic loads. They expose familiar interfaces—standard network APIs, software development kits, and management dashboards—but allow applications to request and monitor stringent timing guarantees. Within 20 years, such networks are likely to be available as configurable services in many regions, though constraints will remain: performance will depend on proximity to edge nodes and high-quality backhaul, energy use and cooling for dense infrastructure will be nontrivial, and specialized spectrum, chips, and timing equipment will be required. Deployment will be capital-intensive, with costs comparable to other major communication and industrial control assets, and subject to regulatory oversight around reliability, safety, and data handling. From a value-creation bottleneck perspective, this technology can reduce the delays and uncertainty that currently prevent remote or automated systems from reacting as quickly and precisely as local humans. It can ease constraints where coordination across many distributed devices is limited by network lag, where fine-grained feedback control is too unstable over today’s connections, where shared digital environments feel sluggish or desynchronized, and where time-critical decision-making is constrained by the need to keep computation and sensing co-located.

## ART 01.003 Edge AI for Sensor Data

Multiple firms, research labs, and standards bodies are developing edge AI for sensor data: hardware and software that let sensors themselves, or small devices very close to them, filter and interpret raw signals in real time. This approach is pursued because continuously streaming unprocessed data is costly, slow, and often impractical, while many environments require immediate, local decisions, stronger privacy, and reliable operation when conditions are messy, noisy, or degraded. By integrating low-power processors and compact AI models into cameras, microphones, meters, wearables, and embedded controllers, the technology aims to improve responsiveness, reduce network load, and enable autonomous operation even when connectivity is intermittent and sensor inputs are imperfect. Within a 20-year horizon, such systems are expected to handle multiple streams of data—video, audio, vibration, chemical readings, location, biometrics—directly at or near the point of capture. They run models that can detect anomalies, classify events, compress data into meaningful summaries, or trigger actions such as alarms or actuator changes, while remaining usable in adverse conditions such as low light, high background noise, occlusion, dust, or strong vibrations. Robustness is supported by techniques like sensor fusion, self-calibration, and uncertainty-aware detection that allow the system to degrade gracefully when data is partial or corrupted. Human interaction typically happens through familiar dashboards, mobile apps, and standard software interfaces, with higher-level systems configuring thresholds, updating models over the air, or coordinating many sensors as a distributed network. Devices learn and adapt over time by periodically synchronizing with more powerful cloud or on-premise systems that retrain models based on aggregated data from diverse, real-world conditions. Constraints remain significant. Energy and thermal budgets limit model size and duty cycles. Specialized chips and toolchains increase design complexity and may depend on specific manufacturing ecosystems. Maintaining robustness in rarely seen or extreme conditions demands extensive data collection, testing, and monitoring. Security and safety requirements can slow deployment, and unit costs may initially be comparable to or higher than advanced sensor modules or compact embedded computers. From a value-creation bottleneck perspective, this technology can ease constraints wherever continuous monitoring is needed but current solutions are too bandwidth-heavy, labor-intensive, fragile in the face of environmental disturbances, or slow to react. It can reduce dependence on centralized expertise by embedding more judgment near the source of events, lower the cost of high-frequency inspection and quality control even in harsh settings, and improve information flow where connectivity is unreliable, data is sensitive, or the physical environment is too unpredictable for conventional sensing setups.

## ART 01.004 Quantum & High Precision Sensing

Over the next two decades, multiple research labs, instrumentation companies, and consortia are expected to converge on a family of quantum and high-precision sensing technologies that make previously invisible phenomena measurable in routine settings. These approaches use carefully engineered quantum states of matter and light, as well as ultra-stable photonic and biochemical structures, because they can respond to tiny changes in fields, forces, time, or molecular composition far beyond the limits of today's sensors. They are being pursued not only for raw sensitivity, but also because many designs can be integrated into chip-scale packages, fiber networks, or compact probes that fit into existing measurement and control systems. In practical terms, this technology bundle

includes magnetometers that detect minute magnetic signatures, clocks that keep time with extreme stability, gravimeters that sense subtle changes in local gravity, and cold-atom inertial measurement units (IMUs) that use atom-interferometric accelerometers and gyroscopes to provide ultra-stable inertial references for navigation in GPS/GNSS-denied environments, as well as optical or biochemical sensors that register individual photons, molecules, or binding events. Devices are read out through standard digital interfaces and software, with built-in calibration and signal processing to filter noise and learn typical patterns over time. Some variants will be deployable as handheld tools or embedded chips; others will remain cabinet-sized instruments comparable in cost to current high-end laboratory or industrial equipment. Progress will be constrained by requirements for shielding, temperature control, and vibration isolation, by the need for specialized materials and fabrication methods, and by the complexity of maintaining and certifying such sensitive devices outside controlled environments. From a value-creation bottleneck perspective, this technology can make it practical to monitor slow, subtle, or distributed processes that today require destructive sampling, long averaging times, or highly skilled operators. It can reduce dependence on dense infrastructures of reference instruments or expert inspection by enabling remote, continuous, or automated measurements. It can ease bottlenecks where decisions are limited by coarse, infrequent, or indirect signals, and where the trade-off between measurement precision, cost, and intrusiveness currently forces crude approximations or wide safety margins.

#### ART 01.005 Micro/Nano Sensor Networks

Across research labs, semiconductor manufacturers, and infrastructure providers, there is active work on micro- and nanoscale sensor networks built from inexpensive chip-scale devices. The motivation is to push sensing closer to the phenomena being measured, in larger numbers and at lower cost than is feasible with conventional instruments. Using familiar manufacturing flows for microelectromechanical systems, printed electronics, and ultra-small integrated circuits keeps the form factor tiny and unit costs comparable to commodity electronic components, while allowing integration with existing packaging, power, and communication infrastructures.

Within a 20-year horizon, these networks are anticipated to consist of large constellations of “specks” and thin-film patches that measure temperature, vibration, strain, motion, chemical markers, humidity, or light, and in some cases simple acoustic or electromagnetic signatures. Individual nodes may harvest energy from light, heat, motion, or radio waves, or rely on very small batteries, and communicate via low-power radios or by modulating and reflecting ambient signals. Clusters of nodes relay data to nearby gateways, where more capable processors filter, compress, and forward information to larger digital systems. Configuration and firmware updates propagate wirelessly, while basic analytics at the edge allow nodes to adapt sampling rates or trigger alerts autonomously.

Key constraints include limited energy budgets per node, finite lifetimes for any embedded power source, and the need for low-cost but reliable manufacturing, calibration, and packaging at very large volumes. Data transport and storage become non-trivial as billions of measurements accumulate, and there are practical limits on wireless spectrum usage and interference. Environmental robustness, safe disposal of materials, and regulatory requirements for radio emissions and data handling also shape deployment. From a cost perspective, individual sensors are expected to be very cheap, but full

deployments resemble other distributed infrastructure investments once installation, gateways, and data systems are included.

From a value-creation bottleneck perspective, this technology can reduce reliance on periodic manual inspections and sparse measurements by providing continuous, fine-grained awareness of distributed physical assets and environments. It can ease constraints where limited human presence, attention, or safety concerns prevent frequent measurements. It can make it feasible to monitor many more points than would be affordable with today's instrumentation, shifting constraints from the cost of sensing hardware toward how information is filtered, interpreted, and acted upon. It can also mitigate bottlenecks linked to early fault detection, gradual degradation, and subtle environmental changes that currently go unnoticed until they cause visible failures or losses.

#### ART 01.006 Privacy Preserving Pervasive Sensing

Across research labs, platform companies, and standards consortia, work is emerging on privacy-preserving pervasive sensing: ways of building sensor systems so that data protection is designed in from the start rather than added later. The basic idea is that as microphones, cameras, wearables, vehicles, and built environments fill with sensors over the next two decades, most of the interpretation and decision-making happens close to where the data is generated, and any information that leaves a device or local cluster is encrypted, heavily compressed, or stripped of identifying details. This approach is pursued because it reduces the need to pool raw data in central servers, lowers legal and reputational risks, and makes continuous sensing more acceptable to regulators and the public, while remaining compatible with existing computing hardware and network infrastructure.

In practice, such frameworks combine on-device analytics, secure chips, and cryptographic protocols. Devices learn patterns over time, update models via secure channels, and share only aggregate or statistically protected outputs rather than full recordings. Configuration happens through standard software interfaces that let users or organizations set policies about what is collected, how long it is retained, and what is shared with whom. Within 20 years, it is plausible that many everyday sensing systems default to this pattern, though constraints remain: processing locally can consume more energy and computing power, strong encryption adds latency, and strict privacy guarantees may limit the resolution or richness of available data. Costs per sensing node are likely comparable to today's networked embedded electronics, with additional expense arising from specialized chips, software stacks, and compliance processes.

From a value-creation bottleneck perspective, this technology can ease constraints wherever continuous observation or fine-grained tracking would be useful but is currently blocked by privacy concerns, legal uncertainty, or lack of social trust. It can reduce the need for manual inspections and audits while limiting exposure of sensitive information, and it can support data-driven optimization without requiring centralized access to raw personal data. It also addresses frictions around cross-border data flows and long-term retention, enabling organizations to use rich sensor inputs while narrowing what must be stored, governed, and secured at scale.

### ART 01.007 Quantum-Resilient and Secure Communication Networks

Over the next two decades, multiple network equipment vendors, cloud providers, cryptography labs, and standards consortia are developing communication infrastructures that remain secure even in the presence of large-scale quantum computers. Quantum-resilient and secure communication networks combine new families of cryptographic algorithms with redesigned network hardware and control layers so that long-lived data, identities, and control signals cannot be decrypted retrospectively when current protections become vulnerable. This approach is attractive because it can be introduced incrementally into existing fiber, satellite, and wireless systems, while offering a path to upgrade individual components as cryptanalytic knowledge and hardware capabilities evolve. In practical terms, such networks use post-quantum encryption and authentication schemes, sometimes augmented by quantum key distribution links, embedded in routers, base stations, and endpoints. They provide end-to-end protection not only for message contents but also for metadata, with mechanisms to limit traffic analysis and impersonation. Policy engines continuously negotiate which cryptographic algorithms and key lengths to use, enabling graceful transition as standards change. Integrated monitoring detects anomalies that might indicate key compromise, protocol downgrade, or hardware tampering, automatically re-routing traffic through more trusted paths. These capabilities are constrained by the computational and energy overhead of more complex algorithms, the cost of specialized secure hardware, and the need for global interoperability standards and certification regimes. In many deployments, the cost profile resembles that of upgrading to a new generation of enterprise networking gear or control infrastructure, rather than a full physical rebuild. From a value-creation bottleneck perspective, this technology can reduce the risk that long-term sensitive information is exposed by future cryptanalytic breakthroughs, lower the coordination burden of maintaining secure communication across many organizations and jurisdictions, and ease constraints where remote operation, high-stakes decision-making, or automated systems are limited by fear of interception, manipulation, or loss of integrity in the underlying networks.

### ART 01.008 Integrated Sensing and Communication (ISAC)

Over the next two decades, multiple wireless equipment vendors, standards bodies, and research consortia are expected to develop integrated sensing and communication (ISAC) systems, in which the same radio infrastructure simultaneously carries data and performs radar-like sensing. This approach is pursued because it can reuse spectrum, base stations, devices, and processing hardware that are already needed for high-capacity wireless networks, rather than deploying separate sensing infrastructure. By tightly coordinating antennas, signal waveforms, and timing across a network, ISAC aims to turn dense communication grids into distributed sensor arrays that are more cost-effective and scalable than standalone sensing installations.

At a functional level, ISAC nodes transmit and receive radio signals that both encode information and measure reflections from objects and environments. The network can infer distance, motion, and coarse shapes, and track how these change over time, while still delivering high-rate data to devices. Advanced signal processing and machine-learning models fuse measurements from many nodes, improving resolution and robustness compared with isolated sensors. Humans and software systems interface with ISAC through familiar devices, dashboards, and APIs, while configuration and adaptation are handled largely by remote software updates and data-driven models that learn typical patterns and anomalies in each environment.



Feasibility is constrained by spectrum allocation, hardware cost, and the need for precise synchronization across many transmitters and receivers. There are trade-offs between sensing resolution and communication throughput, as well as energy use and heat in dense installations. Regulatory requirements, privacy safeguards, and cybersecurity add further complexity. Economically, ISAC capabilities are likely to be introduced as incremental upgrades to existing network equipment, with costs similar to other major communication infrastructure generations rather than entirely new capital categories.

From a value-creation bottleneck perspective, this technology can ease constraints where continuous, fine-grained awareness of physical surroundings is currently too expensive or fragmented, where coordination depends on delayed or partial information, where safety or reliability hinge on detecting small changes in crowded or complex spaces, and where human attention and line-of-sight sensing limit how many assets or processes can be monitored and controlled at once.

## Group 2 - Computing Hardware & Non-Von-Neumann Paradigms

### ART 02.009 Compute-in-Memory & Neuromorphic Chips

Compute-in-memory and neuromorphic chips are being pursued by semiconductor companies, research labs, and joint industry-academic consortia as an alternative to today's conventional processor architectures. The core rationale is to reduce the energy and time wasted moving data back and forth between separate memory and logic units, a bottleneck that becomes especially severe for data-intensive and AI workloads. By tightly fusing memory and computation, often using memristor crossbar arrays or other non-volatile devices, and by introducing neuron-like analog or mixed-signal circuits, these chips aim to offer much higher energy efficiency and throughput within a similar or smaller physical footprint than current accelerators.

Within a 20-year horizon, this technology is anticipated to take the form of specialized chips or chiplets that can be embedded in servers, edge devices, and dense sensor platforms. In compute-in-memory blocks, operations such as matrix multiplications are performed directly where data is stored, while neuromorphic regions process information as streams of sparse "events" rather than as fixed-rate digital signals. The chips expose standard digital interfaces and programming tools so they can be orchestrated alongside CPUs and GPUs, while internal learning or adaptation may use data-driven models, local update rules, or remote updates pushed over networks. Key constraints are likely to include manufacturing complexity, device variability, susceptibility to analog noise, and the need for new software stacks to map algorithms efficiently onto these architectures. Costs are expected to be in the range of advanced application-specific accelerators, reflecting reliance on leading-edge fabrication and sometimes on less mature materials.

From a value-creation bottleneck perspective, this technology can relieve constraints wherever data movement and memory access dominate energy use and latency, enabling continuous processing of rich data streams under tight power or thermal budgets. It can ease limitations where real-time pattern recognition or control is currently too expensive or power-hungry to deploy widely, or where

dependence on remote data centers introduces delay and connectivity risks. It can also mitigate frictions related to the privacy and security of sensitive data by allowing more computation to occur close to where data is generated, reducing the need to transmit raw information over shared networks.

#### ART 02.010 Novel transistor technologies and materials beyond silicon CMOS

Multiple research labs, semiconductor companies, and cross-industry consortia are exploring transistor designs and materials that move beyond the limits of today's silicon-based CMOS chips. These efforts focus on structures built from carbon nanotubes, atomically thin "2D" materials, spin-based devices, and ultra-low-energy switching mechanisms such as tunnel or single-electron transistors, alongside more radical device families that enable reversible logic and superconducting switching with minimal energy dissipation. The rationale is straightforward: conventional silicon scaling is running into physical and economic barriers, so new device concepts are being pursued that can switch with far less energy, pack more functions into a given area, or operate reliably in environments where standard electronics struggle. Over a 20-year horizon, this technology is anticipated to take the form of families of transistor-like components and integrated chips that can be manufactured at large scale and combined with existing digital design flows, in some cases complemented by cryogenic or specialized subsystems where superconducting logic is justified. At the device level, they aim to provide faster or more energy-efficient switching, non-volatile behavior in some cases (retaining state without constant power), more reversible computation steps that reduce waste heat, and the ability to stack logic and memory more densely in three dimensions. These components would still be addressed through familiar digital interfaces, but underlying circuits could support new computational styles, such as very low-power always-on sensing, high-throughput signal processing, or tightly integrated compute and storage close to data. Key constraints include the complexity of manufacturing at atomic or near-atomic precision, variability between devices, integration with established fabrication lines, and ensuring long-term reliability under real operating conditions, with additional infrastructure and operating-cost demands where superconducting operation is used. Costs are likely to resemble or modestly exceed those of advanced semiconductor processes today, with higher expense justified for functions where performance, energy, or form-factor gains are critical. From a value-creation bottleneck perspective, this technology can ease constraints where current electronics are limited by heat and power budgets, where high-performance computation cannot be placed close enough to data or sensors, where device miniaturization is blocked by silicon scaling limits, and where long-lived, ultra-low-maintenance electronics are needed but frequent battery changes, active cooling, or bulky packaging are unacceptable.

#### ART 02.011 Quantum Computing Platforms

Over the next two decades, multiple companies, research labs and public-private consortia are expected to build quantum computing platforms that combine scalable quantum processors with conventional digital infrastructure. These platforms use different physical approaches to realize quantum bits, including superconducting circuits operating at cryogenic temperatures, chains of trapped ions controlled by lasers, photonic circuits guiding single photons, and emerging topological schemes designed to stabilize quantum states. These form factors are pursued because they can, in principle, perform certain calculations in ways that scale more favorably than classical architectures, while still fitting into data-center-like environments and supply chains built around advanced

microelectronics, precision optics and cryogenics. In practical terms, a quantum computing platform in this horizon looks like a tightly integrated system in which a classical control stack prepares, manipulates and reads out qubits through carefully timed electromagnetic or optical pulses. Users interact with it through familiar software interfaces and high-level programming languages, often sending workloads over a network to remote quantum accelerators. The machine is specialized rather than general-purpose: it is most effective for problems where interference among many quantum states can be exploited, such as combinatorial optimization, high-dimensional pattern search, and simulation of complex quantum or stochastic systems. Key constraints include sensitivity to noise and fabrication defects, limited qubit counts and connectivity, the need for extreme cooling or ultra-high vacuum, and specialized talent to design algorithms and operate the hardware. Costs are initially comparable to or above current high-end supercomputing facilities, with access delivered as a metered service. From a value-creation bottleneck perspective, this technology can relax constraints where brute-force exploration of possibilities is currently infeasible, where approximate heuristics dominate because exact methods are too slow, where understanding the behavior of complex interacting components requires oversimplified models, and where requirements for secure communication or verification of computation create overheads that limit the scale, speed or inclusiveness of digital processes.

## ART 02.012 Photonic and Optical Computing

Multiple research groups, equipment manufacturers, and computing companies are exploring photonic and optical computing as a way to overcome the energy and bandwidth limits of electronics. Instead of moving and switching electrical charges on metal interconnects, these approaches use photons traveling through waveguides, fibers, and integrated optical components to perform parts of computation and data movement. The appeal lies in the very high bandwidth, low signal loss over distance, and reduced heat generation that optical signals can offer, alongside the potential to co-design processors, memory, and interconnects around light-based operations.

Within a 20-year horizon, photonic and optical computing is anticipated to appear as a layered stack of technologies: chip-scale optical cores performing specialized operations such as matrix multiplications, ultra-dense optical interconnects linking processing units and memory, and hybrid electro-optic modules where conventional electronics handle control, storage, and general-purpose logic. Computation may exploit interference, modulation, and wavelength multiplexing, with reconfigurable optical elements adjusted by electronic control circuits or programmable materials. Interfaces to humans and existing software will likely remain familiar—standard programming languages, APIs, and development tools—while compilers and runtime systems map workloads onto optical accelerators and interconnects without exposing low-level physics.

Key constraints include the complexity and cost of fabricating precise optical structures at scale, the need for reliable light sources and detectors, and sensitivity to alignment, temperature, and fabrication tolerances. Many designs still depend on electronic conversion at the edges, which can limit end-to-end gains. Systems will also require significant upfront investment in new manufacturing lines, test equipment, and design tools, even if unit costs eventually become comparable to high-end processors and network equipment today.

From a value-creation bottleneck perspective, this technology can ease constraints where information processing is limited by interconnect bandwidth, latency, and energy consumption, enabling more

intensive computation within existing power and cooling envelopes. It can relax bottlenecks where long-distance or high-density data movement is costly or slow, and where scaling up conventional hardware runs into thermal or floor-space limits. It can also reduce frictions in building large, tightly coupled computing systems that must operate continuously, by offering more predictable performance under heavy load and lowering dependence on incremental gains in traditional transistor scaling.

### ART 02.013 Next-Gen Memory & Storage

Multiple research labs, semiconductor firms, and new storage ventures are pursuing a new class of memory and storage technologies, driven by the growth of digital data that is straining the capacity, energy use, and physical footprint of conventional storage and motivating media with higher density and longevity. Over the next two decades, families of “universal” memories based on magnetoresistive and resistive effects, advanced non-volatile flash structures, and molecular or DNA-based encodings are expected to mature from niche experiments into tightly integrated components of computing platforms. DNA-based storage encodes bits in DNA’s ultra-dense, chemically stable structure, enabling long-term archives in tiny volumes, while molecular and DNA-based biocomputing explores using these substrates to perform simple search or logical operations within stored data. In practice, such technologies would allow systems to keep larger datasets live in place, with memories that retain information when powered off, endure many more write cycles than current flash, and in some implementations perform processing directly where the data is stored rather than shuttling it back and forth to separate processors. A next-generation memory stack would combine layers of ultra-fast, byte-addressable non-volatile memory near processors with denser, slower layers for bulk or archival data, potentially including DNA storage libraries accessed through automated handling and sequencing, all orchestrated by software that moves and compresses information dynamically. Key constraints include specialized manufacturing, sensitivity to defects, dependence on particular material or biochemical infrastructures, and demanding error-correction and long-term stability for extremely dense or molecular media; DNA approaches in particular trade high density for high latency and higher operating costs. Early costs are likely comparable to or modestly above current premium memory and solid-state storage, with gradual reductions as volumes rise. From a value-creation bottleneck perspective, this technology can ease constraints where systems are limited by memory size, data movement, or input/output latency; where data growth collides with energy and space ceilings; where the cost or footprint of retention suppresses experimentation or long-term preservation; and where slow loading, backup, or reconstruction of critical state makes digital systems fragile or hard to operate at global scale.

### ART 02.014 Molecular Computing

Over the next two decades, multiple research groups, startups and consortia are likely to push forward molecular computing platforms that use chemical and biological reactions, such as DNA strand interactions, as the basic medium of computation. This direction is pursued because these substrates can operate at extremely small scales, in environments where electronics are hard to deploy, and with energy profiles and parallelism that differ markedly from conventional silicon chips. Rather than moving electrons through transistors on a rigid wafer, information is encoded in the presence, concentration and arrangement of molecules that react according to designed rules. In its mature form, this anticipated technology combines engineered reaction networks, molecular “logic gates,” and

responsive structures that can store, transform and propagate information within liquids, gels or confined microstructures. Computation may occur in bulk solutions, within microfluidic systems, or embedded in living or synthetic assemblies, with external interfaces provided by optical, electrical or mechanical readout and control systems. Reconfiguration would largely be achieved by changing the molecular programs—adjusting sequences, catalysts or reaction conditions—rather than redesigning hardware.

Feasibility over a 20-year horizon depends on advances in high-fidelity synthesis, error-correcting molecular encodings, automated design tools, and standardized reactors. Limitations are likely to include slower raw operation speeds compared to electronic processors, sensitivity to temperature and contamination, and the need for specialized fabrication and operating environments. Cost structures may initially resemble those of advanced analytical instruments or custom materials, but could move toward commodity chemical manufacturing in high-volume applications.

From a value-creation bottleneck perspective, this technology can ease constraints wherever information processing must occur directly within complex chemical or biological environments, reducing the need to extract samples or maintain continuous human supervision. It can address tasks limited by the mismatch between digital abstractions and the fine-grained dynamics of molecular systems, enabling local decision-making, pattern recognition and control that are currently too slow, labor-intensive or imprecise. It can mitigate bottlenecks where energy use, device miniaturization, or harsh operating conditions make traditional electronics impractical, and where existing materials or components cannot tightly couple sensing, computation and actuation at the same microscopic scale.

## Group 3 – Artificial Intelligence & Learning Systems

### ART 03.015 Causal Learning & Reasoning

Multiple research groups, technology companies, and open-source communities are developing causal learning and reasoning systems as a way to move beyond today's pattern-matching AI. The core rationale is that many decisions depend not only on predicting what is likely to happen, but on understanding what will happen if something is changed: a price is adjusted, a setting is tweaked, a new policy is introduced. Over the next 20 years, this technology is anticipated to take the form of software frameworks, libraries, and embedded services that represent cause-and-effect relationships explicitly, infer underlying mechanisms from data and expert input, and simulate the consequences of possible actions. These representations can span both abstract decision structures and physical causal world models that approximate how interventions propagate through real-world systems and environments. In many cases, these systems will be implemented as hybrid, neuro-symbolic architectures that pair neural pattern-learning modules with explicit causal and logical representations. They would ingest historical and real-time data, combine it with structured assumptions or domain knowledge, and maintain models that can answer “what if” and “why” questions, not just “how often.” Causal components may function as stand-alone

decision-support tools or as integrated modules within broader reasoning models, including language- and multimodal-based systems that call causal solvers when they need grounded intervention predictions or counterfactual analyses. They interact with humans via dashboards, natural-language interfaces, and APIs, allowing users to pose counterfactual queries, explore alternative scenarios, and receive suggested interventions with explanations about the assumed causal pathways. Configuration and adaptation would blend data-driven learning with human feedback, using experiments, A/B tests, and observational data to refine causal graphs, physical world models, and associated uncertainty estimates. In practice, causal AI is constrained by data quality, the difficulty of discovering reliable causal structures, and the risk of hidden confounders; it also depends on access to experimentation channels, integration with larger reasoning infrastructures, and sufficient computing resources, and is likely to be priced similarly to advanced analytics and decision-support software. From a value-creation bottleneck perspective, this technology can ease constraints wherever actions must be chosen under uncertainty about side effects, where trial-and-error is slow or risky, where human decision-makers are overwhelmed by complex interdependencies, and where it is difficult to attribute outcomes to specific causes. By making intervention effects more predictable and interpretable, it can reduce costly missteps, improve the design of processes and policies, and support more deliberate trade-offs between efficiency, resilience, and risk.

#### ART 03.016 Federated & Privacy-Preserving Learning

Federated and privacy-preserving learning is being developed by major technology firms, cloud providers, research labs, and domain-specific consortia as a way to train AI systems on sensitive information without moving that information into a single central repository. The underlying rationale is that many of the most valuable datasets are fragmented across organizations and devices, subject to strict confidentiality rules and public expectations of privacy, making traditional “collect everything to one place” approaches increasingly costly, risky, or illegal. Over the next 20 years, this family of techniques is anticipated to mature into a standard AI infrastructure layer in which models are dispatched to where the data resides, learn from it locally, and only return carefully processed updates. These updates can be aggregated so that the global model improves from many participants, while individual records never leave their original environment. The systems will mix several tools: secure hardware zones that isolate computation, cryptographic protocols that ensure updates cannot be easily reverse-engineered, and statistical methods that add controlled randomness to further blur any link to specific people or transactions. At scale, such infrastructures will depend on reliable connectivity, coordination servers, and device capabilities, and will carry overheads in communication, computation, and engineering compared with conventional centralized training. They will also remain constrained by the quality and balance of data available at participating sites and by evolving privacy regulation. Costs are likely to resemble those of operating large distributed software platforms, with additional investment in specialized security and compliance components. From a value-creation bottleneck perspective, this technology can ease constraints wherever useful patterns are locked inside sensitive or fragmented datasets that currently cannot be pooled. It can reduce risks and effort tied to copying and transporting confidential information, and lower barriers to using AI where trust, consent, or



jurisdictional rules limit data sharing. It can help overcome bottlenecks created by scarce technical staff in smaller organizations by enabling them to benefit from shared models without surrendering control of their raw data. It can also address frictions in human–AI interaction by supporting models that adapt to local conditions and individual devices while keeping personal histories and contextual signals close to the user rather than in distant data centers.

### ART 03.017 Trustworthy AI Systems

Multiple research labs, companies, and standards bodies are working toward families of “trustworthy AI systems” that can be deployed in high-stakes settings without requiring constant expert supervision. The underlying rationale is that today’s powerful AI models remain brittle, opaque, and hard to control; this technology line focuses on architectures, tools, and processes that make AI behavior predictable, auditable, and aligned with specified rules and explicit value and fairness criteria, even under stress, error, or malicious interference. Over the next two decades, this is expected to take the form of AI components and platforms that combine robust learning algorithms, formal verification techniques, secure execution environments, and rich monitoring layers with mechanisms for internal self-monitoring and self-correction. These systems expose clear interfaces for configuring objectives, constraints, and escalation paths grounded in human-defined values, and provide human users with explanations, provenance traces, and confidence indicators rather than opaque outputs. They are updated through managed pipelines that track training data sources, model versions, and policy changes, and they incorporate built-in defenses against adversarial inputs, data poisoning, and unauthorized access. Internally, they can detect shifts in their own behavior, identify potential bias or anomalies, and trigger automatic recalibration, safe fallback modes, or requests for human review without external prompting. Practical implementations will face constraints: strong guarantees may only apply within well-specified operating envelopes; achieving robustness, transparency, and value alignment will add computational overhead, data requirements, and engineering complexity; and the technology will depend on high-quality data, cryptographic infrastructure, and organizational governance to be effective. Cost levels are likely to resemble large-scale enterprise software combined with specialized infrastructure and compliance services. From a value-creation bottleneck perspective, this technology can reduce the risk and uncertainty associated with delegating complex tasks to automated systems, lower the cognitive and documentation burden of oversight, and ease frictions where lack of explainability, fairness assurance, or auditability currently blocks the use of AI. It can also address bottlenecks where coordination among many stakeholders, strict safety or integrity requirements, or exposure to adversarial behavior make conventional, non-self-monitoring AI solutions too fragile, opaque, or socially unacceptable to adopt.

### ART 03.018 Automated Machine Learning (AutoML)

Over the next two decades, multiple companies, research labs, and cloud platforms are expected to develop increasingly capable automated machine learning (AutoML) systems that design and train models with minimal human intervention. The rationale is to remove the current dependence on scarce expert practitioners who must manually choose model architectures, tune parameters, engineer features, and manage complex training pipelines. AutoML builds on existing software and hardware environments, wrapping them in orchestration layers that search through many candidate approaches, benchmark their performance, and deploy the best-performing models in a more standardized way. This



increasingly includes not only supervised and generative models, but also reinforcement learning setups where agents are trained through trial-and-error in simulated and real environments.

In mature form, this technology behaves as a configurable “model and agent factory.” Given data, simulators, or live interaction logs and a high-level goal, an AutoML system can clean and transform inputs, propose alternative model families, agent architectures, and training strategies, and iteratively refine them using feedback signals, reward functions, and performance metrics. It interfaces with humans through dashboards, natural language prompts, and standard APIs, allowing non-specialists to request predictive, generative, or decision-making capabilities without understanding the underlying algorithms. For interactive systems, AutoML can manage safe exploration policies, scenario generation, and transfer from simulation to constrained real-world trials. Over time, these systems are expected to become more self-reflective, monitoring failures, suggesting constraints to improve robustness, and automatically retraining or rolling back models and agents when data drifts or behavior degrades.

Constraints remain significant. AutoML depends on large, representative datasets or simulators, substantial computing resources, and reliable infrastructure for experimentation and deployment. It can amplify biases or unsafe strategies if reward functions and guardrails are poorly specified, and governance remains essential. Costs may range from subscription software tiers comparable to other enterprise platforms up to dedicated infrastructure investments similar to other large-scale information systems. From a value-creation bottleneck perspective, this technology can reduce reliance on scarce specialist labor for many routine model- and agent-building tasks, shorten experimentation cycles that currently take weeks or months, and lower the cost of exploring alternative solutions to complex decision and control problems. It can ease constraints where organizations struggle to maintain consistent model and agent quality over time, where inconsistent documentation and hand-tuned codebases create fragility, and where decision-making is limited by the speed and safety with which new data and experience can be translated into functioning predictive, generative, and interactive tools.

### ART 03.019 Collaborative Multi-Agent AI

Collaborative multi-agent AI refers to collections of software agents and physical devices that sense, decide, and act together as a coordinated whole rather than as isolated units. Over the next two decades, research labs, platform providers, and hardware manufacturers are expected to develop architectures where dozens, hundreds, or even millions of agents—ranging from small embedded controllers to mobile robots and virtual services—share information, negotiate roles, and learn joint strategies to achieve common goals. This approach is pursued because distributed agents can cover large areas, handle many small tasks in parallel, and continue operating when individual units fail, while remaining compatible with existing communication networks, sensor hardware, and software interfaces. In practical terms, such systems may combine fixed sensors, mobile machines, and purely digital agents that exchange messages over wireless networks and software APIs, maintain shared maps or task queues, and update their behavior based on collective experience. Coordination mechanisms mix preprogrammed rules with data-driven models so that agents can form ad-hoc teams, allocate tasks dynamically, and adapt to changing conditions without requiring a central controller to micromanage each action. Human interaction typically happens through dashboards, voice or text interfaces, and standard control tools that allow people to set objectives, adjust safety limits, and override decisions at different levels of detail. Key constraints include reliance on robust connectivity and positioning systems, the challenge of avoiding interference and congestion when many agents

communicate at once, and the need for fail-safe behaviors when sensing is unreliable or parts of the network go down. There are also costs associated with deploying and maintaining large numbers of devices, though individual units can be as inexpensive as commodity sensors or consumer-grade machines, with higher costs concentrated in supervisory software and specialized platforms. From a value-creation bottleneck perspective, this technology can reduce the need for sustained human presence in repetitive, dispersed, or hazardous monitoring and intervention tasks, ease limits imposed by finite human attention when many small events must be tracked simultaneously, and enable large-scale search, inspection, or servicing activities that are currently too slow or expensive when performed by a small number of centrally controlled systems. It can also mitigate frictions caused by fragmented data and poor situational awareness, since many agents can continuously share observations, cross-check each other's readings, and feed aggregated insights into human–AI decision-making loops.

### ART 03.020 Quantum-Accelerated AI Systems

Quantum-accelerated AI systems are being pursued by major computing companies, specialized quantum start-ups, and research consortia as they look for ways to push past the scaling limits of classical hardware. The rationale is that certain learning and decision problems become prohibitively slow or energy-intensive on conventional machines once data sizes and model complexity reach current extremes. By coupling AI algorithms to quantum processors—typically accessed remotely via specialized data centers—developers aim to offload the most computationally difficult subroutines while keeping the overall systems compatible with existing software stacks and user workflows. Over the next twenty years, these systems are expected to take the form of hybrid platforms in which classical AI models call quantum routines for tasks such as exploring vast spaces of possible configurations, refining model parameters, or evaluating many candidate solutions in parallel. From the user's perspective, they would interact through standard interfaces such as APIs, dashboards, and conversational agents, while orchestration layers decide when and how to invoke quantum resources. The technology will depend on maturing quantum hardware, error correction techniques, and robust scheduling software, and will likely be constrained to problem classes where quantum speedups or accuracy gains justify higher complexity and cost. Access may resemble that of premium high-performance computing services, with costs comparable to or exceeding large-scale accelerator clusters, and with dependencies on specialized cryogenic and control infrastructure concentrated in a limited number of facilities. From a value-creation bottleneck perspective, this technology can ease constraints wherever current AI systems are blocked by combinatorial explosion, limited search depth, or the need to evaluate many tightly coupled variables under uncertainty. It can relax bottlenecks created by long optimization cycles, high energy use for large-scale training, and the scarcity of bespoke high-end computing capacity, while also reducing frictions in complex planning, allocation, and pattern-finding tasks that are currently too slow or expensive to tackle at full scale.

### ART 03.021 AI-Driven Autonomous Scientific Discovery

Multiple research labs, technology companies, and public–private consortia are developing AI systems aimed at automating large parts of the scientific discovery process. The core rationale is that many research fields are now limited less by instruments and more by human capacity to generate, prioritize, and test ideas within vast spaces of possible hypotheses, experimental configurations, and datasets. An AI-driven autonomous discovery system is designed to operate as a continuously learning “research

engine” that proposes questions, designs experiments or simulations, and interprets results with minimal manual steering, while still remaining inspectable and configurable by human experts.

Within a 20-year horizon, such systems are expected to couple large-scale machine learning models with structured scientific knowledge and access to high-throughput experimental or simulation platforms. They would ingest diverse data streams, detect patterns or anomalies, and then generate candidate hypotheses expressed in human-readable language and machine-executable workflows. The system could schedule and parameterize experiments, interface with robotic instruments or virtual environments, and iteratively refine its models as new results arrive. Human users would interact through natural-language dialogue, visual dashboards, and standard software interfaces, setting goals, constraints, and safety boundaries rather than micromanaging each step. Deployment costs would likely resemble those of major research infrastructure or enterprise software platforms, combining substantial up-front investment with scalable cloud-based or on-premise computing.

Key constraints include dependence on high-quality, well-curated data; significant compute and storage needs; integration with specialized equipment; and requirements for verification, safety review, and regulatory compliance in sensitive domains. From a value-creation bottleneck perspective, this technology can ease constraints wherever exploration spaces are too large for human trial-and-error, where experiments are slow or expensive, where skilled researchers are scarce, or where complex datasets overwhelm human pattern recognition. It can also reduce frictions in monitoring and documenting the research process, systematically tracking assumptions, uncertainties, and negative results, and thereby shortening feedback loops between ideas, experiments, and practical application.

## Group 4 – Human-Machine Interaction & Augmentation

### ART 04.022 Immersive Augmented & Virtual Reality

Over the next two decades, multiple device manufacturers, software platforms, and research consortia are expected to converge on immersive augmented, virtual, and mixed reality systems that make digital content feel co-present with the physical world. Lightweight AR glasses build on existing eyewear and mobile electronics, aiming for all-day wearability, compatibility with current computing ecosystems, and lower marginal costs per user, while more enclosed VR/MR headsets and room-scale installations prioritize full immersion and precise spatial control. Together, these systems are anticipated to offer high-resolution, wide-field-of-view displays, accurate depth perception, and persistent digital objects that remain anchored to real-world surfaces and locations. They will sense their surroundings through cameras and depth sensors, track eye and hand movements, and capture body posture, combining this with spatial audio and optional haptic feedback to create a coherent mixed environment. Users will interact via natural speech, gaze, gesture, and familiar controllers, while standard software interfaces allow existing applications and data systems to be extended into 3D space. Over time, on-device and cloud-based models learn individual preferences and work patterns, adjusting interfaces, filtering information, and updating capabilities remotely. Key constraints remain in battery life, thermal management, optical quality in compact form factors, and the need for reliable connectivity and secure data handling. Production of high-quality spatial content and calibration of devices to diverse users also impose costs, with personal devices expected in a range comparable to smartphones and laptops, and shared immersive spaces closer to vehicles or industrial equipment. From a value-creation bottleneck perspective, this technology can reduce the time and error involved in understanding complex physical

layouts, enable remote participants to share a “first-person” view of environments that are distant or hard to access, and offload cognitive effort by layering just-in-time spatial guidance directly into a user’s field of view. It can ease coordination and training bottlenecks where procedural knowledge is hard to transmit through text or 2D screens, and it can mitigate frictions where limited expert presence, constrained attention, or poor situational awareness currently slow down monitoring, decision-making, and collaborative problem-solving.

#### ART 04.023 Brain-Computer Interfaces (BCI)

Over the next two decades, a range of companies, research institutes, and public–private consortia are advancing brain–computer interfaces (BCIs) that create relatively high-bandwidth communication pathways between human brains and digital systems. These efforts span non-invasive wearable caps that measure electrical or optical signals at the scalp, minimally invasive electrode arrays resting on the brain surface, and fully implanted neural interfaces that can both record and stimulate activity. The rationale for this family of approaches is to bypass some of the bottlenecks of conventional input devices and screens by reading and writing information closer to the underlying neural processes, while still remaining manufacturable, maintainable, and safe at scale. In a mature form, such BCIs would sense patterns of neural activity in real time, translate them into control signals or abstract representations, and send feedback in the form of visual, auditory, haptic, or direct neural stimulation. Users might interact through imagined movements, shifts of attention, or higher-level intentions rather than explicit physical gestures. Over time, adaptive decoding algorithms would personalize to each individual’s brain signals, and software updates would extend capabilities without hardware changes. The hardware would be packaged in wearable or implantable form factors designed for continuous or frequent use, with wireless connectivity to local devices or remote compute resources. Key constraints include surgical risk and biocompatibility for implanted systems, signal quality and noise for non-invasive devices, power consumption, heat, and the need for secure handling of highly sensitive neural data. Costs would likely span from advanced consumer devices to assets comparable in expense to specialized medical or industrial equipment. From a value-creation bottleneck perspective, this technology can ease constraints wherever fine motor control, speech, or conventional interfaces limit how quickly and precisely people can act; where cognitive overload and fragmented attention reduce the quality of decisions; where distance or lack of access to specialized facilities restricts participation; and where current tools cannot capture or modulate internal states with sufficient speed, nuance, or reliability to support learning, coordination, or sustained performance.

#### ART 04.024 Advanced Prosthetics & Exoskeletons

Multiple research labs, robotics firms, and clinical engineering groups are developing advanced prosthetics and wearable exoskeletons that integrate more closely with the human body and nervous system. This direction is pursued because improved sensing, actuation, and bio-integration promise to restore or augment mobility and strength while remaining wearable in everyday environments, interoperable with existing medical and industrial tools, and manufacturable at scale with acceptable reliability and cost. Over the next 20 years, these systems are expected to combine lightweight mechanical structures with high-torque, low-noise actuators, dense sensor arrays, and adaptive control software. Prosthetic limbs will increasingly interface with muscles, peripheral nerves, or residual joints, allowing users to initiate movement through natural signals and to receive some level of haptic or pressure feedback. Exoskeletons will be worn over clothing or integrated into garments, supporting or amplifying the user’s movements, adjusting assistance based on posture, fatigue, or task, and

communicating via simple user interfaces, voice, or standard digital devices. Learning and configuration will rely on a mix of pre-trained models and individualized calibration over time. Constraints are likely to include energy density of batteries, overall mass and comfort, durability of moving parts, and the complexity and cost of surgical or semi-invasive interfaces for deeper integration. Devices may range in cost from that of a small vehicle to an industrial machine, with simpler assistive exosuits priced closer to high-end consumer equipment. From a value-creation bottleneck perspective, this technology can reduce the burden of physically demanding or repetitive tasks, extend the productive participation of people with limited mobility or strength, and mitigate constraints related to fatigue, injury risk, and precision in manual activities, especially where human presence and fine motor control remain essential.

#### ART 04.025 Haptic and Multi-Sensory Feedback Systems

Over the next two decades, multiple research groups, device manufacturers, and human-machine interface companies are likely to pursue advanced haptic and multi-sensory feedback systems that overcome current limitations in how precisely people can control and “feel” artificial or mediated movements. The underlying rationale is that today’s interfaces largely rely on vision and simple vibration or force cues, which are too coarse, delayed, or ambiguous to support fluid, fine-grained control in applications such as prosthetics and exoskeletons, and in other tools that extend or augment human bodies. The anticipated technology combines dense arrays of sensors and actuators with signal-processing and control software to recreate a richer palette of sensations: graded pressure, texture, temperature, motion, and a sense of limb position or tool position in space. Interfaces may be worn on the skin, embedded in soft materials, or linked more directly to nerves and muscles, providing closed-loop feedback that updates in milliseconds. Users would be able to adjust sensitivity, filter out unwanted stimuli, and switch between different “profiles” for different tasks, with systems learning over time from patterns of use. Practical constraints remain significant: such systems must be lightweight, comfortable, and safe over long periods, while consuming limited power and remaining robust to sweat, dust, and mechanical stress. Manufacturing may depend on advanced materials and specialized fabrication methods, and the overall cost is likely to be comparable to other high-end personal assistive or industrial equipment, at least initially. From a value-creation bottleneck perspective, this technology can ease constraints wherever precise, continuous manual control is currently degraded by lack of reliable feedback, where physically demanding or repetitive tasks overstrain joints and muscles, or where distance and mediation make it hard to judge force and contact. It can also reduce errors that arise from sensory overload or underload, support more consistent quality in delicate operations, and expand access to complex physical tasks for people whose natural sensory or motor function is limited.

#### ART 04.026 AI Understanding of Human Intent & Context

Over the next two decades, multiple research labs, platform providers, and device manufacturers are expected to develop AI systems that can infer human intent and context from rich streams of behavioral signals. The rationale is to move beyond today’s command-based interfaces toward interactions where machines can interpret what people mean, not only what they literally say or click. This approach leverages existing microphones, cameras, wearables, and ambient sensors, while gradually adding more specialized modules for capturing gaze, posture, micro-expressions, and other subtle cues. The resulting systems combine speech and text understanding with recognition of emotional tone, social dynamics, and nonverbal communication such as gesture, proximity, and tempo of movement. In

practice, such AI would run on personal devices, shared terminals, and embedded systems, continuously building a situational model: who is present, what roles they appear to play, how engaged they are, and what goals or constraints are likely in play. It adapts its responses, timing, and modality—choosing, for example, between spoken feedback, visual hints, haptic signals, or silent reconfiguration—to match user preferences, accessibility needs, and social norms. Feasibility hinges on advances in sensor fusion, real-time inference, and robust handling of cultural and individual variation, along with strong privacy protections and mechanisms for human review and override. Energy and hardware demands will range from on-device accelerators comparable to current high-end consumer electronics to cloud-based services priced similarly to enterprise software, depending on latency and accuracy requirements. From a value-creation bottleneck perspective, this technology can ease tasks currently constrained by miscommunication, fragmented situational awareness, or limited human attention, reduce the cognitive effort required to operate complex tools, and lower barriers to participation for people whose communication styles differ from prevailing defaults, while also improving monitoring, coordination, and decision support in settings where the emotional and social climate strongly shapes outcomes.

#### ART 04.027 Brain-to-Brain Interfaces

Brain-to-brain interfaces (BBIs) are being explored by neuroscience labs, device manufacturers, and interdisciplinary consortia as a way to move beyond speech, text, and gesture as the main channels of human communication. The rationale is that many forms of knowledge, intention, and experience are difficult or slow to translate into language or manual control signals, and that direct exchange of selected neural patterns could increase bandwidth, reduce ambiguity, and enable new forms of coordination between individuals.

In a 20-year horizon, BBIs combine neural sensing, adaptive decoding software, secure digital links, and neural stimulation into an integrated system. Non-invasive or minimally invasive sensors capture patterns of brain activity associated with perceptions, intentions, or abstract concepts. Machine learning models, trained on each participant's neural signatures, translate these patterns into intermediate digital representations that can be filtered, compressed, and routed. On the receiving side, targeted stimulation or augmented feedback channels reintroduce information as structured experiences, cues, or biases in attention, rather than as fully formed thoughts. Users interact with these systems through configurable “channels” and consent controls, adjusting how much and what type of information is shared.

These systems remain constrained by the fidelity of sensing and stimulation, the need for extensive individual calibration, energy and compute demands for real-time decoding, and strict requirements for security, privacy, and psychological safety. Early versions may resemble specialized installations with costs comparable to other complex human-machine systems, with later generations approaching the cost and portability of high-end personal devices for limited functionality.

From a value-creation bottleneck perspective, this technology can ease constraints wherever communication speed, nuance, or shared situational awareness limit performance. It can reduce reliance on slow, error-prone translation between tacit knowledge and explicit instructions, and support collaboration when participants are separated by distance, language, or differences in sensory or motor ability. It can also help manage tasks currently constrained by fluctuating human attention, fatigue, or



stress, by making these internal states more observable and allowing workflows to adapt dynamically around them.

#### ART 04.028 Memory Prostheses

Multiple research groups, device manufacturers, and neurotechnology consortia are pursuing implantable systems that act as memory prostheses, aiming to restore or enhance human memory by working directly with the brain's own activity patterns. This approach is being explored because many forms of memory loss arise not from complete destruction of brain tissue but from disrupted signaling in defined circuits. By matching the physical layout, electrical properties, and signaling dynamics of these circuits, implantable devices can, in principle, support or substitute parts of the memory-encoding process while remaining compatible with existing neurosurgical tools and clinical monitoring practices. Within about two decades, such memory prostheses are envisioned as small, networked implants placed in or near memory-related regions. They would continuously sense local neural activity, use embedded models to infer when new memories are being formed, and record the corresponding patterns in a compressed, anonymized format. When cued—by internal activity, external prompts, or user intention—they would replay or gently bias these patterns to stabilize weak memories or help reconstruct information that would otherwise be lost. The devices would be configured and updated through secure external interfaces, gradually personalized as they learn an individual's neural “signature” of successful memory formation. Constraints are likely to include the need for invasive implantation, strict limits on heating and power use, finite storage and replay bandwidth, vulnerability to hardware failure, and heavy dependence on reliable connectivity and software updates. Costs would initially resemble major surgical interventions and specialized equipment, potentially declining toward the cost of common implanted devices over time. From a value-creation bottleneck perspective, this technology can reduce the impact of memory deficits that currently limit independent living and productive work, ease tasks that rely on consistent recall over long periods or after interruptions, and support roles where accurate retention of complex procedures or situational details is critical. It can also mitigate frictions where training is lost through injury or aging, where high cognitive load leads to dangerous lapses in recall, and where unequal access to memory-supporting tools constrains participation or performance.

## Group 5 – Robotics & Physical Autonomy

#### ART 05.029 Self-Driving Vehicles

Over the next two decades, multiple companies, research groups, and public–private consortia are expected to field families of self-driving road vehicles: autonomous cars, trucks, and buses that can navigate public roads for extended periods without continuous human control. The road-vehicle form factor is pursued because it can reuse existing roads, depots, maintenance practices, and digital services, while software-defined driving offers potential gains in consistency, utilization, and operating cost once development, validation, and deployment are amortized. In a mature form, these vehicles combine camera-based vision with radar, lidar or equivalent ranging,



high-precision positioning, and onboard computing that runs perception, prediction, and planning (or increasingly end-to-end learned driving stacks) to interpret the scene and generate steering, acceleration, and braking actions in real time. Some systems operate primarily within carefully specified operating conditions supported by detailed maps and curated service areas, while others aim to generalize across large regions with less dependence on pre-mapped zones, using onboard perception and large-scale data to handle diverse road layouts, construction changes, and unpredictable interactions. Another development path relies on very large consumer fleets with camera-centric sensing and frequent over-the-air updates, improving behavior from fleet data and learned models while publicly aiming to progress from supervised assistance toward hands-off and eventually driverless operation across wide regions with limited dependence on pre-mapped zones. Across approaches, redundancy, system-health monitoring, and safe fallback behavior are expected to become more formalized as systems move from supervised use toward unsupervised operation; remote assistance may still be used for rare exceptions, but the objective is routine autonomy with minimal external intervention.

Key constraints are likely to remain in extreme weather and poor visibility, in rare “edge-case” interactions with other road users, and in cybersecurity, verification at scale, and evolving safety and liability regulation. Early systems may carry costs comparable to high-end commercial vehicles due to sensing and compute, with costs trending downward as designs standardize and scale. From a value-creation bottleneck perspective, this technology can ease limits tied to human attention, fatigue, and scheduling; reduce variability in driving quality; enable higher utilization of expensive assets; mitigate delays where skilled operators are scarce or unevenly distributed; and improve safety and energy efficiency by reducing stop–start behavior and avoidable wear.

#### ART 05.030 Drone Swarms & Aerial Robots

Across research labs, robotics companies, and infrastructure operators, coordinated drone swarms and aerial robots are emerging as a distinct class of autonomous systems. The form factor builds on the falling costs and rising reliability of small unmanned aerial vehicles, while extending them into tightly coordinated fleets that can be deployed quickly, cover large or complex areas, and navigate three-dimensional environments without relying on fixed infrastructure. This approach is pursued because it scales more flexibly than single large aircraft, can be adapted through software rather than hardware redesign, and can be integrated with existing digital planning tools, communication networks, and safety protocols.

Within roughly two decades, such systems are expected to consist of heterogeneous fleets of small to medium aerial robots equipped with vision, range, and environmental sensors, onboard localization, and secure communication links. Swarms would share maps, tasks, and constraints in real time, reallocating vehicles as conditions change and learning from previous missions to refine routes and

behaviors. Human operators would typically supervise via high-level interfaces—defining objectives, boundaries, and priorities—while fine-grained navigation, collision avoidance, and task allocation are handled autonomously. Updates to capabilities would largely be software-defined, distributed over the air, and informed by simulation and data collected across many deployments.

Key constraints include limited flight time due to battery energy density, sensitivity to weather and obstacles, dependence on reliable positioning and communication infrastructure, and the need for robust fail-safes in dense airspace. Regulatory frameworks and public safety requirements will bound where and how swarms can operate. Economically, individual units may be priced in the range of advanced consumer electronics up to light vehicles, with fleet-level systems resembling the cost structure of industrial equipment plus ongoing software and maintenance.

From a value-creation bottleneck perspective, this technology can reduce the need for humans to enter hazardous or hard-to-reach environments, lower the time and labor required to inspect, map, or service large or complex areas, and alleviate constraints arising from limited human attention and line-of-sight. It can make continuous, fine-grained monitoring and rapid physical response more affordable where they are currently too slow or costly, mitigate delays caused by distance or scarcity of local expertise by enabling remote supervision of distributed tasks, and ease frictions where precision, repeatability, and high-frequency data are needed but difficult to achieve with manual or ground-based methods.

#### ART 05.031 Humanoid and General-Purpose Robots

Multiple companies, research labs, and consortia are pursuing humanoid and other general-purpose robots that can operate in spaces built for people, using tools, furniture, and infrastructure that already exist. The humanoid form factor and comparable dexterity are being explored because they can, in principle, move through doorways, climb stairs, use hand-operated devices, and interact with objects designed around human reach, grasp, and balance, without requiring a complete redesign of buildings or equipment. Within a 20-year horizon, such robots are expected to combine articulated limbs, agile locomotion, and multi-fingered end-effectors with rich sensing suites, including stereo vision, depth sensors, tactile and force feedback, and audio input. Onboard and networked computation would allow them to build and update 3D models of their surroundings, recognize objects and people, follow spoken or visual instructions, and execute task recipes that can be adjusted on the fly. They may be commanded via speech, gestures, wearable devices, or standard software interfaces, and can learn new tasks from demonstrations, simulation-trained policies, and shared libraries of behaviors updated remotely. Constraints will likely include limited runtime per charge relative to human workdays, performance degradation in cluttered or highly unstructured spaces, and the need for safety-rated control systems that strictly limit impact forces and unsafe motions near people. Production will depend on complex supply chains for actuators, batteries, sensors, and computing hardware, keeping early costs roughly in the range of commercial vehicles or industrial machines, with simpler variants being cheaper but less capable. From a value-creation bottleneck perspective, this technology can reduce dependence on constant human presence for physically demanding, repetitive, or uncomfortable tasks; ease constraints where human attention, precision, or coordination currently limit throughput or quality; make it economically viable to perform frequent inspections, adjustments, and reconfigurations that are now too time-consuming; and mitigate situations where distance, irregular

schedules, or scarcity of skilled personnel create delays, by allowing remote experts to supervise or teleoperate robots that embody their skills across many locations.

#### ART 05.032 Soft Robotics & Bio-Inspired Machines

Over the next two decades, multiple research labs, startups, and industrial consortia are expected to converge on families of soft robots and bio-inspired machines built from flexible polymers, textiles, gels, and hybrid composites that mimic the compliance and movement patterns of animals and humans. This form factor is pursued because deformable bodies can safely contact fragile objects and people, squeeze through confined spaces, and tolerate impacts that would damage rigid mechanisms, while increasingly mature manufacturing methods—such as soft lithography, additive manufacturing, and textile-based actuators—make them scalable and cost-comparable to current industrial machines or specialized vehicles, depending on size and complexity. In their mature form, these systems combine distributed soft sensors, embedded processors, and fluidic, pneumatic, or artificial muscle actuators to perceive forces, textures, and shapes, then adapt their posture and grip in real time. They interface with humans through simple control devices, voice or gesture commands, and software APIs that allow higher-level task specification rather than joint-by-joint programming. Learning and configuration rely on data-driven models, imitation of recorded human motions, and libraries of biologically inspired gait and grasp patterns that can be tuned to new environments. Feasibility is constrained by material fatigue, limitations in actuation speed and strength, energy density of onboard power sources, and the need for specialized fabrication tools and maintenance expertise, as well as emerging safety and certification requirements for close human interaction. From a value-creation bottleneck perspective, this technology can ease tasks that currently expose humans to crushing, contamination, or repetitive strain risks by taking over physically awkward or hazardous manipulation. It can reduce errors in processes limited by human precision and endurance by providing consistent, gentle handling of variable objects. It can make certain activities viable where rigid machines are too dangerous, inflexible, or costly to deploy, especially in cluttered or hard-to-reach spaces. It can also mitigate constraints linked to scarce skilled labor by encapsulating complex coordination, balance, and dexterous control in reusable motion primitives that can be deployed and supervised by fewer or less specialized operators.

#### ART 05.033 Fully Autonomous Drones, Robots & Underwater Vehicles

Multiple companies, research groups and public agencies are developing families of fully autonomous drones, ground robots and underwater vehicles that can operate for long periods with minimal human supervision. The shared rationale is to extend reliable sensing and manipulation into places that are hard, slow or risky for people to reach: high in the air, deep underwater, inside damaged structures, or in remote and unmapped terrain. Over the next twenty years, these platforms are expected to converge on modular designs: standardized airframes, tracked or legged bases, and pressure-tolerant underwater hulls carrying swappable sensor and tool packages. They will navigate using fused data from cameras, radar, sonar, inertial units and satellite or local positioning, building detailed maps in real time and adapting to changing conditions without constant communication links. Onboard computing and learned control policies will allow them to inspect, sample, carry loads, manipulate valves or connectors, and assemble or dismantle simple structures. Humans will interact with them through visual dashboards, natural-language instructions and high-level mission plans, while fine control remains automated. Many units will coordinate in swarms, sharing maps and workload. Constraints are likely to include limited energy storage, especially for flying and underwater units, dependence on reliable components that can withstand harsh conditions, vulnerability to communication loss or

sensor interference, and regulatory limits on fully unsupervised operation in shared spaces. Unit costs will resemble those of vehicles or industrial machines, with cheaper mass-produced variants for routine tasks and expensive, ruggedized systems for extreme environments. From a value-creation bottleneck perspective, this technology can take over work that is currently dangerous or physically inaccessible, maintain continuous presence and monitoring where human shifts are impractical, raise the precision and repeatability of tasks that now depend on scarce expert teams, and reduce delays caused by distance, travel, or the need to assemble specialized equipment and personnel at short notice.

#### ART 05.034 Supportive Infrastructure for Autonomy

Across many research labs, robotics firms, and built-environment developers, a new class of “autonomy-support” infrastructure is being designed as an intentional layer between robots and the physical world. Instead of expecting autonomous machines to cope with arbitrary, unstructured environments, this approach reshapes spaces themselves to be legible, predictable, and serviceable for fleets of mobile robots and fixed manipulators. Over the next two decades, this takes the form of purpose-built elements embedded into buildings, vehicles, and public spaces: robot-readable surfaces and markers, high-density localization fields, standardized docking and transfer nodes for energy and payloads, and distributed “coordination posts” that enforce shared traffic rules and safety envelopes across heterogeneous machines. The infrastructure exposes simple digital interfaces through which robots can request access, reserve lanes or work zones, negotiate priority, and receive environment-specific constraints; humans interact with it through clear physical cues, call points, and oversight dashboards that make machine behavior inspectable and interruptible. The technology remains constrained by the cost and complexity of retrofitting existing spaces, by the need for widely accepted standards so different vendors’ systems can interoperate, and by the requirement for continuous calibration and safety assurance as layouts and usage patterns change. Deployment is therefore likely to concentrate in high-utilization zones, with capital intensity comparable to other major facility upgrades, rather than being universal. From a value-creation bottleneck perspective, this infrastructure can convert environments that are currently unpredictable, risky, or ergonomically harsh for humans into places where robots absorb much of the exposure to dull, dirty, or dangerous work. It can relax constraints that arise from limited human attention, coordination, and endurance by enabling dense, choreographed machine activity that would be unsafe or impractical without shared rules baked into the environment. It can also make previously uneconomical automation tasks viable by reducing the cognitive and sensing burden on each individual robot, allowing simpler, cheaper machines to achieve reliable performance wherever this autonomy-native layer has been installed.

#### ART 05.035 Optical/Microwave Power Beaming for Persistent Robotics

Multiple research groups, equipment manufacturers and infrastructure providers are exploring long-distance optical and microwave power beaming as a way to decouple robotic systems from onboard energy storage. The rationale is to use tightly directed lasers or phased-array microwaves to deliver electricity over line-of-sight links, so robots and fixed devices no longer depend on large batteries, fuel, or frequent human servicing. This approach builds on existing optical communications, satellite power transmission experiments, and radar technologies, while aiming for a cost and reliability profile similar to other fixed infrastructure such as communication towers or local substations.

In a 20-year horizon, a typical system consists of ground or mast-mounted transmitters that generate and steer high-intensity beams, and compact receiver modules integrated into aerial, ground, or

stationary robotic platforms. The receivers convert the incoming radiation into DC power using high-efficiency photovoltaics or rectifying antennas, feeding both propulsion and sensing systems while trickle-charging small buffer batteries or supercapacitors. Robots automatically position themselves to maintain sufficient link quality, assisted by beam-tracking sensors and control software that compensate for motion, wind and minor occlusions. Networked transmitters can hand off a robot between beams, allocate power among multiple devices, and adjust output based on mission priorities, environmental conditions and grid constraints, using standard software interfaces and remote updates.

Constraints include line-of-sight requirements, degradation in adverse weather, limits on maximum distance and beam divergence, and safety regulations around high-power radiation. The infrastructure depends on reliable grid or local generation, precise alignment hardware, and certified exclusion and sensing systems to prevent accidental exposure. Overall costs are expected to be comparable to deploying communication infrastructure plus incremental receiver costs similar to current powertrains, with operating expenses dominated by electricity and maintenance.

From a value-creation bottleneck perspective, this technology can reduce the need for human intervention in remote or hazardous locations by allowing robots and sensors to operate for weeks or months without battery swaps or refueling. It can ease constraints where mission duration, range, or responsiveness are currently capped by battery capacity, charging logistics, or the availability of skilled personnel to service dispersed equipment. It can also address bottlenecks in continuous monitoring and rapid response, where frequent downtime or energy scarcity now forces sparse coverage, short duty cycles, or conservative operating patterns.

#### ART 05.036 Gecko-Inspired Dry-Adhesion Mobility & Manipulation

Across the next two decades, multiple research groups, robotics firms, and materials consortia are expected to converge on gecko-inspired dry-adhesion systems for mobility and manipulation. These designs use engineered micro- and nano-scale surface structures to exploit van der Waals forces, creating strong, reversible adhesion without liquid glues, suction, or mechanical fasteners. This approach is attractive because it works on smooth and many semi-smooth surfaces, leaves no residue, functions in low-pressure environments where suction is ineffective, and can be integrated into existing robotic end-effectors and climbing mechanisms with minimal changes to their broader architectures.

The anticipated technology bundle combines advanced dry-adhesive pads with integrated sensing, actuation, and control. Pads are arranged on articulated fingers, tiles, or tracks whose stiffness, orientation, and preload can be precisely adjusted to switch adhesion on and off. Embedded sensors estimate contact area, load, and surface condition, feeding into local controllers and higher-level software via standard interfaces and APIs. Systems learn safe grip strategies and motion profiles from data and simulation, gradually adapting to different surface textures and contaminants. In a 20-year horizon, the adhesive microstructures are expected to be manufacturable at scale using roll-to-roll or additive processes, with lifetimes measured in hundreds of thousands of attachment cycles and unit costs comparable to other specialized industrial gripping or climbing components.

Key constraints are likely to include reduced performance on very rough, porous, or heavily contaminated surfaces; degradation under abrasive dust or chemical exposure; and a need for periodic cleaning or self-cleaning mechanisms. Force capacities will remain finite, so payload, safety margins, and energy for positioning and control must be managed. Overall system costs, including actuators and control electronics, will be similar to compact robotic platforms or precision handling tools rather than disposable consumables.

From a value-creation bottleneck perspective, this technology can ease tasks that currently rely on bulky clamps, drilling, or temporary fixtures just to hold objects or platforms in place. It can reduce time and risk in operations that require working at height, on vertical or overhead surfaces, or on delicate finishes where damage or residue is unacceptable. It can make precise repositioning and repeated attachment–detachment cycles feasible where suction or magnetic methods are impractical, and support automated handling of objects whose surfaces are too smooth, fragile, or variable for conventional grippers. It can also alleviate constraints where compressed air, vacuum infrastructure, or heavy mechanical supports are unavailable, allowing mobile systems to attach, traverse, and manipulate in environments that are currently hard to reach or too costly to access repeatedly.

## Group 6 – Additive, Agile & Digital Manufacturing

### ART 06.037 Multi-Material & Hybrid 3D Printing

Across the next two decades, research groups, equipment manufacturers, and design software providers are converging on additive manufacturing platforms that can deposit multiple materials in a single continuous build. These multi-material and hybrid 3D printers combine print heads, energy sources, and process controls able to handle polymers, metals, ceramics, and basic electronic materials in one machine, with tightly synchronized motion systems and monitoring. The rationale is to move from printing single, homogeneous parts toward fabricating entire functional assemblies in one step, reducing separate machining, joining, and wiring operations while enabling geometries and internal structures that are difficult or impossible to realize today. In their mature form, these systems are expected to create parts with locally tailored stiffness, thermal behavior, and conductivity, embedding channels, seals, connectors, and simple circuitry directly into the printed structure. They will interface with humans mainly through familiar CAD-style tools, augmented by generative design and simulation that suggest material layouts, plus standard digital interfaces for job scheduling, process monitoring, and remote diagnostics. Over a 20-year horizon, important constraints remain: material compatibility windows will limit which combinations can be co-printed, build rates will be slower than high-volume dedicated production lines, and maintaining calibration, powder or filament quality, and safe operation will require skilled technicians and controlled environments. Machines will be capital assets in the range of advanced industrial tools, while per-part costs will be attractive mainly for complex, customized, or low-volume items. From a value-creation bottleneck perspective, this technology can reduce dependence on multi-step assembly chains, shorten design–build–test cycles, and ease tasks that currently require coordinating many suppliers or specialists. It can relax constraints where existing components force compromises between mechanical performance, thermal management, and integration of sensing or power, and can alleviate frictions where the need for molds, tooling, or intricate hand assembly makes highly customized or geometrically complex products prohibitively slow or expensive.



### ART 06.038 Digital Twin & Simulation-Driven Production

Across many advanced production environments, technology firms, equipment vendors, and research groups are converging on platforms that pair every significant physical asset or process with a continuously updated digital replica. These “digital twin and simulation-driven production” systems are pursued because they promise tighter control over complex operations, better use of data from existing sensors and machines, and a way to test changes virtually before they disrupt physical workflows. The central idea is that each line, cell, or piece of equipment is mirrored in software, with the twin fed by real-time measurements and control signals. Within twenty years, these platforms are expected to combine high-fidelity physics models, data-driven surrogate models, and historical records into digital environments where process changes, new product variants, maintenance actions, and scheduling decisions can be tried out at accelerated timescales. Operators and engineers would interact with these twins through visual dashboards, 3D views, and standard design and planning tools, while automated agents adjust parameters within defined safety and quality constraints. The systems learn from ongoing operation, updating their models via remote software updates and continuous calibration against real outcomes. Feasibility is shaped by computing cost, the difficulty of integrating legacy equipment, and the need for trustworthy, well-instrumented data streams. Deployments are likely to require specialized modeling expertise and robust network and compute infrastructure, with total costs comparable to other large-scale industrial control and planning systems. From a value-creation bottleneck perspective, this technology can reduce downtime and scrap caused by poorly understood process interactions, ease coordination between design and production by making impacts of design changes visible before implementation, and shrink the time and risk involved in ramping up new products or process configurations. It can also mitigate constraints arising from limited expert availability, by embedding expert knowledge into reusable models, and address resource and energy inefficiencies by making the consequences of alternative operating strategies more visible and analyzable in advance.

### ART 06.039 Reconfigurable & Agile Factories

Across the next two decades, equipment suppliers, robotics firms, software vendors, and research consortia are expected to converge on “reconfigurable and agile factories” as a way to cope with volatile demand, shorter product lifecycles, and increasing pressure for customization. Instead of fixed, single-purpose production lines, facilities are organized around modular workcells that combine robots, machine tools, sensors, storage, and quality-control stations on standardized mechanical and digital interfaces. The same physical cell can be repurposed by swapping end-effectors, fixtures, or process modules and by loading new digital recipes, making it feasible to switch between product variants or entirely different product families without lengthy rebuilds. At the systems level, orchestration software coordinates material flow, schedules tasks, and configures cells using model-based planning and data-driven optimization. Human operators interact with the system through visual dashboards, augmented reality overlays, and increasingly natural language, specifying desired outputs and constraints rather than low-level machine instructions. Over a 20-year horizon, such factories are likely to remain capital-intensive and dependent on reliable power, networking, and a supply of standardized modules. There will be limits to the range of processes that can be safely automated in modular form, and frequent reconfiguration may introduce new failure modes, verification burdens, and cybersecurity concerns. Economic feasibility will typically resemble that of current mid- to large-scale production facilities or fleets of industrial machines, with higher upfront investment but lower changeover and downtime costs over the asset lifetime. From a value-creation bottleneck perspective, this technology can reduce



delays and waste associated with redesigning lines for each new product, ease constraints where production is currently locked into large batch sizes to amortize setup costs, and mitigate risks when demand is uncertain or highly seasonal. It can help address shortages of specialized technicians by encapsulating expertise into reusable modules and digital templates, and it can enable more local, small-batch, or experiment-heavy production without sacrificing consistency. By making capacity more fluid and re-assignable, reconfigurable factories can also relieve coordination bottlenecks between product design, process engineering, and operations, allowing information and intent to flow more quickly into physical outcomes.

## ART 06.040 Circular & Sustainable Manufacturing

Across the next two decades, many manufacturers, equipment suppliers, and research groups are converging on “circular and sustainable manufacturing” platforms that treat waste and by-products as primary inputs rather than disposal problems. These systems are being pursued because they promise to decouple production capacity from volatile raw material markets, reduce regulatory and disposal costs, and fit within emerging requirements for traceability and environmental performance.

Technically, they build on familiar process equipment and digital controls, but are reconfigured around continuous material recirculation, low-energy transformation steps, and new families of bio-engineered materials that are designed from the outset for circular use.

In their mature form, these platforms combine in-line sensing, automated sorting, and additive processes in one tightly integrated flow. Scrap and end-of-life products are mechanically or chemically broken down, characterized, and requalified, then reprinted or refabricated into new components with predictable properties. Bio-based and recyclable feedstocks—such as engineered polymers, composites, and binders derived from renewable sources—are complemented by bio-engineered materials grown or structured with the help of biological systems, for example through fermentation, biofabrication, or enzymatic assembly. These materials are tuned for high functional performance while remaining recyclable, repairable, or safely biodegradable, and for compatibility with repeated reprocessing. Low-temperature sintering, photopolymerization, and enzymatic or electrochemical fabrication methods reduce energy use compared with today’s high-heat, batch operations. A software layer connects design tools, digital product passports, and production planning, so that material recipes and geometries can be automatically adjusted to both recycled and bio-derived feedstock streams.

Practical constraints remain. Material performance still drifts after many recirculation or regeneration cycles, contamination must be tightly controlled, and both bio-based and bio-engineered feedstocks depend on specific cultivation routes, additives, and processing know-how. Capital costs for advanced sorting, monitoring, and additive lines are comparable to other mid-scale industrial equipment, with economics sensitive to local energy prices, biomass availability, and the reliability of recovered material streams. Regulatory requirements around safety, certification, and disclosure for novel materials can slow adoption.

From a value-creation bottleneck perspective, this technology can reduce dependence on scarce or toxic raw materials, turn accumulated waste and by-products into usable feedstock, and lower the labor and energy burden associated with handling, transporting, and disposing of materials. It can ease constraints where high-quality components are currently too expensive because they rely on virgin

inputs, specialized chemistries, or long, fragile supply chains. By substituting conventional substances with bio-engineered, eco-compatible materials and providing detailed, real-time data on material origin, composition, usage, and fate, it can reduce frictions around durability, safety, and environmental footprint, and enable more predictable planning and investment in long-lived physical assets.

#### ART 06.041 Bio-fabrication technologies

Across the next two decades, multiple companies, research labs, and public-private consortia are advancing bio-fabrication platforms that can reliably produce human tissues and other living or biologically derived products at useful scale. These technologies combine 3D bioprinting, engineered scaffolds, and tightly controlled culture environments, because this approach can integrate with existing laboratory and manufacturing infrastructure while offering more precise control over structure, cell composition, and function than traditional culturing methods. A typical system couples high-resolution print heads that deposit cell-laden “bioinks” and supportive biomaterials with automated incubators, perfusion systems, and sensor arrays that monitor and adjust temperature, nutrients, oxygen, and mechanical stimuli. Over a 20-year horizon, such platforms are expected to generate standardized tissue patches, organoids, and specialized cell constructs with tunable mechanical properties, vascular-like channels, and embedded sensing. They may also produce non-tissue products such as cultured biomolecules, cell-based reagents, and bio-based materials with consistent performance characteristics. Users interact through software interfaces that manage digital design files for tissues, process recipes, and quality-control protocols, with remote updates adding new cell types, scaffold chemistries, or validated workflows. Key constraints remain: bio-fabrication is energy- and resource-intensive, requires high-grade inputs (cells, growth factors, sterile disposables), and depends on specialized facilities, skilled technicians, and rigorous oversight to manage safety, contamination risk, and long-term stability of products. Capital costs are likely comparable to current advanced imaging systems or industrial robotic workcells, with facility-scale investments similar to mid-sized manufacturing or processing plants. From a value-creation bottleneck perspective, this technology can ease constraints where access to suitable human tissues or consistent biological products is limited, where manual handling of living cells is slow, fragile, and highly dependent on scarce expertise, and where batch-to-batch variability and spoilage create uncertainty and waste. It can reduce reliance on donor-derived materials, shorten development cycles for new biological constructs by enabling iterative, programmable design, and support more distributed production, mitigating bottlenecks linked to distance from central facilities, cold-chain logistics, and single-source supply of critical biological inputs.

#### ART 06.042 4D Printed & Programmable Materials

Across the next two decades, multiple research groups, design firms, and manufacturing consortia are working on “4D printed” and programmable materials: structures produced additively that can change their shape or function after fabrication in response to heat, light, moisture, electrical fields, or chemical cues. This approach builds on existing 3D printing platforms but introduces formulations and architectures that embed actuation and memory directly into the material. The rationale is to move complexity out of traditional mechanical assemblies and electronics and into the geometry and chemistry of the material itself, improving robustness, simplifying assembly, and enabling structures that can be shipped flat, deployed compactly, or adapt to their environment over time.

In a 20-year horizon, these materials are expected to behave as quiet “physical software.” A single printed component might fold, twist, or stiffen on command, open or close pores, change permeability or thermal properties, or selectively lock into new shapes when triggered. Control can range from simple passive responses (e.g., swelling when wet) to active behavior coordinated by small embedded controllers or external fields. Designers would specify not just the final geometry, but a sequence of states over the object’s lifetime, using libraries of programmable patterns. Interfaces to humans and other systems would be straightforward: triggering via temperature changes, illumination, small actuators, or standard control electronics and software APIs.

Constraints include the complexity of multi-material printing, durability under repeated transformations, and dependence on specific polymers, composites, or microstructures that may be sensitive to supply, regulation, or recycling infrastructure. Energy demands are modest for passive systems but higher for rapidly actuated or load-bearing transformations. Costs are likely comparable to specialized engineered components or high-performance composites, rather than commodity materials.

From a value-creation bottleneck perspective, this technology can reduce the need for intricate assemblies and frequent manual adjustments, ease constraints where reconfigurable structures are currently too fragile or expensive, and enable components that self-calibrate, self-deploy, or self-protect in response to environmental change. It can address bottlenecks where limited access, infrequent maintenance, or harsh conditions make static designs unreliable, and where current materials force trade-offs between adaptability, robustness, and lifecycle cost.

#### ART 06.043 Volumetric Additive Manufacturing

Across the next two decades, research groups, equipment manufacturers, and materials companies are advancing a family of “volumetric additive manufacturing” techniques that can form solid three-dimensional objects in a single step. Instead of depositing material layer by layer, these systems project carefully shaped light or other energy fields into a transparent, photosensitive volume, selectively solidifying regions throughout the entire interior at once. This approach is pursued because it can drastically shorten production times from hours to seconds or minutes, reduce geometric artifacts associated with layering, and simplify mechanical design by removing the need for extensive support structures. In its mature form, the technology combines high-resolution projectors or beam-shaping optics, fast computation for calculating volumetric exposure patterns, and resin-like materials whose chemistry is tuned for precise, reversible reactions. The resulting printers are expected to produce complex, smooth, and mechanically robust parts with internal channels, lattices, and moving elements that are difficult or impossible to achieve with conventional fabrication. Objects might be defined digitally, updated through software, and produced on demand in devices with footprints comparable to office equipment or small industrial tools. Constraints include dependence on specialized feedstock materials, limitations on object size set by optical paths and resin volumes, challenges in removing unreacted material from internal cavities, and the need for careful control of heat and curing to ensure reliability. Energy use and unit costs may initially be comparable to high-end additive systems or precision machining tools, with gradual reductions as volumes scale. From a value-creation bottleneck perspective, this technology can compress prototyping and small-batch production cycles, lowering the

time and coordination effort needed to move from a digital design to a physical artifact. It can ease constraints where intricate geometries, internal channels, or customized shapes are currently too expensive or slow to manufacture. It can also reduce reliance on large centralized facilities by enabling compact, automated production units that operate with minimal human handling, mitigating bottlenecks related to skilled labor availability, multi-step assembly, and the storage and transport of specialized parts.

## Group 7 - Advanced Materials & Nano-engineering

### ART 07.044 Metamaterials for Novel Optics & Connectivity

Across the next two decades, multiple university labs, defense and space agencies, telecommunications suppliers, and advanced manufacturing firms are likely to converge on “metamaterials” as a practical way to shape light and radio waves using structure rather than chemistry alone. Instead of relying on naturally occurring optical crystals or bulky antenna geometries, these engineered materials embed carefully designed micro- and nano-scale patterns that interact with electromagnetic waves in programmable ways. The form factor is attractive because it can be fabricated as thin layers, tiles, coatings, or inserts that retrofit into existing devices, while offering performance gains that would otherwise require larger apertures, tighter tolerances, or more power.

Within roughly 20 years, metamaterials for novel optics and connectivity are anticipated to behave like wave-control “surfaces” that can steer, focus, filter, absorb, or scatter specific frequencies on demand. In optics, this could enable flat lenses with reduced thickness and weight, tunable filters, compact beam shapers, and selective glare or signature management, including limited “cloaking” effects over narrow bands and angles. In radio frequencies, related structures can produce high-gain, low-profile antennas, frequency-selective panels, and reconfigurable reflecting surfaces that dynamically redirect signals around obstructions. Many designs would be configured via software to adjust phase, polarization, or resonance in real time, and could interface through standard device control electronics rather than bespoke mechanical actuators.

Key constraints will include sensitivity to fabrication defects, bandwidth limits (many effects work best over a limited frequency range), and performance trade-offs under temperature, vibration, or weathering for exposed surfaces. Some variants will depend on scarce or expensive conductors and dielectrics, and high-precision manufacturing may keep early systems priced like specialized industrial components or premium communications hardware, with costs falling as tooling and yield improve.

From a value-creation bottleneck perspective, this technology can reduce the need for large, heavy, power-hungry wave-handling hardware by shifting capability into thin, manufacturable surfaces; improve reliability and throughput of information links in cluttered or obstructed environments; enable higher precision sensing and targeting without proportionally increasing system size; and support safer, more controllable operation by selectively shaping exposure, interference, and signal leakage in complex physical settings.

## ART 07.045 Room-Temperature Superconductors

Across the next two decades, multiple materials companies, national labs, and device manufacturers are plausibly driven toward “room-temperature superconductors” because electrical resistance remains a stubborn tax on power delivery, heat management, and magnetic performance, and because a truly ambient superconductor would fit many existing form factors—wires, tapes, thin-film coatings, and laminated stacks—without the operational burden of cryogenic cooling. In practical terms, the technology would be a family of engineered compounds whose internal structure is tuned so electrons can move with effectively zero resistive loss at or near everyday temperatures, ideally at normal pressure and in strong magnetic fields. Early deployments would likely appear as composite conductors: a superconducting layer protected by stabilizing metals and tough outer jackets, with standardized connectors, bend radii, and monitoring electronics that detect instabilities and redirect current before damage occurs. Manufacturing would emphasize repeatable purity, grain alignment, and defect control, because small imperfections can reintroduce loss or trigger abrupt “quench” events under high current or changing fields. Even at maturity, constraints would remain: some variants may require modest cooling, strict humidity control, or encapsulation; performance can degrade under mechanical strain; joining long lengths without weak points is nontrivial; and strong fields introduce design challenges around shielding and safety. Costs would likely range from premium-grade conductor pricing for high-performance tapes to expensive specialty materials for bulk components, comparable to other advanced engineered materials rather than commodity metals. From a value-creation bottleneck perspective, this technology can reduce losses and heat in systems limited by wasted energy, enable compact high-current pathways where size and thermal budgets are tight, raise the ceiling on magnetic and sensing performance where today’s materials saturate or overheat, and simplify operations in places where cooling infrastructure, maintenance labor, or downtime currently dominate total cost and risk.

## ART 07.046 Self-Healing & Smart Polymers

Across the next two decades, multiple chemical companies, materials startups, and university–industry consortia are likely to converge on “self-healing and smart polymers” as a practical way to extend the working life of everyday parts that are currently replaced due to small cracks, abrasion, or gradual property drift. This form factor is being pursued because polymers already sit at the interface of cost, mass manufacturability, and design freedom: they can be molded, coated, laminated, or printed into complex shapes, and small chemistry changes can translate into large changes in durability or function.

Within 20 years, these materials are anticipated to combine two capabilities in a single platform. First, autonomous repair: microcracks and punctures can be sealed through reversible chemical bonds, dispersed “healing” agents released from microcapsules, or microchannel networks that re-deliver repair chemistry to damaged zones, often restoring a meaningful fraction of strength and barrier performance without disassembly. Second, adaptive behavior: the same polymer network can shift stiffness, damping, permeability, adhesion, or electrical conductivity in response to temperature, moisture, strain, light, or chemical exposure, with simple control interfaces ranging from passive triggers to low-power embedded sensing and firmware-like calibration via standard test signals. Many versions will be formulated as composites, pairing the polymer with fibers, fillers, or conductive networks to tune mechanical and functional performance.

Key constraints remain: healing may be slow or incomplete for large fractures, repeated repair cycles can fatigue the chemistry, and some systems require heat, light, or specific humidity to activate. Manufacturing can be more complex than conventional plastics, and recyclability may be harder unless the chemistry is designed for reprocessing. Costs are likely to span from modest premiums over engineering plastics for coatings and seals to “specialty material” pricing for high-performance composites.

From a value-creation bottleneck perspective, this technology can reduce downtime driven by minor damage, ease reliability limits set by wear and microfractures, and lower the labor and coordination burden of inspection, repair, and replacement. It can also improve performance in environments where access is difficult, where small defects propagate into failures, or where safety margins and quality assurance currently require overbuilding, frequent checks, or early retirement of components.

### ART 07.047 Nano-Catalysts & Advanced Coatings

Across the next two decades, multiple materials companies, university labs, and equipment suppliers are likely to converge on a family of nano-catalysts and advanced coatings that deliberately shape matter at the scale of billionths of a meter. This approach is pursued because many critical surface and reaction behaviors are determined by the first few nanometers: by controlling particle size, pore structure, and surface chemistry, developers can raise useful activity per gram of material, reduce unwanted byproducts, and add “designed” surface functions without redesigning entire machines or structures. The practical form factor is often a replaceable catalyst cartridge, a thin-film layer, or a retrofit coating that fits existing tools, pipes, vessels, filters, and components.

In mature versions, these materials behave like engineered interfaces. Nano-catalysts accelerate specific chemical transformations while resisting deactivation from heat, moisture, or contaminants; some are tunable in the field by changing temperature, light exposure, or the surrounding chemistry to favor different outputs. Advanced coatings provide tightly defined surface properties—low friction, corrosion resistance, anti-fouling, selective permeability, thermal control, optical tuning, or controlled wetting—applied by scalable methods such as spraying, dipping, or thin-film deposition, and monitored via embedded markers that indicate wear or loss of function. Configuration is largely digital: recipes, quality metrics, and lifecycle models are updated remotely and tied to standard material databases.

Key constraints remain. Producing consistent nanostructures at scale can be sensitive to impurities and process drift; some high-performing formulations rely on scarce elements, and long-term durability under abrasion, cycling temperatures, or harsh chemicals can be the limiting factor. Costs are expected to span from “premium protective finish” (tens to hundreds of euros per square meter installed) to “major consumable replacement” for high-activity catalyst loads.

From a value-creation bottleneck perspective, this technology can reduce the time, energy, and material waste needed to achieve precise transformations; extend component lifetimes by preventing corrosion, buildup, and friction-driven losses; enable safer handling by making surfaces less reactive or easier to clean; and improve reliability where performance today degrades unpredictably due to wear, contamination, or inconsistent process conditions.

## ART 07.048 High-Entropy Alloys & Advanced Metals

Multiple actors—including specialty-metal producers, national labs, and industrial consortia—are plausibly developing high-entropy alloys (HEAs) and related advanced metals as a way to escape the trade-offs of conventional alloying, where one “base” metal is tweaked with small additions. By using several principal elements in carefully tuned proportions, these materials aim to achieve combinations of strength, toughness, and heat stability that are difficult to obtain simultaneously with today’s steels, superalloys, or titanium alloys, while remaining compatible with familiar routes like casting, forging, powder metallurgy, and increasingly, metal additive manufacturing.

Within roughly the next 20 years, HEAs are anticipated to appear not as a single “wonder metal,” but as a family of composition “recipes” delivered as bar stock, sheet, wire, powders, and thin coatings. A practical HEA platform would couple materials databases and computational design with high-throughput testing so that engineers can select alloys for specific needs such as resistance to creep at high temperature, oxidation and corrosion tolerance, fatigue life, wear resistance, or stability under thermal cycling. Advanced processing controls—real-time melt chemistry monitoring, microstructure imaging, and post-processing heat treatments—would help deliver consistent properties, while standardized joining and surface-treatment methods would make the materials usable in complex assemblies.

Key constraints remain: some promising compositions rely on costly or supply-sensitive elements; manufacturing windows can be narrow, with risks of segregation, cracking, or difficult machining; and certification requires long-duration reliability data. Early deployments may cost hundreds of euros per kilogram, with mature “workhorse” grades trending toward premium-alloy pricing.

From a value-creation bottleneck perspective, this technology can reduce failures in harsh conditions, extend component lifetimes, and relax maintenance cycles where replacement is slow or risky. It can enable smaller, lighter, or higher-temperature-capable hardware without sacrificing safety margins, improve dimensional stability and precision under heat and vibration, and lower lifecycle material use by making long-lived structures and surfaces that resist wear, corrosion, and thermal damage.

## ART 07.049 Advanced CO<sub>2</sub> Capture Materials for Climate Mitigation

Multiple research groups, materials companies, and public–private consortia are plausibly developing advanced CO<sub>2</sub> capture media based on metal–organic frameworks (MOFs) because MOFs offer a rare combination of “designer porosity” and chemical tunability: their internal surfaces can be engineered to preferentially bind CO<sub>2</sub> while



letting most other gases pass, and their crystal structures can be tailored to fit into familiar contactor formats (coated monoliths, pellets, fibers, membranes, or modular cartridges) that work with existing ducts, fans, and control systems. Over the next 20 years, a mature MOF-based capture platform is anticipated to behave less like a one-off material and more like a configurable capture “family,” where different MOF formulations are selected for CO<sub>2</sub> concentration, humidity, contaminants, and required cycling speed, then deployed in standardized modules with embedded sensors that track loading, pressure drop, and degradation. Regeneration would typically occur via modest heating, vacuum, humidity swings, or electro-assisted methods, producing a concentrated CO<sub>2</sub> stream suitable for downstream handling, while routine performance tuning arrives through swapped cartridges and updated operating recipes rather than full equipment replacement.

Key constraints remain material lifetime under real-world impurities and moisture, the energy and heat-management cost of regeneration, and the challenge of manufacturing tons to megatons of consistent, mechanically robust sorbent without relying on brittle supply chains for linkers, metals, or solvents. Early deployments may resemble the cost profile of industrial filtration systems plus consumables, with sorbents priced like specialty bulk materials and replaced on multi-month to multi-year schedules.

From a value-creation bottleneck perspective, this technology can reduce the time and risk humans face when managing hazardous or constrained gas streams, loosen throughput limits set by bulky equipment and slow chemistry, enable capture where space, skilled labor, or continuous oversight are scarce, and improve predictability by turning CO<sub>2</sub> removal into a metered, monitorable service unit with clearer trade-offs between energy, capture rate, and reliability.

#### ART 07.050 Graphene and Nanotube Composites for Lightweight Strength

Multiple actors—materials startups, aerospace and automotive suppliers, university labs, and national research consortia—are plausibly developing graphene- and carbon-nanotube-reinforced composites as a next step beyond today’s carbon-fiber systems. The form factor is attractive because these nanomaterials can, in principle, be mixed into familiar polymer resins, coatings, and laminates, allowing partial compatibility with existing composite manufacturing while targeting large gains in strength-to-weight, fatigue resistance, and crack tolerance without relying on exotic operating conditions.

Within the next 20 years, these composites are anticipated to behave less like “strong plastic” and more like engineered fabrics where nanoscale reinforcements bridge microcracks, spread loads, and slow wear. Parts could be produced as sheets, molded structures, or layered laminates, with tunable stiffness and impact performance across different directions, and with improved thermal and electrical conductivity compared to

conventional composites. That conductivity can enable embedded sensing: components that self-report strain, damage progression, or delamination through simple electrical measurements, and interface with standard monitoring electronics via wired connectors or wireless modules. In some variants, surface treatments and coatings could improve moisture resistance, corrosion protection for adjacent materials, and bonding to metals or other composites.

Key constraints remain practical: achieving uniform dispersion at scale, controlling impurities, ensuring repeatable quality, and preventing performance loss at joints, holes, and interfaces. Manufacturing may require specialized mixing, filtration, and inspection equipment, and some formulations may face occupational health and regulatory scrutiny around nanoparticle handling. Early deployments may be priced like premium composite parts or industrial equipment upgrades, with costs falling as supply chains and process control mature.

From a value-creation bottleneck perspective, this technology can reduce penalties where weight drives energy use, payload limits, or structural size; extend service life by slowing fatigue and hidden crack growth; and cut inspection downtime by enabling continuous condition monitoring. It can also ease constraints where human safety, access, or precision limits maintenance, where performance is capped by the cost/quality trade-off of existing materials, and where durability and environmental exposure currently force overbuilding, frequent replacement, or heavy protective layers.

#### ART 07.051 Smart Thermal Materials for Energy-Efficient Heating & Cooling

Multiple actors—materials companies, university labs, and appliance and equipment manufacturers—are plausibly converging on “smart thermal materials”: layered insulations, coatings, interface pads, and embedded structures designed to control where heat goes, when it moves, and how quickly it is released. This form factor is being pursued because it can often be applied as a retrofit (sprayed, laminated, wrapped, printed, or bonded), fits within existing fabrication and maintenance workflows, and targets a stubborn cost driver: unwanted heat loss and the growing burden of keeping systems within safe, efficient temperature ranges.

Within the next 20 years, these materials are anticipated to function as a coordinated suite rather than a single product. Some variants behave like “thermal valves,” shifting from insulating to heat-spreading states as temperature or an electrical signal changes. Others store and release heat by changing phase—like a controlled melt-freeze cycle—smoothing spikes without bulky tanks. Ultra-porous solids and vacuum-like laminates reduce heat leakage with thinner layers, while tough, high-conductivity paths move heat away from hotspots. Surface films can also tune how an object absorbs sunlight or

radiates heat to the sky, reducing cooling demand without moving parts. Many implementations embed low-cost sensors and identifiers so control systems can read local temperatures, estimate remaining heat-storage capacity, and adjust pumps, fans, or power levels through standard industrial controllers.

Key constraints include long-term durability (cracking, moisture ingress, and fouling), fire and toxicity compliance, performance drift over thousands of thermal cycles, and manufacturability at large area/volume with consistent quality. Some high-performance versions may depend on constrained feedstocks or require specialized encapsulation and end-of-life separation. Costs are likely to span from “premium insulation/coating” pricing per square meter to “industrial component” pricing for integrated modules.

From a value-creation bottleneck perspective, this technology can reduce losses that currently force over-sized energy inputs, cut peak cooling and heating loads that strain infrastructure, and stabilize temperatures in environments where precision and reliability are limited by human monitoring. It can also make thermal control less dependent on skilled, continuous intervention by enabling passive or semi-passive regulation, improve safety margins where overheating causes damage or downtime, and ease trade-offs between comfort, performance, and resource use when space, weight, noise, or maintenance access are constrained.

#### ART 07.052 Rare-Earth-Free Magnets for Sustainable Motors

Multiple research labs, magnet manufacturers, and motor-system integrators are developing rare-earth-free permanent magnets as an alternative to neodymium-based magnets, motivated by a desire to reduce exposure to concentrated supply chains while keeping high torque density and efficient operation. The approach focuses on compositions and microstructures that can be produced with more widely available inputs and that fit into familiar manufacturing routes for magnet powders, sintered blocks, or bonded magnet shapes, so they can be adopted without redesigning every upstream tool and assembly process.

Within the next 20 years, these magnets are anticipated to form a practical “family” of materials that cover several performance tiers: some optimized for high magnetic strength and temperature stability, others for lower cost, easier shaping, or improved corrosion resistance. Instead of being a drop-in match for today’s best neodymium grades in every metric, the technology is likely to deliver magnets whose performance is engineered to be “good enough” at the system level through better thermal management, motor geometry, and control software that compensates for different magnetic behaviors. Manufacturers may offer standardized magnet modules with predictable tolerances and aging profiles, allowing designers to specify magnets much

like other industrial materials—with datasheets describing field strength, coercivity, operating temperature range, and expected lifetime under vibration and cycling. Costs could range from commodity-like for lower-performance grades to premium industrial-material pricing for high-performance variants, comparable to other critical motor components.

Key constraints will include maintaining magnetic performance at high temperatures, achieving consistent quality at scale, and controlling manufacturing energy use and defect rates; some formulations may still rely on less-common alloying elements or specialized heat treatments. From a value-creation bottleneck perspective, this technology can reduce delays and redesign cycles caused by material scarcity, stabilize performance and cost under volatile input markets, enable more predictable maintenance and lifetime guarantees by improving resistance to demagnetization and corrosion, and lower the need for tightly controlled sourcing and purification steps that currently slow down high-volume production.

#### ART 07.053 Nano-Engineered Membranes for Low-Energy Desalination

Multiple research labs, membrane manufacturers, and infrastructure consortia are plausibly advancing nano-engineered desalination membranes over the next 20 years, because the core constraint in today's systems is not the basic physics of separating salt from water, but the practical losses: pressure requirements, fouling, and uneven performance over long operating cycles. By engineering pores and surface chemistry at the nanometer scale—using graphene-derived layers, nanocomposites, and other ultrathin selective films—these membranes aim to let water pass quickly while rejecting salts and trace contaminants with fewer energy and pressure penalties, in form factors that fit existing pump-and-module hardware.

In a mature form, the technology looks like modular membrane “cartridges” with highly uniform nanoporous pathways, anti-fouling surfaces that resist organic buildup, and coatings that reduce scaling from dissolved minerals. Some variants integrate simple embedded sensing (pressure drop, conductivity, flow) and allow remote tuning of operating modes, cleaning cycles, and replacement schedules via standard control interfaces. Compared with current membranes, the key property bundle is higher permeability at the same rejection, longer stable run times between cleanings, and more consistent output quality across varying feedwater conditions.

Feasibility hinges on scaling defect-free manufacturing, maintaining mechanical robustness under cyclic pressure, and managing end-of-life recycling or safe disposal of composite materials. Energy use still depends on intake conditions and recovery hardware, and concentrate handling remains an external constraint. Costs are likely to fall into the range of other containerized process equipment, with per-unit membrane replacement resembling a recurring consumable rather than a one-time capital item.

From a value-creation bottleneck perspective, this technology can ease constraints where clean water is limited by high operating energy, frequent maintenance, and the need for skilled oversight; reduce

exposure of workers to harsh chemical cleaning and high-pressure failures; improve reliability in settings where distance delays repairs and spare parts; and enable tighter, faster feedback in monitoring and control so output quality is less dependent on constant human attention.

#### ART 07.054 Ultra-Wide-Bandgap (UWBG) Power Semiconductors

Multiple research labs, device manufacturers, and materials suppliers are developing a new class of power semiconductors that use ultra-wide-bandgap materials—especially gallium oxide and engineered diamond—to push beyond today’s heat and high-voltage limits in power electronics. These materials are being pursued because their fundamental “electrical hardness” allows devices to block much higher voltages in thinner layers and to switch currents with lower resistive loss, which in turn can shrink converters and reduce wasted energy. Gallium oxide is attractive because it can be grown into relatively large single-crystal wafers by melt-based methods, while diamond is attractive because it conducts heat extremely well and can serve as both an active semiconductor and a heat-spreading platform.

Within the next 20 years, this technology is anticipated to appear as standardized power modules—switches and diodes packaged with sensors and control interfaces—that operate at higher junction temperatures, higher switching frequencies, and higher voltages than silicon-based components, and often beyond what today’s silicon carbide and gallium nitride can reliably sustain. These modules would plug into familiar electrical architectures, expose conventional control pins and digital diagnostics, and enable more compact, quieter systems with fewer passive components (like bulky inductors and cooling hardware). Likely constraints include the difficulty of producing low-defect wafers, controlling dopants and interfaces under extreme electric fields, packaging that survives repeated thermal cycling, and managing heat (especially for gallium oxide, which may require advanced heat spreaders or diamond composites). Early costs may resemble premium industrial power hardware—ranging from hundreds to thousands of euros per high-power module—before scaling reduces prices.

From a value-creation bottleneck perspective, this technology can ease constraints where equipment is limited by overheating, bulky cooling, or safety margins imposed by high voltage. It can reduce losses that currently force oversized hardware, shorten lifetimes, or drive high operating costs. It can also improve reliability and observability through built-in monitoring, lowering the human attention needed for maintenance and fault diagnosis, and enabling systems to be deployed where space, weight, noise, or service access are tightly constrained.

#### ART 07.055 Solid Hydrogen Storage Materials for Safe, Dense Fuel

Multiple actors—materials startups, national labs, and industrial gas consortia—are plausibly advancing solid hydrogen storage over the next 20 years because it changes hydrogen from a high-pressure, low-temperature handling problem into a materials engineering problem. Instead of relying mainly on heavy cylinders or cryogenic tanks, these approaches “pack” hydrogen into a solid medium: either by chemically absorbing it into alloys (often called metal hydrides) or by physically adsorbing it onto the internal surfaces of highly porous materials such as metal–organic frameworks and engineered carbons. The pursued form factors—granules, pellets, coated foams, or modular

cartridges—are attractive because they can be integrated into familiar container geometries, allow passive safety features, and offer higher volumetric density at much lower pressures than compressed gas.

In a mature configuration, a storage module would behave like a reversible sponge: it is charged by exposing the material to hydrogen under controlled pressure and temperature, and it delivers hydrogen by gently heating the bed or reducing pressure. Embedded heat exchangers and sensors manage temperature, flow, and state-of-charge, while standardized valves and digital interfaces allow swapping, diagnostics, and remote tuning of charge/discharge profiles. Key constraints remain: some materials require significant heat to release hydrogen, add mass that reduces gravimetric density, degrade over many cycles, or depend on costly alloying elements; many porous adsorbents are sensitive to impurities, moisture, and manufacturing variability. Early systems may cost like premium industrial pressure equipment or a battery pack, with costs trending downward as synthesis and shaping scale.

From a value-creation bottleneck perspective, this technology can reduce the hazards and overhead of handling high-pressure or ultra-cold hydrogen, ease constraints where space is limited but energy storage is needed, and improve reliability where refueling, transport, or on-site storage is slowed by specialized infrastructure, trained labor, or stringent safety procedures. It can also shift performance limits from bulky containment hardware toward repeatable, inspectable material cartridges, improving monitoring, predictability, and lifecycle management in dispersed or hard-to-access operations.

## Group 8 - Energy Generation, Storage & Conversion

### ART 08.056 Fusion Energy Reactors

Multiple actors—national laboratories, venture-backed developers, and international consortia—are pursuing practical fusion energy reactors because they promise a concentrated source of steady power from abundant light isotopes, with no combustion emissions and comparatively small volumes of long-lived waste. Over the next 20 years, leading approaches are likely to include magnetic confinement systems (such as tokamaks and stellarators) that hold a superheated plasma in place with strong magnets, as well as inertial approaches that use precisely timed laser or particle pulses to compress fuel to fusion conditions. The core objective is to turn brief, delicate fusion reactions into a controllable, continuously operating heat source that can be converted to electricity or delivered as high-temperature thermal output.

A mature fusion plant would resemble a tightly instrumented industrial facility: dense arrays of sensors monitoring plasma shape, temperature, radiation, and vibration; fast control systems adjusting magnetic fields, fueling, and exhaust; and heavily shielded

“hot cell” environments where robotic systems swap components exposed to intense neutron flux. Operators would rely on simulation-based “digital twins” and remote procedures to tune performance, schedule maintenance, and manage off-normal events. Early deployments are likely to be expensive—comparable to other large, capital-intensive infrastructure assets—and dependent on specialized supply chains for superconducting magnets, high-performance materials, and fuel handling (including tritium breeding, accounting, and containment). Key constraints include materials degradation under neutron bombardment, reliable heat extraction, uptime of complex subsystems, and licensing and safety-case standardization.

From a value-creation bottleneck perspective, this technology can ease constraints where reliable, high-density, around-the-clock energy is limited by fuel logistics, land footprint, emissions limits, or intermittency; where process heat requirements are hard to meet with low-carbon options; where long-lived waste and decommissioning complexity create friction; and where human access to hazardous environments is a limiting factor that favors remote operation and robotics.

#### ART 08.057 Small Modular Fission Reactors (SMRs)

Multiple reactor vendors, engineering firms, national laboratories, and public–private consortia are developing small modular fission reactors as a way to deliver nuclear energy in smaller, repeatable units rather than one-off megaprojects. The design approach emphasizes compact reactor cores, standardized layouts, and factory production so that major components can be built under controlled conditions, shipped as modules, and assembled with fewer site-specific changes. This form factor is being pursued to reduce construction risk, shorten build schedules, improve quality assurance, and enable safety features that rely on physics (such as natural circulation and gravity-fed cooling) instead of complex operator actions during emergencies.

Within the next 20 years, SMRs are anticipated to function as packaged energy plants that provide steady output in the tens to a few hundreds of megawatts (electric-equivalent), often with the option to deliver usable heat directly. Many designs are expected to incorporate passive safety systems intended to keep the reactor cooled even during loss of external power, with compact containment structures and increased use of sealed, long-life fuel assemblies to extend refueling intervals. Operation would likely include extensive instrumentation, continuous diagnostics, and remote expert support through secure digital interfaces, with software updates and “digital twin” models used to optimize performance and maintenance planning.

Key constraints remain material qualification, nuclear-grade manufacturing capacity, licensing timelines, fuel supply requirements, security obligations, and long-term handling of used fuel and decommissioning. Economically, individual units would still



resemble major infrastructure purchases (often hundreds of millions to over a billion dollars), with cost reductions depending heavily on serial production and standardization.

From a value-creation bottleneck perspective, this technology can ease constraints where dependable, high-density energy and heat are needed regardless of weather, where transporting large volumes of fuel is costly or risky, where downtime carries outsized consequences, and where complex construction coordination limits how quickly capacity can be added. It can also reduce exposure to hazardous operating conditions through higher automation and remote monitoring, while lowering the land and material footprint per unit of delivered energy compared with many diffuse alternatives.

#### ART 08.058 Thin-film solar cells

Multiple actors—including established photovoltaic manufacturers, materials startups, and university–industry consortia—are plausibly advancing thin-film solar cells as a complementary route to conventional wafer-based modules. The design logic is less about maximizing peak efficiency on rigid panels and more about enabling new form factors: depositing micrometer-scale semiconductor layers onto glass, metal foils, or flexible polymer sheets allows power-generating surfaces to be manufactured in large areas, shaped to fit complex geometries, and integrated into existing products and structures with fewer mechanical constraints. This approach is pursued because it can reduce weight and mounting requirements, enable roll-to-roll or high-throughput coating methods, and broaden where electricity generation can be placed without redesigning the underlying object.

Within the next 20 years, thin-film solar systems are anticipated to look like a family of coated surfaces and laminates that can be applied during manufacturing or retrofitted as “skins.” They convert ambient light into direct electrical power and connect through standardized wiring, thin busbars, or embedded connectors to inverters, batteries, or direct-current loads. Many variants will be semi-transparent, color-tunable, or textured, allowing them to function as functional surfaces while maintaining optical or architectural requirements. Performance will be managed by embedded power electronics that monitor temperature, shading, and degradation, and that can reconfigure cell strings to reduce losses. Configuration and diagnostics will increasingly be software-defined, with remote updates, automated fault detection, and lifecycle tracking to support maintenance and end-of-life handling.

Key constraints will remain: thin films can be more sensitive to moisture ingress, heat cycling, and micro-cracking, so encapsulation quality and long-term reliability are critical. Some chemistries depend on constrained materials or specialized deposition equipment, and achieving consistent yields at scale can be challenging. Costs are likely to span from commodity-building-material-like pricing for standard laminates to vehicle- or industrial-equipment-range costs for highly engineered integrated assemblies, depending on durability and integration complexity.

From a value-creation bottleneck perspective, this technology can ease constraints where power availability is limited by weight, surface geometry, or the inconvenience of installing rigid modules; where energy access depends on centralized infrastructure rather than locally harvested electricity; where maintenance and inspection of distributed assets strain human attention; and where durability, aesthetics, and safety requirements currently force trade-offs between adding functionality and preserving existing form and performance. It can also reduce delays created by scarce skilled installers by shifting more of the work into standardized manufacturing steps and software-assisted commissioning.

#### ART 08.059 Bionic Leaf Technology

Multiple research groups, catalyst developers, and clean-tech consortia could plausibly advance what is commonly meant by a “bionic leaf” over the next two decades: a sunlight-driven surface that performs artificial photosynthesis, directly turning simple inputs into reduced chemical compounds. The rationale for the leaf metaphor is practical as well as aesthetic: a leaf is an efficient light-collection geometry with built-in pathways for moving fluids and managing heat, and those same ideas translate into engineered panels that combine light absorbers, catalysts, and micro-channel networks in a compact, modular form. This approach is pursued specifically to avoid a two-step “make electricity first, then run separate chemistry” architecture, instead coupling light capture and chemical conversion inside the same device.

Within ~20 years, a bionic leaf is likely to look like a thin, sealed panel or tile with a textured front layer that captures sunlight and a layered interior that routes water and a carbon source through microfluidic channels. Under illumination, embedded photoactive materials and catalysts drive reactions that convert these inputs into storable outputs such as hydrogen-rich liquids, carbon-based intermediates (for example formate-like solutions), or other reduced compounds that can be collected as fluids. Integrated sensors track light intensity, temperature, pressure, pH, and product concentration, while onboard control software adjusts flow rates and operating modes, flags degradation, and exposes standard telemetry and control interfaces for remote supervision and automated dispatch.

Feasibility depends on catalyst lifetime, resistance to fouling and poisoning, safe containment of reactive intermediates, and practical product separation at the panel edge. Performance remains constrained by intermittency, surface area requirements, and the need for reliable supplies of water and a carbon feed stream. Early systems may be priced more like specialized industrial skids per installed module, with costs trending toward those of premium solar-plus-processing hardware as manufacturing scales.

From a value-creation bottleneck perspective, this technology can relieve constraints where access to low-carbon molecules is limited by centralized infrastructure, complex multi-step conversion chains, or the cost and hazard of transporting pressurized gases. It can also reduce human exposure to unpleasant monitoring and maintenance tasks by embedding condition sensing and remote control, enable distributed production where distance and permitting slow deployment, and shift the cost/quality trade-off in chemical supply toward processes that use abundant inputs while lowering reliance on scarce or geopolitically concentrated feedstocks.

#### ART 08.060 Grid-Scale Energy Storage

Multiple actors—equipment manufacturers, utilities, startups, and national labs—are developing long-duration, grid-scale energy storage because electricity supply and demand increasingly drift out of sync across hours, days, and sometimes seasons. The design approaches being pursued emphasize durable hardware that can be sited near existing electrical infrastructure, scaled in modular increments, and operated safely with predictable maintenance, rather than relying solely on short-duration batteries optimized for minutes-to-hours balancing.

Within the next 20 years, this technology is anticipated to look less like a single “battery” and more like a family of storage plants sized by both power (how fast energy can be delivered) and energy (how long it can run). Implementations may include low-cost aqueous and metal-based electrochemical systems designed for multi-day discharge, including iron–air and other metal–air chemistries that trade higher mass and lower round-trip efficiency for very low cost per stored kilowatt-hour and long endurance. Other approaches may include mechanical stores that raise/lower mass or compress working fluids, thermal stores that hold heat in engineered media and convert it back to electricity, and chemical pathways that store energy in simple molecules for multi-week to seasonal use. These systems will integrate bidirectional power electronics, dense sensor networks, and control software that estimates state-of-charge and state-of-health, schedules charging against forecasts and constraints, and supports remote operation with standardized digital interfaces.

Key constraints will remain: round-trip efficiency varies widely by approach; some options depend on site conditions, land, water, or specialized containment; and some chemistries require careful management of air exposure, corrosion, and cycling wear over years of operation. Permitting, fire risk, gas handling, and end-of-life recycling can dominate timelines. Economically, projects are likely to be financed like major infrastructure—often costing from several million to hundreds of millions of euros per site—while the marginal cost of adding stored-hours, particularly for multi-day coverage, becomes increasingly decisive.

From a value-creation bottleneck perspective, this technology can reduce delays and losses caused by timing mismatches, stabilize systems that are otherwise limited by human attention and fast coordination, and lower the need to overbuild capacity just to cover rare shortages. It can also ease constraints where distance, access to skilled operators, or volatile input supplies create fragility, while improving safety and predictability in environments where failures are costly and difficult to repair quickly.

#### ART 08.061 Solid-State Batteries

Multiple actors—including cell manufacturers, materials suppliers, and research consortia—are developing solid-state batteries that replace today's flammable liquid electrolyte with a solid ion-conducting layer. This design approach is pursued because it can reduce fire risk under abuse or damage, enable tighter packaging, and potentially allow the use of lithium-metal anodes that store more charge per unit mass than the graphite used in most current cells. Over the next 20 years, mature solid-state cells are anticipated to combine higher energy density with improved thermal stability, using thin solid electrolytes and engineered interfaces that keep ions moving quickly while limiting the growth of needle-like lithium structures that can short-circuit a cell.

In practical systems, these batteries would be delivered as modular cells and packs with embedded sensing for temperature, pressure, and internal resistance, feeding a battery management controller that estimates state of charge and health, enforces safe operating windows, and receives periodic firmware updates to refine charging profiles as the pack ages. Compared with many present lithium-ion packs, solid-state designs could support faster charging at moderate temperatures, longer calendar life, and less reliance on bulky cooling and protective housings, though performance may still vary with cold conditions and sustained high-power use.

Key constraints remain: manufacturing requires extremely clean, precise layering and intimate contact between solids, and some electrolyte chemistries depend on specialized materials that could face supply or cost volatility. Early products may be priced at a premium, while later generations could approach cost levels comparable to

established lithium-ion packs for similar capacity as yields improve and production scales.

From a value-creation bottleneck perspective, this technology can ease safety and insurance frictions tied to thermal runaway, reduce downtime and maintenance caused by conservative charging limits, expand what is feasible where space and weight are tightly constrained, and improve reliability in environments where skilled oversight or complex cooling infrastructure is scarce. It can also shift bottlenecks toward quality control, recycling pathways, and standardized health data that supports longer, more predictable asset lifetimes.

#### ART 08.062 Green Hydrogen & Power-to-X

Multiple actors—equipment manufacturers, clean-energy developers, chemical engineering firms, and public-private consortia—are advancing “green hydrogen & power-to-X” systems that convert clean electricity, water, and captured carbon into hydrogen and synthetic energy carriers. This design approach is pursued because it can translate variable renewable power into storable, transportable molecules, while leveraging familiar industrial unit operations (electrolyzers, compressors, reactors, tanks, pipelines) and increasingly standardized digital control systems. Over the next ~20 years, these systems are anticipated to mature into modular plants ranging from container-sized units to large integrated facilities, with electrolyzer stacks operating dynamically to follow power availability and with downstream synthesis modules that can be reconfigured to produce different outputs (e.g., hydrogen, ammonia-like carriers, or liquid hydrocarbons) depending on local constraints and market signals.

In practical terms, a power-to-X plant senses electricity price and carbon intensity, water quality, equipment health, and product purity in real time, then adjusts setpoints automatically to maximize yield and reliability. Operators interact through standard industrial interfaces and remote dashboards; performance updates arrive as software and firmware revisions, while predictive maintenance models reduce downtime by scheduling component replacement before failures. Key constraints remain: access to low-cost clean electricity and water, siting and permitting for safety, compression and storage energy penalties, and the need for reliable supply chains for catalysts, membranes, and power electronics. Costs are likely to span from “industrial equipment purchase” scales for small systems to “major infrastructure project” scales for large plants, with operating costs dominated by electricity and utilization rates.

From a value-creation bottleneck perspective, this technology can reduce dependence on scarce or intermittent energy inputs by converting surplus clean power into molecules that can be stored for weeks or shipped long distances; it can ease coordination constraints by buffering volatility in power supply and enabling more

predictable energy delivery; it can lower the safety and handling burden of high-pressure or cryogenic fuels through improved carriers, monitoring, and automated controls; and it can improve quality and traceability by embedding measurement and certification data directly into production, enabling buyers to verify origin, carbon content, and consistency without slowing transactions.

#### ART 08.063 High-Efficiency Wind Turbines

Multiple actors—including turbine manufacturers, composite-material suppliers, offshore engineering firms, and research consortia—are steadily pushing wind machines toward higher energy capture per unit of installed hardware over the next two decades. The core design logic is to sweep a larger area of moving air with structures that remain light, fatigue-resistant, and manufacturable at scale, while using better sensing and control to keep the rotor operating near its aerodynamic optimum in changing winds. This drives trends toward extremely long, lightweight blades (often exceeding 100 meters) for large offshore units, but also toward alternative form factors such as vertical-axis turbines that can tolerate turbulent flows and pack differently into constrained sites, and airborne wind systems that fly tethered wings or drones to access stronger, steadier winds at higher altitude.

Within roughly 20 years, high-efficiency wind systems are anticipated to look less like static mechanical machines and more like cyber-physical platforms: distributed sensors measure wind shear, gusts, vibration, icing, and structural strain; onboard models and remote updates tune blade pitch, yaw, generator loading, and flight trajectories (for airborne systems) to balance power output against lifetime wear. Advanced composites, coatings, and modular blade sections enable repair and replacement without full disassembly, while embedded condition monitoring reduces unexpected downtime. Constraints remain significant: transporting and installing oversized components, maintaining reliability in salt spray and extreme storms, managing noise and wake interactions, and meeting safety, aviation, and environmental permitting requirements. Capital costs are typically comparable to other large industrial assets, with economics sensitive to financing, maintenance access, and connection infrastructure.

From a value-creation bottleneck perspective, this technology can ease constraints where energy supply is limited by the efficiency, availability, and operating life of large machines in harsh or remote environments; where human inspection and maintenance are slow, risky, or skill-constrained; where variability and forecasting errors create coordination burdens; and where material intensity, rare inputs, and end-of-life disposal make high-performance hardware difficult to scale without cost, reliability, or footprint trade-offs.

## ART 08.064 Wireless & Space-Based Power Transfer

Multiple actors—space agencies, satellite operators, infrastructure consortia, and specialized startups—are plausibly developing wireless and space-based power transfer systems that deliver usable electricity without physical cables. This approach is pursued because it can bypass terrain, permitting, and right-of-way constraints, and because orbital platforms can access steadier sunlight than most ground locations. A leading configuration is space-based solar power: very large collector arrays in geostationary orbit, potentially approaching kilometer-scale in deployed area, convert sunlight to electricity and then to a tightly controlled microwave or laser beam for continuous delivery to Earth-based receivers.

Within roughly the next 20 years, the technology is anticipated to consist of modular transmitter nodes (ground, airborne, and orbital) that convert electrical energy into steerable beams, paired with receiver arrays that convert it back into direct current and condition it for local use or interconnection. Receivers may range from compact panels for mobile equipment to large, lightweight rectenna fields designed to accept orbit-to-Earth beaming at utility-relevant power levels, behaving operationally like a dispatchable generation asset. Software-defined beam shaping, encrypted control links, and continuous sensing would verify alignment, power density, and exclusion zones, while standard power electronics and secure monitoring APIs provide familiar human and machine interfaces. Over time, firmware updates and adaptive control models are likely to improve pointing accuracy, conversion efficiency, and fault detection.

Key constraints remain: end-to-end efficiency losses, atmospheric absorption and weather sensitivity (especially for optical links), electromagnetic compatibility and spectrum allocation, public safety limits on beam intensity, and resilience against mispointing, spoofing, or orbital hazards such as debris and station-keeping failures. Early deployments may be priced like major infrastructure assets—receiver sites comparable to substations, and orbital segments comparable to large satellites plus launch—while costs decline with mass production and reusable launch.

From a value-creation bottleneck perspective, this technology can reduce delays caused by distance and access by supplying power where physical connections are slow or impractical, enable temporary or mobile operations without fuel delivery or heavy cabling, lower human exposure to hazardous installation and maintenance work, and provide a controllable energy bridge when local generation or wired networks are disrupted or capacity-constrained.



## ART 08.065 Advanced geothermal technology

Multiple actors—drilling firms, materials laboratories, geoscience institutes, and project consortia—are plausibly advancing “advanced geothermal” systems that tap deep subsurface heat in far more places than today’s naturally porous, high-temperature regions. The design emphasis is on super-deep wells (roughly 5–10+ km) into superhot rock, combined with engineered circulation pathways or sealed, closed-loop heat exchangers, because heat is widespread while naturally productive reservoirs are not. By pushing depth and temperature, the approach seeks higher energy density per well and more predictable, round-the-clock output, using form factors that can integrate with standard surface heat-to-power equipment, industrial heat exchangers, and common monitoring-and-control software.

Within the next 20 years, a typical system is anticipated to include high-temperature drilling methods (including faster rock-breaking and more durable bits), corrosion- and creep-resistant casing and cement, and downhole sensors that can survive extreme pressure and heat. Surface and subsurface controls would continuously regulate flow, pressure, and thermal drawdown, with data-driven models updating reservoir estimates, forecasting performance, and flagging anomalies. Depending on configuration, the system could deliver high-grade heat directly, convert it to electricity via standard thermal cycles, or provide both, with modularity to scale from a few wells to multi-well “heat fields.”

Key constraints remain substantial: drilling and completion costs are likely comparable to other large engineered infrastructure projects (often tens to hundreds of millions per site), supply chains for extreme-temperature components may be limiting, and careful risk management is needed for induced seismicity, well integrity, and long-term thermal decline. Regulatory permitting, subsurface data availability, and access to water or working fluids can also govern feasibility.

From a value-creation bottleneck perspective, this technology can reduce dependence on location-specific resources, provide a steady energy and heat source where intermittency or fuel logistics create planning friction, compress timelines for deploying high-capacity thermal systems, and shift difficult human work toward remote supervision by improving subsurface sensing, control precision, and automated diagnostics in harsh environments.

## ART 08.066 Resilient microgrids

Resilient microgrids are being developed by utilities, equipment manufacturers, software firms, and research consortia as a pragmatic way to keep electricity available

when wider networks are stressed by outages, congestion, or fast-changing supply. The core design choice—building a self-contained “local grid” that can either synchronize with a larger system or separate from it—fits well with today’s distributed generators, inverters, and standardized electrical protection hardware, while allowing incremental expansion as local demand grows.

Within roughly the next 20 years, a mature resilient microgrid is likely to look like a coordinated bundle of local power sources (such as rooftop or ground-mounted renewables, small engines, and batteries) connected through power electronics and monitored by dense sensing of voltage, frequency, and equipment health. Control software continuously balances supply and demand, dispatches storage, and performs “islanding” and “reconnection” with minimal interruption, including limited black-start capability to restore power without relying on an external feed. Operators interact through dashboards and alarms, with automation handling routine switching and optimization; configuration updates and performance tuning are delivered remotely, and models adapt to changing usage patterns, weather forecasts, and asset aging.

Key constraints remain: engineering and permitting complexity, protection coordination with upstream infrastructure, cybersecurity of control interfaces, and dependence on critical battery and inverter components. Reliability hinges on maintenance and testing, and operational rules may be shaped by safety codes and grid-interconnection regulation. Costs vary widely, but many deployments are likely to be comparable to other large site-level capital upgrades—often in the range of a major industrial system plus ongoing software and service contracts.

From a value-creation bottleneck perspective, this technology can reduce downtime where interruptions are costly or unsafe, compress recovery time after disruptions, and ease coordination limits by automating real-time decisions that exceed human attention and reaction speed. It can also lower the resource intensity of “overbuilding” backup capacity by sharing and scheduling local assets, improve power quality for sensitive processes, and extend reliable access in locations where distance, congestion, or scarcity of skilled operators makes centralized reliability hard to guarantee.

## Group 9 - Bio-engineering & Life-Science Technologies

### ART 09.067 Next-Generation Gene Editing

Multiple research groups, companies, and public–private consortia are likely to develop next-generation gene editing systems that build on CRISPR but behave more like programmable “molecular repair tools,” aiming to change DNA (and, in some cases, RNA) with far tighter control over where and how edits occur. This design direction is being pursued because today’s editing approaches can be limited by unintended

changes, uneven performance across cell types, and the practical difficulty of delivering editing machinery to the right cells at the right dose; incremental improvements in guide design, enzyme engineering, and error-checking chemistry offer a plausible path to higher reliability while remaining compatible with widely used lab workflows and sequencing-based verification.

Within roughly the next 20 years, these tools are anticipated to support a broader menu of edits than simple “cut and replace,” including single-letter corrections, small insertions or deletions, targeted gene switching (turning activity up or down without rewriting the sequence), and multiplex edits coordinated across many sites. Editing systems would be packaged with delivery methods tuned to different contexts—such as temporary editor “payloads” that degrade after use—and accompanied by standardized measurement of off-target risk, edit completeness, and long-term stability. Human interaction would likely resemble a software-driven design-and-validate loop: users specify desired genetic changes in a sequence editor, simulation and historical performance data suggest candidates, automated test pipelines generate evidence, and updates improve performance across new genomes and cell states. Key constraints will remain: delivery to hard-to-reach tissues, immune reactions, mosaic outcomes where only some cells are edited, complex manufacturing and quality control, and governance requirements around consent, traceability, and ecological containment; early applications may cost like high-end bespoke biological interventions, with later routinized uses trending toward costs comparable to specialized laboratory services.

From a value-creation bottleneck perspective, this technology can reduce the time and uncertainty required to identify, test, and implement precise biological changes; shift work away from slow trial-and-error optimization toward more verifiable, repeatable edits; lower the human labor and expertise needed to produce organisms with stable, measurable traits; and improve safety margins by making outcomes more predictable, auditable, and reversible through layered controls and monitoring.

#### ART 09.068 mRNA Therapies & Vaccines

Multiple actors—pharmaceutical companies, academic labs, and manufacturing consortia—are plausibly advancing mRNA therapies and vaccines as a platform over the next two decades, because the “active ingredient” can be redesigned largely in software and synthesized with repeatable, standardized steps. Instead of delivering a finished protein or an inactivated pathogen component, these treatments deliver short-lived messenger RNA instructions so a person’s own cells temporarily produce a therapeutic protein or an immune-training antigen. The approach is being pursued because it can shorten design-to-production cycles, reuse much of the same

manufacturing equipment across many products, and enable rapid iteration when new targets or variants appear.

Within 20 years, mRNA products are anticipated to look like configurable “recipes” paired with increasingly reliable delivery carriers (such as improved lipid nanoparticles, polymers, or engineered particles) that control which tissues receive the message, how strongly it is translated, and how long expression lasts. Formulations may expand beyond cold-chain vials into more stable presentations (lyophilized powders, prefilled devices, or patch-like applicators), and dosing could be guided by routine biomarkers so that schedules and amounts are adjusted to balance effect and tolerability. Software-connected manufacturing could support smaller-batch or personalized sequences while maintaining tight quality control via automated analytics that verify identity, purity, and potency before release.

Key constraints remain: innate immune activation and rare inflammatory reactions, the difficulty of precise targeting without off-target uptake, dependence on specialized lipids and enzymes, and a regulatory burden that grows with personalization and frequent updates. Costs are likely to range from commodity-like per-dose pricing for high-volume products to biologic-like course pricing for customized regimens, with logistics and quality testing often dominating.

From a value-creation bottleneck perspective, this technology can reduce reliance on slow, facility-intensive protein production; compress development timelines when speed matters; make high-precision, adaptable interventions feasible under uncertainty; and ease frictions caused by scarce specialized labor, limited manufacturing capacity, and the need to coordinate design, production, distribution, and monitoring with minimal errors.

#### ART 09.069 Cellular Agriculture & Cultured Meat

Multiple actors—including food producers, biotechnology firms, equipment suppliers, and research laboratories—are developing cellular agriculture to produce animal-like products and protein ingredients using controlled cell growth and fermentation rather than raising whole animals. The approach is being pursued because it can separate output volume and composition from land availability, seasonal weather, and biological shocks, while drawing on process-control methods and hardware already used in modern biomanufacturing.

Over the next 20 years, cellular agriculture is anticipated to mature into modular production systems with two complementary tracks. In one, animal cells are expanded in sterile vessels and guided to form muscle- and fat-like tissues using carefully formulated nutrient media and structured growth environments. In the other, precision

fermentation and microbial cultivation produce functional components and, in some cases, bulk protein biomass directly: microorganisms are fed carbon sources that can include purified CO<sub>2</sub> and hydrogen generated from water using renewable electricity, producing a nutritious biomass that can be dried into a stable powder and blended into foods as a protein ingredient. Across both tracks, operators rely on dense sensing (temperature, acidity, dissolved gases, nutrients, biomass density, and contaminants) and software that adjusts feed rates, gas composition, mixing, and timing to keep yields and composition consistent. Human interaction resembles running a small industrial plant: standardized procedures, in-line quality checks, traceability records, and remote monitoring through dashboards and APIs.

Key constraints will remain. Sterility failures and contamination can halt batches, while scaling depends on reliable supplies of affordable inputs (growth media components, purified CO<sub>2</sub> streams, water, and electricity) and specialized vessels, filtration systems, and downstream processing. Gas-fed systems add safety and engineering demands around hydrogen handling, ventilation, and monitoring. Regulatory approval and verification practices will shape allowable ingredients, processes, and labeling claims. Early installations are likely to be capital-intensive assets comparable to other industrial production lines, with costs improving as media formulations, energy efficiency, and standardized equipment designs mature.

From a value-creation bottleneck perspective, this technology can reduce dependence on variable biological and environmental conditions by moving production into monitored, controllable environments, improve consistency in composition and quality, and shorten feedback loops through data-rich process control. It can ease constraints where reliability, safety, traceability, or contamination risk limit throughput, where distance or access to suitable land and skilled labor creates delays, and where current methods face hard trade-offs among cost, resource intensity, and predictable output.

#### ART 09.070 Organoids & Tissue Engineering

Multiple actors—university labs, startup platforms, major equipment vendors, and consortia linking biobanks with manufacturing partners—are plausibly advancing organoids and tissue engineering over the next 20 years because today's models of living tissue often fail to predict how real human biology will respond. The form factor of miniature, lab-grown tissues is being pursued because it can fit into existing workflows (multiwell plates, microscopes, incubators, fluidic chips) while offering a closer approximation of structure and function than flat cell layers, with a cost curve that can improve through standardization and automation.

Within two decades, this technology is anticipated to produce repeatable “living test articles” ranging from millimeter-scale organoids to centimeter-scale tissue patches, grown from stem cells or reprogrammed adult cells and shaped by biodegradable scaffolds, controlled signaling cocktails, and programmable mechanical cues. Many constructs will incorporate microchannels that mimic blood vessels, embedded sensors that track oxygen, acidity, and secreted molecules in real time, and co-cultures that include supporting cell types to better reproduce barrier function, contraction, filtration, or hormone-like signaling. Systems will be configured through software recipes and monitored by imaging plus machine-learning quality control that flags abnormal growth, contamination, or drift between batches.

Key constraints are likely to remain: incomplete maturation compared with adult organs, variability between cell sources, limits on size without robust perfusion, sensitivity to handling, and regulatory and biosecurity oversight for human-derived living materials. Costs may range from high-end lab assays for standardized organoids to industrial-instrument scale for automated bioreactor lines.

From a value-creation bottleneck perspective, this technology can reduce reliance on slow, expensive, and sometimes misleading surrogate models; compress iteration cycles by enabling early, higher-fidelity feedback on how complex living systems respond; improve quality control where biological variability currently forces overengineering or waste; and expand access to scarce biological material by producing consistent, on-demand constructs that can be shipped, archived, and compared across sites under shared standards.

#### ART 09.071 Synthetic Biology & Designer Microbes

Multiple actors—university labs, industrial biotech firms, and public–private consortia—are plausibly developing “designer microbes” that act as programmable living factories over the next 20 years. The rationale is that microorganisms already excel at turning low-value inputs into complex molecules under mild conditions; by making their genetic “control logic” more modular and predictable, developers can shift production away from multi-step, energy-intensive processing toward distributed, fermentation-like systems that fit into existing bioreactors, waste-handling equipment, and quality-control workflows.

Within two decades, this technology is anticipated to include standardized microbial chassis (such as bacteria, yeast, or mixed communities) paired with software-defined genetic circuits that control when and how the cells make target outputs. The microbes would sense local conditions—nutrients, contaminants, temperature, acidity, or signaling molecules—then adjust metabolic pathways to synthesize specific chemicals, polymers, pigments, enzymes, or structured biomaterials. Some variants

would be optimized for robustness and containment, with built-in dependencies on supplied nutrients, self-limiting lifespans, and “kill switches” to reduce persistence outside controlled environments. A subset may also perform simple information processing by converting chemical signals into measurable outputs, enabling biological sensing-and-reporting that interfaces with standard instruments and digital dashboards.

Key constraints remain material: scaling can be limited by feedstock purity, contamination risk, bioreactor design, downstream separation costs, and regulatory requirements for containment and traceability. Performance may vary across batches, and some products will still require costly purification. Economics are expected to span from commodity-like outputs priced similar to bulk chemicals to higher-value specialty materials comparable to premium industrial additives, with capital costs akin to mid-sized process equipment rather than large megaplants.

From a value-creation bottleneck perspective, this technology can reduce dependence on high-temperature, high-pressure processing; expand production in places lacking large centralized infrastructure; and convert\_toggle between different outputs with faster reconfiguration than retooling physical plants. It can also ease constraints where quality, selectivity, or waste generation currently make production slow, hazardous, or expensive, and where monitoring is difficult by embedding sensing and reporting directly into the production organism.

#### ART 09.072 Microbiome Engineering

Multiple actors—academic labs, consumer product companies, environmental engineering firms, and public-private consortia—are advancing microbiome engineering as a practical way to steer complex microbial ecosystems rather than treating biology as a black box. The approach is being pursued because microbial communities already run many critical chemical transformations in soil, water, and the human gut; small, well-targeted changes can sometimes shift outcomes more efficiently than rebuilding whole systems with new infrastructure or drugs, and the interventions can often be delivered using familiar form factors (coatings, pellets, capsules, sprays) and monitored with fast sequencing and low-cost sensors.

Within roughly the next 20 years, microbiome engineering is anticipated to become a configurable toolkit that combines (1) measurement (rapid profiling of community composition and activity), (2) design (models that predict how a community will respond to specific inputs), and (3) actuation (precision “nudges” such as tailored nutrient blends, selective antimicrobials, bacteriophages, or engineered strains designed to perform a single function and then fade out). In the human gut, this could look like personalized, periodically updated formulations that shift metabolism,



inflammation signaling, or pathogen resistance without requiring continuous dosing. In soil and water, it could mean inoculants or substrates that encourage desired breakdown pathways, suppress harmful blooms, or stabilize nutrient cycling, with performance tracked via simple field or at-home tests and software dashboards.

Key constraints remain: microbial ecosystems can be unpredictable, effects may be temporary, and safety depends on avoiding unintended spread, gene exchange, or ecosystem disruption; many uses will face stringent oversight and long validation cycles. Costs are likely to span from consumer-test and supplement-like price points for mild interventions to enterprise-scale service contracts for high-reliability monitoring and control.

From a value-creation bottleneck perspective, this technology can reduce reliance on slow trial-and-error in living systems, stabilize output quality where biology introduces variability, replace harsh broad-spectrum interventions with narrower ones, extend effective operation in settings where contamination and decay impose constant maintenance, and improve decision-making by turning invisible microbial dynamics into measurable, actionable signals that non-specialists can use.

#### ART 09.073 Precision Medicine & Genomic Diagnostics

Multiple actors—research hospitals, sequencing firms, diagnostics manufacturers, pharmaceutical developers, and public genomics consortia—are plausibly converging on precision medicine and genomic diagnostics because today’s “one-size-fits-most” prevention and treatment often fails to explain why two people with similar symptoms respond differently. Over the next ~20 years, the practical form factor is likely to be a combined testing-and-decision platform that pairs low-cost whole-genome (or near-whole-genome) reads with repeatable molecular snapshots from blood, saliva, or other minimally invasive samples, then translates those signals into actionable risk estimates, likely response profiles, and monitoring markers. Instead of returning raw genetic data, the system would generate plain-language summaries, confidence levels, and recommended follow-up steps, while also exposing standardized software interfaces so authorized tools can query results (for example, to flag contraindications, suggest dose ranges, or track molecular changes over time). The “learning” component would come from continuously updated reference datasets and models trained on diverse populations, with audit trails that show which evidence supports each recommendation.

Key constraints remain: results depend on sample quality, representation in reference datasets, and the fact that genes are only one part of the story alongside environment and behavior. False positives, uncertain variants, and shifting interpretations will require confirmatory testing and careful communication. Costs are likely to move from

high hundreds or thousands per comprehensive profile toward tens to low hundreds for routine panels, with premium analyses priced more like enterprise software subscriptions plus laboratory fees. Strong privacy controls, consent management, and regulation around sensitive biological data will be unavoidable.

From a value-creation bottleneck perspective, this technology can reduce trial-and-error by narrowing options earlier, shorten time to correct decisions when stakes are high, enable earlier detection through continuous molecular monitoring, and lower coordination burdens by turning complex biological signals into standardized, comparable outputs that can travel across organizations and over time.

#### ART 09.074 Organs-on-Chips & Bio-Computational Hybrids

Multiple actors—including academic labs, semiconductor and microfabrication firms, and biotech consortia—are plausibly advancing organs-on-chips and bio-computational hybrids because they fit into existing cleanroom and lab workflows while enabling a tighter coupling between living biology and programmable electronics. The core form factor is a small, sealed microfluidic chip that routes tiny volumes of fluid through channels lined with living cells, combined with embedded sensors, electrodes, and control circuits that can read and shape biological activity in real time. This approach is pursued because it can reproduce key aspects of tissue behavior with less material, faster iteration cycles, and more controllable conditions than many current experimental setups, while remaining compatible with standardized imaging, automation, and data systems.

Within roughly the next 20 years, these devices are anticipated to evolve from single-function “mini-tissue” models into modular platforms where several tissue types can be linked by fluid exchange, timed stimulation, and automated sampling. Integrated electronics would continuously monitor signals such as electrical activity, barrier integrity, metabolic byproducts, and mechanical responses, while onboard control loops adjust flow rates, nutrient composition, temperature, and stimulation patterns. In bio-computational hybrids, engineered cell networks—selected for stable signaling or adaptive response—would interface with conventional processors so that some tasks (pattern detection, anomaly response, or adaptive control) are performed by living components trained through repeated inputs, then read out through electrodes or optical sensors. Interfaces would include simple software APIs, standardized cartridges, and remote calibration/firmware updates, allowing reproducible deployment across facilities.

Key constraints remain: maintaining long-term cell stability, preventing contamination, ensuring consistent chip-to-chip behavior, and managing regulatory requirements when results are used for high-stakes decisions. Manufacturing complexity and quality

assurance are nontrivial, and performance depends on reliable consumables, sterile handling, and data infrastructure. Costs are likely to span from high-end instrument levels (comparable to specialized lab equipment) for integrated systems, down to per-chip consumables priced like premium lab cartridges as volumes scale.

From a value-creation bottleneck perspective, this technology can reduce reliance on slow, labor-intensive testing cycles by enabling rapid, instrumented experiments with continuous readouts and fewer manual steps. It can ease constraints where safety, uncertainty, or ethical limits restrict experimentation by providing controllable biological proxies that capture relevant responses without requiring full-scale trials. It can also relieve bottlenecks driven by scarce expertise and inconsistent procedures by packaging complex biological preparation into standardized modules with automated monitoring and self-correcting control, improving repeatability across distributed teams. Finally, it can reduce information frictions by turning biological responses into high-frequency data streams that can be compared, audited, and integrated into decision pipelines, while enabling adaptive systems that respond to biological variability rather than assuming fixed conditions.

#### ART 09.075 Biological Aging & Longevity Barriers

Multiple actors—including pharmaceutical firms, biotech startups, and academic consortia—are developing interventions aimed at the biological barriers that drive aging, because age-related decline appears to be partly driven by specific, addressable cellular states rather than an indistinct “wear and tear” process. Two complementary approaches are likely to mature over the next 20 years: senolytic and senomorphic drugs, and controlled epigenetic reprogramming therapies. Senolytics are anticipated to work by selectively removing senescent “zombie” cells that accumulate after stress and damage, while senomorphics aim to quiet the harmful cocktail of signals these cells release, reducing persistent inflammation-like activity that can degrade tissue function. Epigenetic reprogramming therapies are expected to use transient, tightly timed gene-regulation programs—delivered via familiar modalities such as injections, infusions, or localized delivery systems—to partially reset cell “settings” toward a more youthful pattern without erasing cell identity.

Within a 20-year horizon, these technologies would likely be configured using biomarker panels that indicate senescent burden, inflammatory signaling, and tissue-specific function, with dosing schedules that look more like periodic maintenance than continuous daily treatment. Key constraints remain significant: avoiding off-target cell loss, immune reactions to delivery vehicles, uneven distribution across tissues, and the possibility of promoting abnormal growth if reprogramming is too strong or too long. Manufacturing complexity (especially for advanced delivery systems), long follow-up requirements, and stringent safety regulation are likely; early costs may be in the tens

to hundreds of thousands of euros per person per year, with declines as platforms standardize.

From a value-creation bottleneck perspective, this technology can reduce time and capability lost to gradual functional decline, lower the burden of managing slow-building damage states that demand constant monitoring, and improve reliability in human performance where fatigue, recovery time, and inflammation-driven variability currently constrain precision, coordination, and sustained effort.

#### ART 09.076 Engineered Living Materials

Engineered Living Materials refer to a class of structural composites that intentionally incorporate living cells—often microbes, algae, fungi, or engineered mammalian cells—into a supportive matrix so the resulting material can behave less like an inert substance and more like a slow, responsive “living” system. Multiple actors, including university labs, materials companies, construction-chemistry suppliers, and defense or infrastructure consortia, are plausibly advancing this approach because it offers a pathway to materials that maintain performance over time with fewer replacements, and because it can be manufactured in shapes and formats compatible with existing fabrication methods (panels, blocks, coatings, fibers) while gradually improving through process optimization and standardized “starter cultures.”

Within roughly the next 20 years, these materials are anticipated to be produced as composites where the non-living portion provides baseline strength, stiffness, and weather resistance, while embedded cells perform targeted functions: sealing microcracks by precipitating minerals or polymerizing repair agents; adjusting porosity or moisture handling within a narrow range; and capturing carbon by converting CO<sub>2</sub> into stable mineral phases or long-lived biopolymers locked into the structure. They would be monitored through simple indicators (color change, electrical resistance, acoustic signatures) and optionally connected to low-power sensors for condition tracking, with performance “tuned” through nutrient delivery, humidity management, or periodic activation cycles rather than continuous feeding. Key constraints include the need to keep the living components within survivable temperature, moisture, and chemical ranges; slower response times than mechanical repairs; limits on maximum structural loads versus conventional high-strength materials; and manufacturing complexity around sterility, shelf life, and quality control. Early versions are likely priced like premium engineered composites, with costs falling as bioprocessing and supply chains mature.

From a value-creation bottleneck perspective, this technology can reduce downtime and labor tied to inspection and repair by making degradation detectable and partially correctable in place, ease durability and safety trade-offs by slowing crack propagation

before failures, and lower resource intensity by extending service life and enabling regeneration rather than replacement. It can also reduce dependence on scarce high-energy inputs by shifting part of material formation to low-temperature biological processes, and it can improve environmental footprint constraints by turning passive surfaces and structures into distributed, long-lived carbon sinks whose performance can be verified and audited through embedded condition signals.

#### ART 09.077 Gene Drive Pest Control

Multiple research labs, public agencies, and commercial biotechnology groups are plausibly developing gene drive pest control systems that can bias inheritance in wild populations, because a self-propagating genetic change offers a scale advantage over conventional, repeatedly applied controls. Rather than relying on frequent human intervention, a gene drive is designed so that a chosen genetic trait is copied and passed on to a larger-than-normal share of offspring, allowing the trait to spread through a target population over successive generations.

Within the next 20 years, this technology is anticipated to function as a configurable “genetic control layer” for certain sexually reproducing species, tuned either to reduce population viability (suppression) or to shift a population’s characteristics (modification). In practical terms, the system would be designed, validated, and manufactured in controlled facilities, then introduced through tightly managed releases, with field monitoring that tracks genetic spread, population response, and ecosystem effects. Human interaction would center on software-driven design and risk modeling, standardized sampling and sensing protocols, and governance controls that define where and when releases can occur. The technology would increasingly incorporate design features intended to limit geographic spread, slow propagation, or enable partial reversal, but it would still be constrained by evolutionary uncertainty (e.g., resistance emerging), uneven spread in complex environments, and substantial regulatory and social authorization requirements. Total program costs are likely to resemble other multi-year, high-scrutiny environmental interventions, dominated by testing, monitoring, and long-term stewardship rather than materials.

From a value-creation bottleneck perspective, this technology can reduce reliance on repetitive, labor-intensive control efforts; lower human exposure to hazardous or unpleasant mitigation tasks; improve precision compared to broad, non-specific interventions; and address situations where distance, coordination burdens, or scarcity of skilled teams make sustained control slow, expensive, or inconsistent. It can also ease constraints created by the durability limits of current approaches, where benefits decay quickly unless continuously maintained, by shifting some of the work into persistent biological processes—while introducing new bottlenecks around verification, reversibility, and accountability.

## ART 09.078 Artificial Wombs & Synthetic Embryos

Multiple research labs, hospital-linked engineering groups, and cross-species developmental biology consortia are plausibly developing artificial womb systems and “synthetic embryo” models because they offer a controlled, instrumented alternative to parts of gestation that are currently difficult to observe, support, or standardize in living bodies. The dominant form factor is likely a sealed, sterile bioreactor: a fluid-filled chamber that maintains temperature, pressure, and biochemical composition while a placenta-like exchange interface delivers oxygen and nutrients and removes waste. This approach is being pursued because it can be made compatible with existing bioprocess equipment, allows continuous sensing, and enables repeatable protocols that can be audited and improved over time. Many components are expected to be adaptable across mammals, including non-human animals such as livestock, with species-specific parameter sets and interfaces.

Within the next ~20 years, the mature version of this technology is anticipated to combine (1) ex-vivo gestation support for specific windows of development and (2) embryo-like “synthetic” constructs grown from stem cells that reproduce selected features of early development without being identical to a conventional embryo. Systems would rely on dense sensor arrays (oxygenation, metabolites, hormones, immune markers), imaging, and closed-loop control software that adjusts flows and additives in real time. Human operators would interact through dashboards and alarms, with remote specialist oversight possible via secure APIs. Configuration would be protocol-driven, with validated parameter sets updated as evidence accumulates.

Key constraints include high energy and reliability requirements, strict contamination control, dependence on specialized consumables, and unresolved regulatory and ethical boundaries—especially around what stages of development are permissible and what constitutes an embryo or embryo-like construct. Cross-species deployment adds constraints around biosecurity, anatomical differences, and evidence standards for safety. Early-stage development is likely to remain the hardest to support robustly. Costs would plausibly resemble other high-end regulated life-support assets: high six figures per unit plus substantial per-use consumables and staffing.

From a value-creation bottleneck perspective, this technology can reduce risks and variability in fragile, time-sensitive developmental processes that demand continuous expert attention; expand access where distance or scarcity of specialized facilities causes delays; improve quality control by turning hidden biological states into measurable signals; enable faster learning cycles through controlled, parallel experimentation; and support managed breeding and conservation efforts by reducing dependence on scarce biological samples, unpredictable environments, and labor-intensive monitoring.

## Group 10 – Space & Aeronautical Engineering

### ART 10.079 Satellite Mega-Constellations & Space Internet

Multiple actors—commercial operators, national space agencies, launch providers, and research consortia—are plausibly developing satellite mega-constellations: fleets of thousands of small, low-Earth-orbit satellites designed to operate as a single, coordinated system. This form factor is pursued because small satellites can be mass-manufactured, refreshed on short cycles, and launched in batches, while low orbit reduces signal delay and enables higher revisit rates for sensing. The same networked architecture also supports in-space routing via laser crosslinks, so data can move satellite-to-satellite toward available gateways rather than relying on a single ground station.

Within the next 20 years, such constellations are anticipated to provide a blended bundle of capabilities: near-global, low-latency connectivity for standard user terminals; continuous positioning and timing augmentation in areas where terrestrial signals are weak; and detailed Earth observation using complementary sensors that can see reflected light, heat signatures, and, in some cases, surface structure even through cloud cover. “Space-based AI” shifts part of the compute into orbit: satellites run onboard models that filter and prioritize imagery, detect changes or anomalies, compress data intelligently, and coordinate tasking across the fleet. This reduces downlink needs and speeds up time-to-insight, while allowing configurable policies (e.g., what gets stored, what gets transmitted, and at what confidence threshold).

Key constraints remain material and systemic: limited onboard power and cooling restrict model size and runtime; radiation hardening and fault tolerance add cost; spectrum rights, cross-border data rules, and space traffic management shape deployment; and debris mitigation and end-of-life deorbiting become hard requirements. Economically, a full constellation is likely a multi-billion-euro asset with ongoing replenishment, while user terminals trend toward consumer-electronics to small-appliance price points.

From a value-creation bottleneck perspective, this technology can ease frictions caused by distance and uneven infrastructure by providing consistent links where terrestrial build-out is slow, fragile, or costly; reduce delays in situational awareness by turning raw sensing into prioritized, machine-readable signals before they reach the ground; improve coordination across distributed assets by offering a shared, resilient communications layer; and lower the human attention burden in monitoring by automating detection, triage, and verification under constrained bandwidth and time.



## ART 10.080 Space Resource Utilization (SRU)

Multiple actors—launch providers, deep-space robotics companies, commodity traders with engineering arms, and public–private exploration consortia—are plausibly developing Space Resource Utilization focused on returning high-value space-mined materials to Earth, because it targets a simple economic logic: if a small fraction of an asteroid’s mass contains unusually concentrated platinum-group metals, nickel-iron alloys, or rare-earth-bearing phases, then moving kilograms to tons of refined concentrate may be more viable than moving thousands of tons of rock. The preferred form factor over the next 20 years is likely a fleet of small, standardized spacecraft that can be mass-produced, ride-share to deep space, and then combine prospecting, extraction, and “mass-reduction” processing before Earth return.

Within that horizon, SRU for Earth return is anticipated to look like a pipeline: reconnaissance probes map composition using spectral sensors and radar, then rendezvous vehicles deploy anchoring tools and low-force cutters designed for microgravity. Instead of “mining” like on Earth, the system would corral rubble into sealed processing drums, use mechanical sorting plus controlled heating or chemical leaching in closed loops to separate metal-rich fractions, and compress the output into dense ingots or pellets. Those concentrates would be loaded into hardened reentry capsules with tamper-evident seals and tracked continuously via telemetry, with recovery operations designed around predictable landing corridors and rapid chain-of-custody handoff for independent assay on Earth. Human interaction would be mostly supervisory, through mission-planning software and exception handling, with autonomy covering minutes-to-hours delays.

Key constraints remain decisive: identifying targets with reliably high concentrations is uncertain; operations are limited by power, tool wear, and the difficulty of anchoring to loosely bound surfaces; and Earth-return adds strict safety and regulatory hurdles for reentry risk, contamination control, and ownership claims. Early end-to-end missions could cost in the range of a major spacecraft program or large industrial megaproject, with costs falling only if vehicles are reused and launches are routine.

From a value-creation bottleneck perspective, this technology can ease constraints where critical materials are geographically concentrated, slow to permit and expand, or tied to hazardous extraction; where supply is vulnerable to long lead times and price shocks; where the environmental and social footprint of obtaining marginal new material is rising; and where verifiable provenance, consistent purity, and predictable delivery schedules are difficult to achieve with existing sourcing and recycling alone.

## ART 10.081 Closed-Loop Life Support System

Multiple actors—space agencies, habitat developers, shipbuilders, and specialist engineering labs—are likely to advance closed-loop life support systems over the next 20 years because long-duration living away from Earth is fundamentally constrained by resupply mass and the fragility of “open” consumables. The most practical designs combine bioregenerative modules (controlled plant, algae, or microbial growth that converts carbon dioxide to oxygen and helps stabilize water and nutrients) with physico-chemical hardware (compact reactors, filters, and sorbents that scrub trace gases, purify water, and break down wastes). In a mature configuration, the system functions like an integrated “utility plant” for a habitat: it continuously senses air composition, humidity, pressure, water quality, and microbial load; routes flows through redundant loops; and automatically tunes valves, lighting, temperature, and processing cycles to keep conditions within safe bounds. Crew interact through simple dashboards and maintenance prompts, while adaptive control software learns routine patterns, flags anomalies early, and supports remote updates and diagnostics when connectivity allows.

Feasibility is bounded by energy availability, the need for high reliability under vibration and partial gravity, susceptibility to biofouling and contamination, and the reality that some materials and nutrients still require periodic top-ups. Manufacturing complexity and certification constraints mean early systems remain expensive, but costs may trend toward the range of high-end industrial equipment or building-scale utility plants rather than bespoke one-off prototypes.

From a value-creation bottleneck perspective, this technology can reduce dependence on frequent deliveries of critical consumables, shift routine monitoring and manual upkeep into automated control, and make prolonged presence possible where distance, isolation, and limited skilled labor would otherwise force conservative operating margins. It can also improve safety by detecting invisible hazards (trace toxins, microbial blooms, slow leaks) sooner, and by enabling tighter control over resource use when water, air-processing capacity, and waste-handling throughput are the limiting factors.

## ART 10.082 High-Altitude Platforms & Balloons

Multiple actors—telecommunications firms, aerospace primes, start-ups, and research consortia—are developing high-altitude platforms (HAPs) such as stratospheric balloons, airships, and solar-powered fixed-wing drones that loiter above ~60,000 feet for weeks to months. This form factor is pursued because it can deliver wide-area coverage and persistent sensing without the launch schedules, orbital

constraints, or full lifecycle costs of conventional satellites, while remaining physically recoverable, upgradable, and redeployable.

Within the next 20 years, mature HAP systems are likely to operate as “pseudo-satellites” that hold position or follow managed corridors using autonomous flight control, wind-field forecasting, and cooperative station-keeping among multiple vehicles. Payloads may combine communications relay, navigation augmentation, and multi-sensor observation (optical, infrared, and radio) with onboard computing that filters and prioritizes data before downlink. Human interaction is expected to resemble cloud-managed infrastructure: operators set service areas, performance targets, and safety boundaries through dashboards and standard APIs, while continuous remote updates refine autonomy, power management, and payload behavior. Platforms may form mesh networks, hand off tasks between vehicles, and gracefully degrade when components fail.

Key constraints remain: payload mass and power are limited by solar collection and battery storage; stratospheric winds and seasonal variability can reduce station-keeping precision; operations depend on ground gateways, spectrum access, and airspace permissions; and reliability is shaped by UV exposure, temperature cycles, and maintenance logistics. Costs are plausibly comparable to procuring and operating small aircraft or specialized industrial equipment per platform, plus ongoing service and regulatory overhead.

From a value-creation bottleneck perspective, this technology can reduce delays caused by limited connectivity or monitoring in remote or disrupted areas, decrease reliance on scarce skilled teams for rapid deployment, improve coordination when human attention cannot continuously track large regions, and lower the cost of persistent coverage where existing options are either too slow to launch, too expensive to maintain, or too inflexible to adapt as requirements change.

## Group 11 - Digital Platforms & Collective-Intelligence Systems

### ART 11.083 Decentralized Trust Networks (Web3 & Blockchain)

Decentralized Trust Networks are being developed by open-source communities, standards groups, startups, large software vendors, and research labs as a way to coordinate transactions and shared records across many parties without relying on a single operator to host the “source of truth.” The design is pursued because it can make tampering and retroactive edits difficult, enable verification with widely available cryptographic tools, and reduce dependence on bespoke point-to-point integrations that break when participants change systems or incentives.

Within the next 20 years, these networks are likely to look less like a single “blockchain” and more like a layered trust fabric: shared ledgers for ordering events, smart-contract runtimes for programmable rules, privacy-preserving techniques for selective disclosure, and interoperability protocols to move proofs and assets across networks. Users may interact through familiar interfaces—mobile apps, browser-based wallets, embedded sign-in and authorization flows, and standard APIs—while organizations run nodes or use managed node services. Identity and permissioning can be handled through decentralized identifiers and verifiable credentials, allowing a party to prove specific attributes without exposing full underlying data. Many systems will rely on external data feeds (“oracles”) and on formal verification, audits, and monitoring to reduce failures in deployed code.

Key constraints will remain: throughput and latency under peak load, the complexity of key management and recovery, the risk concentrated in cross-network “bridge” components, and regulatory requirements around governance, liability, and auditability. Energy use is likely to be manageable for most deployments, but compute-heavy verification and on-chain storage will still impose costs; operating budgets may resemble enterprise software plus cloud infrastructure, with per-operation fees ranging from fractions of a cent to several dollars depending on security and congestion.

From a value-creation bottleneck perspective, this technology can reduce time-consuming reconciliation and dispute resolution, enable coordinated workflows where participants do not fully trust each other, improve traceability and accountability of shared records, support fine-grained access control and consent across boundaries, and automate rule enforcement in ways that reduce human attention overhead while preserving an inspectable audit trail.

#### ART 11.084 Platform Cooperatives & Fair Work

Multiple actors—including cooperative federations, open-source communities, municipal innovation labs, fintech providers, and incumbent platform vendors experimenting with new ownership models—are plausibly developing worker- or user-owned digital marketplaces as an alternative to investor-controlled platforms. The rationale is partly structural: software marketplaces scale quickly but concentrate bargaining power through opaque ranking, pricing, and access rules. A cooperative form factor is being pursued because it can encode shared economic rights (revenue share, data rights, decision rights) directly into the platform’s operating logic, while remaining compatible with familiar tools like mobile apps, digital payments, and standard identity checks.

Within the next 20 years, this ART is likely to look like a modular “co-op operating system” for marketplaces: configurable software that handles member onboarding,

credentialing, scheduling, pricing guidance, dispute resolution, pooled benefits, and audited payouts. Governance features are built into the interface, letting members propose policy changes, vote on fee structures, elect administrators, and review algorithmic rules through plain-language dashboards. The platform can expose APIs so external services (payments, insurance, training, compliance tools) plug in without capturing the core relationship. Data is logged in tamper-evident audit trails so members and regulators can verify how rankings, fees, and penalties were applied, while privacy controls limit what is shared beyond the co-op.

Key constraints include slow legal harmonization across jurisdictions, the difficulty of raising capital without diluting member control, and the ongoing challenge of preventing fraud, collusion, and coercive “voting blocs.” Reliability depends on robust governance processes and secure identity infrastructure. Costs are likely comparable to enterprise software subscriptions plus member equity contributions, with additional expenses for compliance and arbitration.

From a value-creation bottleneck perspective, this technology can reduce coordination overhead in large, distributed workforces; make pay, fees, and rule changes more legible and contestable; lower the cost of trust and enforcement between strangers; and improve resilience when access to income or services is mediated by opaque gatekeepers, limited human oversight, or mismatched incentives between participants and platform owners.

#### ART 11.085 Open Data Sharing Marketplaces

Multiple actors—cloud providers, standards bodies, data brokers, startups, and cross-organization consortia—are developing open data sharing marketplaces because most useful data remains trapped in incompatible systems, governed by one-off contracts, and shared through slow, high-trust relationships. The marketplace form factor is being pursued because it can align incentives (paying contributors, charging consumers), standardize legal and technical interfaces, and make secure sharing repeatable at scale rather than a bespoke integration project each time.

Within the next two decades, these marketplaces are likely to look like interoperable “exchanges” where datasets are listed with machine-readable descriptions, quality signals, and usage terms, and where access is granted through programmable permissions rather than manual handoffs. Data can be delivered directly, or analyzed in place via “compute-to-data” options that let approved algorithms run inside a controlled environment so raw records do not leave the owner’s custody. Identity, consent, and policy enforcement would be built in: contributors set granular rules (who can use what, for which purposes, for how long), users authenticate, and every access is logged for auditing and billing. Interfaces would range from self-service dashboards

and contract templates to software APIs that let systems request data, negotiate terms, and settle payments automatically.

Feasibility hinges on governance, interoperability, and safeguards against misuse: preventing re-identification, handling disputed ownership, verifying provenance, and maintaining reliability when many parties update or withdraw data. Operating costs include secure storage, encryption overhead, and compliance processes, with pricing likely resembling enterprise software subscriptions plus per-query or revenue-share fees.

From a value-creation bottleneck perspective, this technology can reduce coordination and trust barriers between parties, speed up access to scarce or fragmented information, improve the timeliness and accuracy of monitoring and decisions, reduce redundant data collection, and make high-quality data resources usable by smaller actors that lack specialized infrastructure or negotiating power.

#### ART 11.086 Secure & Resilient Social Platforms

Multiple actors—commercial platform builders, open-source communities, academic security labs, and standards consortia—are likely to develop secure and resilient social platforms over the next two decades as online coordination becomes more exposed to outages, targeted blocking, data harvesting, and manipulation. The design approach being pursued combines familiar app-like interfaces with “security-by-default” building blocks: identity that can be verified without forcing real-world disclosure, private messaging and group spaces that keep content readable only to intended participants, and network architectures that avoid single points of failure by automatically replicating data across independent servers and, where permitted, user devices.

Within 20 years, these platforms are anticipated to operate as interoperable systems rather than walled gardens: users can move their contacts, reputation signals, and content archives between compatible services, while organizations can run their own nodes or contract hosted nodes without losing compatibility. Content distribution is designed to degrade gracefully—when a server is down or a route is blocked, clients can fetch from alternate mirrors, queue posts locally for later delivery, or route through multiple relays. Privacy protections extend beyond encryption to minimizing what the system learns by default (for example, reducing unnecessary metadata and allowing selective proof of attributes). Human-facing controls emphasize transparent settings, understandable safety prompts, and auditable moderation and policy changes, with APIs that allow integration into existing workflows.

Key constraints remain: stronger privacy and redundancy can increase bandwidth, storage, and computational overhead; key recovery and account safety require careful

usability; and regulatory and governance pressures may limit some deployment models. Costs are likely comparable to other large-scale online services, ranging from low single-digit euros per user per year at scale to enterprise-grade deployments costing tens of thousands to millions annually depending on resilience requirements.

From a value-creation bottleneck perspective, this technology can reduce dependence on fragile centralized infrastructure, lower the risk and cost of data exposure, and improve continuity of coordination when connectivity is degraded or contested. It can also ease constraints created by limited trust between parties, by enabling collaboration with verifiable integrity, configurable privacy, and clearer accountability for rule changes—without requiring participants to surrender control of their identity, data, or social ties to a single intermediary.

#### ART 11.087 Collective Open Innovation Networks

Collective Open Innovation Networks are emerging as a class of online platforms being developed by a mix of software firms, research organizations, standards groups, and large multi-party consortia that need to coordinate invention across organizational boundaries. The core design choice—an internet-native network rather than a single-company tool—reflects a practical aim: to make high-friction R&D collaboration work at scale with existing workflows, while lowering the cost of finding the right contributors, evidence, and experimental pathways for a given problem. Over the next 20 years, these platforms are likely to evolve into “full-stack” innovation environments that combine challenge definition, participant discovery, secure workspaces, testing resources, and outcome adjudication within one interoperable system.

In day-to-day use, a network would let an organizer post a problem in plain language and structured requirements, attach data and constraints, and define what counts as a valid result. Contributors—individuals, teams, or specialized automated agents—could propose approaches, run simulations in shared sandboxes, attach lab notes or proofs, and iteratively merge work through version-controlled “innovation branches” that track provenance. Interfaces would mix familiar collaboration tools (documents, code repos, video, whiteboards) with structured components for experiments, benchmarks, and validation, so non-experts can review claims without reading every underlying artifact. Reputation signals would increasingly be based on demonstrated performance in past challenges, with audit trails showing how outputs were produced and which inputs were used.

Feasibility over a 20-year horizon depends on robust identity, access control, and dispute-resolution mechanisms, plus reliable ways to protect sensitive inputs while still enabling meaningful peer review. Limitations will include dependence on high-quality data and test infrastructure, uneven participant incentives, and governance



complexity when rules differ across jurisdictions. Costs will likely resemble enterprise software plus optional pay-per-use compute and testing—ranging from small-team subscriptions to multi-million-euro annual deployments for large networks.

From a value-creation bottleneck perspective, this technology can reduce the time and coordination burden of assembling capable teams, turning scattered expertise into usable progress without requiring co-location or long hiring cycles. It can shift work away from brittle handoffs by keeping evidence, assumptions, and intermediate results in a shared, machine-readable trail that improves trust and reusability. It can also make risky or expensive exploration more economical by routing problems to many parallel attempts, filtering them through transparent validation, and preserving “failed” pathways as searchable knowledge—helping groups overcome attention limits, skill scarcity, and the cost–quality trade-offs that slow complex invention.

#### ART 11.088 Scalable Decentralized Governance

Multiple actors—open-source communities, fintech vendors, academic labs, and consortiums of organizations with shared assets—are likely to keep advancing scalable decentralized governance systems over the next 20 years. The core design choice is to encode parts of governance (membership, proposals, voting, budgeting, and rule enforcement) in software so that decisions can be made and audited without relying on a single administrator. This form factor is being pursued because it can reduce coordination overhead across distance, create tamper-evident records of who decided what and when, and make rule changes explicit and testable before they take effect.

Within roughly two decades, these systems are anticipated to look like “governance stacks”: a rule engine that expresses bylaws and decision thresholds; a secure identity and permission layer that can use a mix of verified credentials, pseudonyms, and reputation; and a transparent execution layer that can automatically trigger agreed actions such as releasing funds, updating access rights, or commissioning work. Human interaction would be handled through familiar web and mobile interfaces that guide participants from deliberation to proposals to structured votes, with APIs for integrating existing tools. To handle scale, they are likely to support delegation, sampling, and preference-aggregation methods that reduce voter fatigue, alongside privacy-preserving audits that prove participation and outcomes without exposing sensitive individual choices.

Key constraints remain: preventing fake identities and coordinated manipulation, managing software vulnerabilities, aligning automated enforcement with real-world

accountability, and meeting evolving legal and compliance requirements. Operational costs would likely be comparable to enterprise collaboration and governance software—low per participant for routine decisions, plus periodic security audits and incident-response capacity when stakes are high.

From a value-creation bottleneck perspective, this technology can reduce the time and friction required for large groups to reach binding decisions, increase the reliability of shared records and accountability, lower the overhead of managing pooled resources under contested trust, and improve the speed and quality of coordination when participation is distributed, intermittent, or expertise is scarce.

#### ART 11.089 Digital Learning Networks and Skill Credentialing

Multiple actors—platform companies, assessment providers, standards bodies, and research groups—are likely to converge on digital learning networks that combine large-scale online instruction with open, portable skill credentialing over the next 20 years. This form factor is being pursued because it fits existing internet infrastructure and devices, scales globally with relatively low marginal cost, and can be integrated into everyday workflows through web apps, messaging interfaces, and software APIs rather than requiring new physical facilities.

In mature form, these networks resemble a continuously updated “skill exchange” where people learn through short modules, guided practice, and peer communities, while also completing evidence-based assessments that can be verified outside the platform. AI tutors provide personalized explanations, generate practice problems, and run interactive simulators that approximate real tasks, adapting difficulty based on performance and offering feedback in text, voice, or visuals. AI-automated skill credentialing links assessments to a transparent rubric and produces cryptographically signed, verifiable credentials that can be stored in a personal wallet and selectively shared, reducing reliance on any single institution’s transcript. Reputation and anti-fraud systems combine identity checks, behavioral signals, and audit trails to discourage gaming, while human reviewers handle edge cases and contested outcomes.

Feasibility depends on reliable connectivity, robust identity and privacy controls, and ongoing model evaluation to manage bias, hallucinations, and security risks. Costs are likely to resemble consumer subscriptions for individuals and enterprise software licenses for organizations, with higher pricing for high-stakes assessment and verification.

From a value-creation bottleneck perspective, this technology can reduce delays caused by limited access to qualified instructors and assessors, expand the supply of structured practice and feedback beyond human attention constraints, and lower the cost of demonstrating competence when skills are gained informally or across locations. It can also improve coordination and trust in multi-party settings by making capabilities easier to verify, while preserving privacy through selective disclosure and standardized, machine-checkable credentials.

#### ART 11.090 Prediction-Market Forecasting Platforms

Multiple actors—research labs studying collective intelligence, fintech startups, enterprise-software vendors, and public-interest consortia—are likely to develop prediction-market forecasting platforms over the next 20 years because they offer a structured way to turn scattered, partially held beliefs into a single, continuously updated probability. The core design approach borrows the discipline of prices and trading (where participants are rewarded for being right) while packaging it in interfaces that feel like ordinary planning tools: users pose questions in natural language, see probability ranges and confidence cues on dashboards, and pull forecasts into other systems through standard APIs.

Within roughly two decades, these platforms are anticipated to operate as hybrid systems that combine market mechanisms with automated “question engineering,” identity and reputation layers, and audit trails. They would support forecasts about discrete events, timelines, and numeric thresholds, and could automatically break broad uncertainties into linked sub-questions so that evidence updates propagate through a forecast graph. To reduce manipulation and low participation, systems may use model-assisted market making, caps on exposure, anomaly detection, and participant reputation that improves with demonstrated calibration over time. Where outcomes are hard to verify, platforms would rely on agreed settlement rules, independent data feeds, or human adjudication panels, with clear dispute processes and logged rationales.

Key constraints remain: forecasts depend on liquidity and diversity of informed participants, and on credible outcome verification. Safety and feasibility are shaped by regulation, identity privacy, information security, and incentives that must avoid encouraging harmful behavior. Costs would likely resemble other decision-support software—ranging from per-seat subscriptions to enterprise licenses and per-market fees—plus optional spend for verification, moderation, and integration.

From a value-creation bottleneck perspective, this technology can reduce delays caused by fragmented information and slow consensus-building, convert tacit expert judgment into measurable signals that update in real time, improve coordination when

many teams must act under shared uncertainty, and lower the cost of testing assumptions by making forecast accuracy trackable, comparable, and continuously learnable across repeated decisions.

## Group 12 - Protocols, Standards & Socio-Technical Infrastructure

### ART 12.091 Universal IoT Interoperability Standards

Multiple actors—including device manufacturers, cloud providers, standards bodies, and open-source consortia—are plausibly converging on universal interoperability standards for connected devices, because today’s device ecosystems are fragmented by proprietary formats, incompatible discovery methods, and uneven security practices. Over the next 20 years, this work could mature into a globally adopted bundle of open protocols and certification profiles that let billions of devices reliably identify themselves, advertise capabilities, negotiate permissions, and exchange data across networks without bespoke integrations or vendor-specific gateways. In practical terms, a newly installed device could join a local or wide-area network, publish a machine-readable description of its sensors and controls, and interoperate through common APIs for telemetry, event messaging, time synchronization, and firmware updates; humans would manage it through familiar setup flows (QR/NFC onboarding, mobile and web dashboards), while software agents and applications would interact through standardized schemas and permission models.

The standards would likely include baseline security requirements—hardware-backed identities where available, end-to-end encryption, signed updates, auditable access logs, and revocation mechanisms—plus profiles for constrained devices with limited power and bandwidth. Key constraints remain: legacy device migration, certification overhead, regional regulatory differences around data handling, and the operational burden of key management and patching at massive scale. Costs would be comparable to today’s connectivity and device-management stack: low per-device certification fees, plus enterprise-grade management platforms priced like mainstream software subscriptions, with additional spending for security modules in higher-assurance deployments.

From a value-creation bottleneck perspective, this technology can reduce integration time and coordination overhead when many independent devices must work together, shift effort from custom adapters to reusable building blocks, improve reliability by standardizing update and failure-reporting pathways, and lower the cognitive load on operators by making device behavior legible and consistent. It can also reduce safety and compliance friction by making identity, permissions, and data provenance easier to verify, while enabling faster scaling of monitoring and control systems that are currently

limited by manual configuration, incompatible data formats, and slow troubleshooting across heterogeneous fleets.

## ART 12.092 Interoperable Digital Twin Ecosystems

Multiple actors—industrial software vendors, cloud providers, standards bodies, and large asset owners—are converging on interoperable digital twin ecosystems: shared protocols and reference models that let virtual representations of physical assets move between tools without being rebuilt each time. This form factor is being pursued because today’s digital twins are often trapped inside a single platform or contractor relationship, while real assets typically involve many parties over long lifecycles. Interoperability aims to make twins portable, auditable, and continuously synchronized, so that monitoring, planning, and optimization can persist through ownership changes, tool upgrades, and cross-organization collaboration.

Within the next 20 years, such ecosystems are likely to resemble a “network layer” for digital twins. A twin would be a structured package that includes geometry, configuration, operating history, sensor streams, maintenance events, and behavioral models, plus explicit assumptions and uncertainty bounds. Standard interfaces would support real-time syncing (event streams), batch reconciliation (snapshots), and scenario simulation (what-if runs) across different vendors’ software. Humans would interact through familiar dashboards and 3D viewers, but also through conversational and query interfaces that can explain why a twin’s state changed, what data supports a prediction, and which parameters are user-configurable. Organizations could attach policies—who can see what, at what resolution, and for what purpose—while automated checks flag inconsistent units, missing provenance, or drift between the virtual model and the physical world.

Key constraints include sensor coverage and calibration, latency and bandwidth for high-frequency assets, secure identity and access management, and governance for liability when models disagree. Costs are likely comparable to enterprise software subscriptions plus ongoing cloud compute and integration work, with higher tiers for high-fidelity simulation and compliance-grade audit trails.

From a value-creation bottleneck perspective, this technology can reduce coordination overhead when many parties must make decisions about the same asset, lower the time and expertise required to diagnose complex problems, and improve precision in planning by making assumptions explicit and comparable. It can also ease safety and downtime constraints by enabling remote inspection and rehearsal of interventions, and it can reduce waste caused by duplicate modeling, incompatible data formats, and delayed information flow between monitoring, analysis, and action.

## ART 12.093 Global Supply Chain Traceability Networks

Global supply chain traceability networks are being developed by combinations of manufacturers, logistics operators, standards bodies, and software firms as shared “data rails” that follow products and materials from origin to end use. The approach centers on common data models and governance rules rather than any single company’s platform, because the main challenge is not sensing alone but getting many independent actors to record, share, and trust compatible information across organizational boundaries. Over the next 20 years, these networks are expected to function as interoperable registries that link physical identifiers (tags, markings, embedded chips, or packaging codes) with tamper-evident digital records of custody, transformation, testing, and compliance events, updated automatically through scanners, connected equipment, and enterprise systems.

In practical terms, the technology would allow a product or batch to carry a portable “history file” that can be queried through standard APIs or simple user interfaces, revealing what it is, what it contains, where it has been, what was done to it, and which documents or measurements support those claims. Different participants would be able to contribute data under defined permissions, with cryptographic signatures, audit trails, and selective disclosure so that sensitive commercial details can be hidden while still proving required attributes. Configuration would rely on shared schemas, certification programs, and automated validation rules that flag inconsistencies, missing steps, or suspicious patterns. Key constraints will include the cost and reliability of tagging and scanning at high volume, uneven data quality, integration burden with legacy systems, connectivity gaps, and the need for credible dispute resolution. Costs are likely to resemble a mix of enterprise software subscriptions plus per-unit identification and verification costs, with higher assurance levels requiring more instrumentation and audits.

From a value-creation bottleneck perspective, this technology can reduce time lost to manual paperwork and reconciliation, lower the risk and cost of quality failures by enabling faster root-cause analysis, and improve coordination when many parties must act on the same facts. It can ease constraints created by low trust between organizations, limited visibility across distance, and the difficulty of verifying claims about origin, composition, handling, or authenticity. It can also improve decision-making by making real-time status and provenance information more accessible to humans and automated systems, while supporting tighter controls over counterfeits, diversion, waste, and environmentally or socially sensitive inputs without requiring every participant to reveal all proprietary details.

## ART 12.094 Personal Data Portability & Trust Frameworks

Multiple actors—standards bodies, privacy regulators, large online platforms, device makers, and open-source consortia—are likely to converge over the next 20 years on personal data portability and trust frameworks that treat personal information as something an individual can permission, move, and revoke with the same ease as changing devices or switching providers. This approach is being pursued because today’s data-sharing is fragmented: each service uses different formats and consent flows, while security incidents and compliance obligations raise the cost of integrating new partners. A common framework improves interoperability, reduces duplication of identity checks, and makes “safe-by-default” sharing cheaper than ad-hoc integrations.

In mature form, the technology looks like a standardized “personal data wallet” plus a set of common data schemas, permission APIs, and verification methods. Individuals can store references to their data (and, where appropriate, encrypted copies) and grant time-bound, purpose-bound access to specific fields rather than broad account-level access. Services can request data through consistent prompts, receive machine-readable consent receipts, and prove what they received and why through tamper-evident logs. Built-in revocation, automatic expiration, and selective disclosure (sharing a claim like “meets requirement” without revealing the underlying details) reduce over-collection. Human interaction is designed to be legible: clear dashboards, portable privacy settings, and “sharing profiles” that can be reused across services.

Feasibility depends on widespread adoption, usable recovery mechanisms, and robust security against phishing and account takeover; the framework also requires governance for updating standards and handling disputes. Costs would likely resemble a modest subscription for individuals (or be bundled with devices) and an enterprise-grade compliance/integration cost for organizations.

From a value-creation bottleneck perspective, this technology can reduce friction caused by repeated form-filling and redundant verification, lower the coordination cost of trusted data exchange between unfamiliar parties, improve decision quality by enabling fresher and more accurate information with explicit permission, and make it easier to limit exposure to fraud, misuse, and unnecessary retention while still allowing legitimate, user-directed sharing at scale.

## ART 12.095 Interoperable Digital Currency Payment Networks

Multiple actors—central-bank technology teams, open-source communities, standards bodies, and infrastructure providers—are likely to develop interoperable digital currency payment networks over the next 20 years to reduce today’s fragmentation



across CBDCs, cryptocurrencies, and mobile money systems. The core rationale is pragmatic: instead of forcing the world to converge on a single currency or ledger, these networks treat each currency system as a “local network” and connect them through common protocols, much like the internet connected incompatible computer networks through shared rules for addressing, messaging, and routing.

In practice, the technology would be a layered protocol stack that enables discovery (finding a recipient across systems), quoting (real-time exchange and fees), authorization (consent and identity/credential checks), and settlement (atomic delivery-versus-payment so one side cannot complete without the other). Wallets and enterprise systems would connect via standard APIs and software toolkits, while routing nodes and liquidity providers manage path selection across multiple rails. Privacy features would likely include selective disclosure—proving required facts (e.g., eligibility or limits) without exposing full transaction histories—alongside audit hooks for jurisdictions that require traceability. The network would support multiple transaction types, from simple transfers to conditional payments with time locks or rule-based releases, while remaining compatible with offline or low-connectivity modes through signed vouchers that later reconcile.

Key constraints include governance (who updates standards and resolves disputes), cybersecurity, latency under peak demand, uneven regulatory alignment, and dependence on reliable identity and compliance data. Integration costs would resemble enterprise middleware deployments, with ongoing operating costs comparable to running other mission-critical network services.

From a value-creation bottleneck perspective, this technology can reduce coordination delays and manual reconciliation between disconnected payment systems, lower the cost and risk of moving value across distance and administrative boundaries, improve reliability in low-connectivity environments, and enable finer-grained automation where today’s processes require human review, repeated data entry, or trust in a single intermediary.

#### ART 12.096 Machine-Readable Regulation (Rules as Code)

Multiple actors—including public administrations, standards bodies, legal publishers, civic-tech groups, and enterprise software vendors—are already experimenting with making parts of regulation machine-consumable, and over the next 20 years this could mature into “rules as code” as a routine publishing format alongside traditional legal text. The rationale is pragmatic: legal requirements increasingly need to be interpreted by software systems at scale, and structured, testable representations can reduce ambiguity, speed updates, and make compliance logic interoperable across tools rather than re-implemented in countless ad hoc ways.

In this anticipated form, governments (and other rule-issuing authorities) publish regulations as a versioned package: human-readable text plus a formal model of definitions, thresholds, exceptions, procedures, and required data fields. The package is distributed through secure APIs and developer toolkits, with reference implementations and validation tests that let software simulate “what the rule means” for a given set of inputs. Interfaces are designed for both specialists and non-specialists: dashboards that show how decisions were reached, change logs that explain what moved between versions, and configurable “policy profiles” for local variations. Systems can run rules in sandbox mode to forecast the impact of a change, or in production mode to check forms, contracts, transactions, and records against current requirements, while producing auditable traces of which clauses and parameters were applied.

Key constraints remain: not all legal language can be deterministically encoded; edge cases, intent, and discretionary judgment still require human review. Maintaining semantic consistency across jurisdictions and frequent updates demands strong governance, cryptographic signing, rigorous testing, and clear liability boundaries. Costs would likely resemble major enterprise software programs—high upfront modeling and integration effort, followed by ongoing licensing, hosting, and maintenance comparable to other compliance-grade platforms.

From a value-creation bottleneck perspective, this technology can reduce time lost to manual interpretation, lower coordination friction between organizations that must align on the same rules, improve accuracy and traceability in high-volume decision processes, shorten the feedback loop for updating systems when rules change, and expand access for smaller actors who currently cannot afford specialized expertise to understand and operationalize complex requirements.

#### ART 12.097 Open Metaverse Interoperability Protocols

Multiple actors—standards bodies, game-engine vendors, device manufacturers, cloud providers, and open-source consortia—are plausibly developing open metaverse interoperability protocols to reduce today’s fragmentation across 3D virtual environments. This approach is being pursued because it aligns with how the internet scaled: shared rules for identity, addressing, content formats, and secure exchange allow many competing services to interconnect without a single operator controlling the whole system. Open, implementation-agnostic standards also lower switching costs, let tools and marketplaces compete on features rather than lock-in, and improve long-run reliability by enabling independent auditing and broad developer adoption.

Within the next 20 years, these protocols are anticipated to function as a common “connective tissue” for immersive spaces, defining how users authenticate and carry

persistent identities (including privacy-preserving credentials), how digital items and environments are described and rendered across engines, and how permissions, royalties, and usage rights travel with assets. A user could move between virtual worlds while maintaining social graphs, inventories, accessibility settings, and reputation signals, with consistent controls for what data is shared. For creators and platform operators, the protocols would expose standard software interfaces for real-time interaction, physics/animation semantics, moderation signals, and transaction settlement, while supporting automated conversion pipelines that adapt assets to different performance budgets and device capabilities.

Key constraints remain: interoperability adds overhead in latency, computation, and security review; high-fidelity assets will still be bounded by bandwidth, local compute, and energy use on wearables; and governance of identity, safety, and dispute resolution will require regulatory compliance across jurisdictions. Costs are likely comparable to enterprise software stacks and content pipelines, with meaningful ongoing expenses for validation, hosting, and certification.

From a value-creation bottleneck perspective, this technology can reduce coordination friction between otherwise incompatible systems, lower the cognitive and administrative burden of managing multiple identities and asset libraries, improve trust by making provenance and permissions portable, and enable higher utilization of digital goods by turning one-off creations into reusable components. It can also ease constraints where access, distance, or scarce expertise limits participation, while making monitoring, auditing, and human–AI interaction in immersive environments more consistent and measurable across contexts.

#### ART 12.098 Content Authenticity Infrastructure

Multiple actors—including camera and editing-tool vendors, major online platforms, standards bodies, and cryptography research groups—are developing a shared “content authenticity infrastructure” that makes the origin and edit history of digital media easier to verify. This approach is being pursued because it can fit into existing creation workflows (capture, edit, export, publish) while adding a lightweight, machine-checkable layer of trust that survives copying and reformatting better than today’s ad-hoc watermarks or platform-specific labels.

Within roughly the next 20 years, this infrastructure is anticipated to operate as a set of interoperable standards, developer libraries, and verification services that attach tamper-evident “content credentials” to images, audio, video, and synthetic media at the moment of capture or generation. Credentials can record who created the media (or which tool created it), when and where it was produced (when available and consented), what edits were applied, and whether AI tools were used, using

cryptographic signatures and linked records that can be checked without contacting the original platform. Verification may be built into operating systems, browsers, messaging apps, and professional tools so that people can view a simple “provenance summary,” while software systems can query an API to assess confidence, detect missing steps, or flag suspicious breaks in the chain of custody. The system is likely to support selective disclosure so creators can prove integrity without exposing all identifying details, and it may include durable identifiers for capture devices and certified software builds.

Key constraints include uneven adoption, key management and revocation, incentives for honest labeling, and the fact that provenance cannot prove truthfulness—only traceable handling and tool lineage. Robustness depends on secure hardware roots, widespread verifier availability, and governance that resists capture. Costs are expected to be comparable to common enterprise security tooling and creator software subscriptions, with additional expenses for certification and auditing in higher-assurance contexts.

From a value-creation bottleneck perspective, this technology can reduce coordination costs around trust by letting people and systems quickly distinguish attributable, traceable media from unprovenanced copies; lower the cognitive load of manual verification when attention is scarce; make high-volume screening and triage more precise by automating integrity checks; and reduce the operational risk of sharing or acting on manipulated content by enabling finer-grained access policies (e.g., “accept only credentialed sources” in sensitive workflows). It can also ease disputes over authorship and permitted modifications by providing a common, auditable record of transformations, while supporting privacy-preserving proof for creators who need credibility without full exposure.

#### ART 12.099 Privacy-Preserving Collaboration Protocols

Multiple actors—including cloud providers, cryptography labs, and industry consortia—are plausibly developing privacy-preserving collaboration protocols that let separate organizations compute shared results over combined data without revealing their underlying records. This design approach is pursued because it fits existing digital workflows (data warehouses, APIs, batch analytics), reduces the need to centralize sensitive datasets, and offers a path to collaboration when legal, competitive, or trust constraints make traditional data sharing impractical.

Within roughly the next 20 years, these protocols are anticipated to mature into “MPC networks” that behave like a neutral compute layer between participants. Each participant keeps its data behind its own boundary, while cryptographic methods split computations into fragments that are exchanged and recombined so that only

approved outputs become visible. Users interact through familiar interfaces—SQL-like queries, dashboards, and programmable endpoints—while policy modules specify who can request which analysis, at what frequency, and with what privacy guarantees (for example, limiting outputs that could be reverse-engineered to infer individuals or proprietary details). The system can support iterative analytics and some forms of collaborative model training, with configurable accuracy–privacy trade-offs, auditable logs, and automated “safe output” checks.

Feasibility constraints remain material: MPC can be slower and more bandwidth-intensive than conventional computation, performance depends on network latency and reliable key management, and some analyses may require careful redesign to fit secure computation primitives. Deployment is likely to depend on standardized identities, governance rules, and compliance evidence acceptable to regulators and counterparties. Costs would typically resemble enterprise software plus specialized compute and integration—ranging from mid-six figures annually for small networks to multi-million deployments for large, high-assurance collaborations.

From a value-creation bottleneck perspective, this technology can reduce coordination friction when parties need joint insight but cannot safely pool data, shift work away from manual redaction and contractual overhead toward machine-enforced controls, and enable higher-frequency decision-making where today collaboration is delayed by audits and approvals. It can also improve precision in settings limited by fragmented information, support safer experimentation on sensitive populations or assets without exposing raw traces, and expand access to advanced analysis for groups that lack a single trusted central operator.

#### ART 12.100 Manufacturing-specific Standards, Conformance Testing & Certification Infrastructure

Multiple actors—equipment makers, metrology firms, standards bodies, regulators, insurers, and large buyers—are likely to develop manufacturing-specific standards, conformance testing, and certification infrastructure to make advanced production methods comparable, auditable, and contractable across organizations. The rationale is practical: as manufacturing machines become more software-defined and processes more data-driven, performance claims, safety assurances, and quality guarantees increasingly depend on repeatable measurement rather than vendor reputation or local expertise. A shared framework is pursued because it can reduce integration risk, shorten qualification cycles, and allow new machines and processes to plug into existing procurement, training, and compliance routines without bespoke audits for every site.

Within the next 20 years, this technology is anticipated to function as a layered system combining standardized test artifacts, digital test procedures, accredited labs and on-site verification tools, and machine-readable certificates linked to production data. It would define common performance metrics (for accuracy, repeatability, throughput, energy use, emissions, and failure modes), reference test pieces or benchmark jobs, and interoperable “conformance suites” that can be run on machines or production lines. Results could be packaged into tamper-evident certificates that travel with a machine configuration, a process recipe, or a batch record, with APIs for enterprise systems to check certification status automatically. Human interaction would resemble a mix of inspection workflows and software dashboards: operators run prescribed tests, instruments capture traceable measurements, and auditors review standardized evidence rather than ad hoc reports.

Feasibility depends on robust measurement instrumentation, secure data handling, and governance that keeps standards current without locking out innovation. Limitations may include high up-front setup costs, slow consensus processes, and uneven global recognition. Costs could range from an enterprise software subscription plus recurring audit fees to capital-like expenditures comparable to specialized industrial test equipment for high-assurance applications.

From a value-creation bottleneck perspective, this technology can reduce uncertainty when adopting unfamiliar processes, lower the cost and time of qualifying new equipment, and make quality claims easier to verify across distant sites. It can ease coordination failures where multiple parties must trust each other’s measurements, reduce rework driven by inconsistent testing, and enable faster scaling by turning tacit know-how into repeatable, auditable procedures. It can also improve safety and reliability by standardizing how failure risks are detected and documented, while creating clearer pathways for accountability when performance deviates from certified expectations.

# Attachment 5. GVN descriptions used in ART impact assessment

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## 1 Passenger Transport

**Goal:**



- **Transport People from One Place to Another:**
  - Provide means for individuals to move between locations.

### **Qualitative Values:**

- **Safety:**
  - Prioritize the well-being of passengers and bystanders.
  - Minimize accidents and enhance protection.
- **Efficiency:**
  - Optimize the use of resources to facilitate timely movement.
  - Reduce travel times and improve punctuality.
- **Comfort:**
  - Ensure smooth and pleasant travel experiences.
  - Provide physical ease and amenities during journeys.
- **Freedom:**
  - Offer flexibility in choosing travel times and destinations.
  - Enable passengers to engage in activities of their choice while traveling.
- **Cost-Effectiveness:**
  - Maintain affordability for passengers.
  - Optimize costs for providers and society.
- **Environmental Responsibility:**
  - Reduce environmental impact through sustainable practices and technologies.
- **Accessibility:**
  - Ensure transportation services are available to all individuals, including those without a driver's license or with mobility challenges.

### **Means and Values of the Dominant Regime:**

#### **Current Means:**

- **Private Cars:**
  - Primary mode of transport for many individuals.
  - High ownership rates with significant underutilization.
  - Offer personal control over travel.
- **Public Transport:**
  - Includes buses, trains, and other mass transit systems.
  - More prevalent and efficient in urban areas.
  - Less accessible in sparsely populated regions.
- **Infrastructure:**

- Road networks and urban planning designed to accommodate private vehicles.
- Extensive provision of streets and parking areas.

#### **Values:**

- **Personal Independence:**
  - Car ownership symbolizes autonomy and freedom.
  - Vehicles as status symbols reflecting personal success.
- **Convenience:**
  - Preference for private cars due to perceived ease and comfort.
  - Flexibility to travel at preferred times without relying on schedules.
- **Economic Justification:**
  - High fixed costs of car ownership encourage frequent use.
  - Desire to maximize the value derived from owning a vehicle.
- **Urban Design Favoring Cars:**
  - City layouts prioritize roads and parking for private vehicles.
  - Services and amenities are often designed with car access in mind.

#### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Autonomous Vehicles and Robotization:**
  - Development of self-driving cars that do not require human drivers.
  - Potential to revolutionize personal and public transportation.
- **Mobility as a Service (MaaS):**
  - Shift towards on-demand, shared mobility solutions.
  - Reduction in the need for private car ownership.
- **Shared Mobility Platforms:**
  - Easy access to various modes of transport when needed.
  - Enhanced flexibility and convenience through technology.
- **Electric and Sustainable Technologies:**
  - Adoption of electric vehicles powered by renewable energy.
  - Commitment to reducing emissions and environmental impact.
- **Advanced Infrastructure:**
  - Implementation of precise digital mapping and supportive services.
  - Development of technologies to support autonomous transport.

#### **Values Promoting Change:**

- **Efficiency:**
  - Optimizing transportation systems for better utilization.
  - Reducing congestion and improving flow.
- **Cost Savings:**
  - Lowering transportation expenses for individuals and society.
  - Economies of scale through shared services.
- **Environmental Consciousness:**
  - Emphasis on sustainability and reducing ecological footprints.
  - Desire to mitigate climate change effects.
- **Innovation and Progress:**
  - Embracing new technologies to enhance quality of life.
  - Being at the forefront of transportation advancements.
- **Accessibility:**
  - Providing mobility options for all, including those unable to drive.
  - Enhancing inclusivity in transportation services.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Increased Efficiency:**
  - Higher utilization rates of vehicles.
  - Reduced need for parking spaces, freeing up urban areas.
- **Enhanced Safety:**
  - Potential reduction in accidents through autonomous driving.
  - Minimizing human error in transportation.
- **Cost Reduction:**
  - Decreased expenses due to shared services and reduced ownership.
  - Savings for both individuals and society.
- **Environmental Benefits:**
  - Lower emissions from electric and shared vehicles.
  - Contribution to sustainability goals.
- **Improved Accessibility:**
  - Mobility services available to a broader population.
  - Assistance for those without a driver's license or with mobility challenges.

### **Risks:**

- **Legal and Liability Issues:**
  - Uncertainty about responsibility in autonomous vehicle accidents.

- Need for new legal frameworks and insurance models.
- **Security Concerns:**
  - Vulnerabilities to hacking and software failures.
  - Risk of misuse for malicious purposes.
- **Privacy Challenges:**
  - Handling of personal data collected by transportation systems.
  - Ensuring data protection and user consent.
- **Technological Dependence:**
  - Overreliance on technology may lead to issues if systems fail.
  - Need for robust backup solutions.

#### **Inhibitors:**

- **Cultural Resistance:**
  - Attachment to car ownership as a symbol of freedom and status.
  - Reluctance to adopt shared mobility models.
- **Economic Barriers:**
  - High initial costs for new technologies and infrastructure.
  - Financial losses from depreciating value of existing vehicles.
- **Infrastructure Requirements:**
  - Significant investment needed for supportive services.
  - Development of charging stations, maintenance, and cleaning facilities.
- **Regulatory Hurdles:**
  - Existing laws may not accommodate new transportation models.
  - Slow adaptation of policies to emerging technologies.
- **Technical Expertise Gap:**
  - Insufficient knowledge among authorities and providers.
  - Challenges in managing the transition effectively.

## **2. Logistics**

### **Logistics**

#### **Goal:**

- **Transfer Goods and Materials from One Place to Another:**
  - Facilitate the movement of goods, equipment, animals, raw materials, and waste between locations.

## **Qualitative Values:**

- **Ease:**
  - Efficiency, suitability, and simplicity of transport methods.
- **Accuracy:**
  - Reliability and smoothness of transport; security of supply.
- **Cost-Effectiveness:**
  - Minimizing financial sacrifices associated with transfers, including modes of transport and routes.
- **Standardization and Prevalence:**
  - Widespread use of transport methods reduces investment risks and offers cost benefits through standardization.
- **Flexibility:**
  - Ability to handle heterogeneous, transient, and volatile flows of goods.
- **Accessibility:**
  - Ease in purchasing and comparing transport options, enabled by globalization and e-commerce.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Industry and Trade-Centric Logistics:**
  - Logistics solutions primarily serve the needs of large-scale industry and trade.
- **Shared Infrastructure with Passenger Transport:**
  - Freight transport often uses the same infrastructure as passenger vehicles.
- **Containerization and Bulk Transport:**
  - Use of containers for ocean shipping; bulk transport of raw materials.
- **Homogeneous Packaging and Large Shipments:**
  - Goods are packed uniformly, favoring large retailers and major trade companies.
- **Consumer Self-Transport:**
  - Home delivery frequently carried out by consumers using personal vehicles.
- **Influence on Urban Planning:**
  - Need for parking spaces influences shop locations and land use planning.

## **Values:**

- **Adherence to Established Norms:**
  - Maintaining traditional practices and regulatory frameworks.
- **Preservation of Existing Structures and Jobs:**
  - Desire to sustain traditional sectoral structures and employment.
- **Spending Habits:**
  - Consumer preference for in-person shopping and established purchasing behaviors.

### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Smart Robotization:**
  - Autonomous transport of goods using robots and self-driving vehicles.
- **Unique Identification and Packaging:**
  - Development of unique labeling and packaging to facilitate automation.
- **Autonomous Vehicles and Drones:**
  - Use of autonomous trucks, delivery vans, ships, and drones for freight transport.
- **Digital Platforms and MaaS in Logistics:**
  - Creation of open digital platforms linked to freight transport, enabling Mobility as a Service (MaaS) for goods.
- **Crowdsourced Participation:**
  - Involving individuals and decentralized resources in the logistics process.
- **Cloud Services and Smart Infrastructure:**
  - Cloud-based services for unique identification, location data, and control of goods and vehicles.
- **Shared Smart Lockers:**
  - Secure, shared storage solutions allowing access to authorized transporters.

#### **Values Promoting Change:**

- **Individuality and Home-Centric Lifestyle:**
  - Catering to personalized needs and preferences, supporting home delivery.
- **Cost-Effectiveness:**
  - Reducing costs through automation and efficient resource utilization.
- **Ease and Convenience:**

- Simplifying purchasing and comparison of options via globalization and e-commerce.
- **Flexibility and Responsiveness:**
  - Adapting to diverse, transient, and volatile flows of goods.
- **Environmental Sustainability:**
  - Potential reduction in emissions through optimized logistics and autonomous electric vehicles.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Improved Efficiency:**
  - Smoother delivery reduces the need for personal errands and storage.
- **Enhanced Distribution Logistics:**
  - Reduces congestion and improves urban structures and availability of goods.
- **Better Access in Remote Areas:**
  - Improved availability and delivery capacity in sparsely populated regions.
- **Increased Competition:**
  - Manufacturers gain direct access to consumers without dependence on wholesalers.
- **Reduced Waste and Losses:**
  - Minimizes expiry and prediction errors through timely deliveries.

### **Risks:**

- **Employment Effects:**
  - Automation may lead to job losses in traditional logistics roles.
- **Slow Job Creation:**
  - New jobs may not be created quickly enough or may require scarce skills.
- **Systemic Vulnerabilities:**
  - Centralized systems may be prone to mechanical failures or cyberattacks.
- **Security Concerns:**
  - Risk of anonymous delivery of prohibited or dangerous substances.
- **Regulatory Challenges:**
  - Need for updated regulations to address new logistics models and ensure safety.

### **Inhibitors:**



- **Resistance from Organizations:**
  - Opposition from employer and employee groups to changes that affect jobs.
- **Consumer Habits:**
  - Preference for in-person shopping and familiar brands and channels.
- **Existing Infrastructure and Planning:**
  - Land use planners favoring established practices; reluctance to overhaul distribution methods.
- **Low Variable Costs of Personal Vehicles:**
  - Personal cars remain cost-effective, reducing consumer incentive to change habits.
- **Vertical Industry Structure:**
  - Strong vertical integration hinders structural change; lack of horizontal collaboration.
- **Lack of Regulatory Support:**
  - Insufficient attention from regulators to digitalization in logistics.

### 3. Manufacturing of goods

#### Manufacturing of Goods

##### Goal:

- **Provide Physical Goods and Equipment:**
  - Manufacture and make available physical goods and equipment from available raw materials.

##### Qualitative Values:

- **Functionality:**
  - Appropriateness and usability for intended purposes.
  - Includes aesthetic appeal if the item is meant to please the eye.
  - Ease of use and practicality in maintenance situations.
- **Perceived Quality:**
  - Expectations regarding surface materials and physical durability.
  - Long service life through compliance with standards or modular design.
  - Ease of maintenance and repair.
- **Ease of Purchasing:**

- Minimal effort required to seek out, compare, and obtain products.
- Reduced waiting periods and simplified recycling processes.
- **Cost-Effectiveness:**
  - Reasonable purchase costs and expected operating expenses.
  - Value for money for consumers.
- **Customization:**
  - Ability to meet individual needs and preferences.
  - Personalization of products to suit specific requirements.
- **Variety:**
  - Availability of a wide range of products.
  - Diverse options catering to different tastes and needs.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Mass Production in Large Industrial Facilities:**
  - Use of automated equipment performing repetitive tasks.
  - Centralization of production for economies of scale.
- **Global Centralization and Economies of Scale:**
  - Production relocated to countries with low labor costs.
  - Decrease in logistics costs supports centralization.
- **Hierarchical Distribution Logistics:**
  - Subcontractors supply components to manufacturers.
  - Products are mass-produced and distributed through multiple steps to retail stores.
- **Separation of Design and Manufacturing:**
  - Design is often subordinate to manufacturing constraints.
  - Subcontractors have limited influence over product design.
- **Influence of Large Brands and Mass Marketing:**
  - Consumption habits shaped by branding and advertising.
  - Emphasis on controlling market preferences through imagery.

### **Values:**

- **Normative Safety and Compliance:**
  - Adherence to established standards and regulations.
  - Prioritizing safety through conformity.
- **Established Trade and Logistics Structures:**
  - Reliance on existing distribution channels and supply chains.
  - Preference for traditional methods over innovative approaches.

- **Risk Aversion:**
  - Unwillingness to take risks in developing new methods.
  - Preference for stability in domestic and export markets.

### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Advancement of Robotization and Digital Manufacturing:**
  - Decentralization of production structures.
  - Increased local manufacturing near customers to meet individual needs.
- **Flexible Production Lines and Contract Manufacturing:**
  - Movement toward customizable production processes.
  - Production and service merging closer together.
- **3D Printing and Additive Manufacturing:**
  - Use of digitally controlled, flexible machines that adjust operations as needed.
  - Manufacturing of diverse products, from industrial parts to consumer goods.
- **Evolving Automation and Multi-Skilled Robotics:**
  - Robots capable of performing a variety of tasks, resembling human versatility.
  - Reduction or elimination of traditional production lines.
- **Artificial Intelligence and Customized Design:**
  - AI-assisted design processes speeding up customization.
  - Automated measurement of user needs and operational environments.
- **Integration of Design and Manufacturing:**
  - Digital manufacturing combining design and production tasks.
  - Increased responsibility for subcontractors through model-based definitions.
- **Digital Manufacturing Chains:**
  - Linking digital and physical worlds to reduce order-to-delivery times.
  - Eliminating or combining various production phases for efficiency.

#### **Values Promoting Change:**

- **Customization and Personalization:**
  - Meeting individual customer needs and preferences.
  - Emphasis on small production volumes and special requirements.
- **Flexibility and Competitive Adaptability:**
  - Ability to respond quickly to market changes and customer demands.

- Competitive advantage through agility.
- **Variety and Innovation:**
  - Offering a wide range of products.
  - Embracing new technologies and production methods.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Reduced Need for Storage and Logistics:**
  - Local production decreases reliance on extensive supply chains and warehousing.
  - Simplifies logistics for products made of simple raw materials and components.
- **Resource Efficiency:**
  - Decreased need for raw materials and packaging.
  - Less waste due to on-demand production.
- **Added Value to Customers:**
  - Customization and suitability enhance customer satisfaction.
  - Products better meet individual needs.
- **Facilitated Maintenance and Repair:**
  - Ability to manufacture replacement parts quickly and locally.
  - Extends product lifespan and reduces downtime.
- **Increased Local Employment:**
  - Boosts employment opportunities within communities.
  - Supports local economies.
- **Reduced Vulnerability to Global Disruptions:**
  - Decentralized production less susceptible to international crises.
  - Enhances resilience against supply chain interruptions.

### **Risks:**

- **Product Safety and Liability Issues:**
  - Unclear responsibility in decentralized manufacturing settings.
  - Potential inconsistencies in product safety and quality.
- **Intellectual Property Challenges:**
  - Difficulties in protecting rights when products are locally produced without authorization.
  - Potential for widespread infringement.
- **Quality Control:**
  - Ensuring consistent quality across decentralized production sites.

- Challenges in maintaining standards.

#### **Inhibitors:**

- **Consumer Habits and Resistance to Change:**
  - Preference for mass-produced goods and familiar brands.
  - Slow adoption of customized products.
- **Reluctance of Trade and Service Sectors:**
  - Unwillingness to integrate new opportunities into existing supply chains.
  - Resistance from established businesses.
- **Incomplete Technologies:**
  - Technologies may not be fully developed for widespread adoption.
  - Limitations in current capabilities.
- **Lack of Skills and New Business Models:**
  - Need for expertise in new production methods and innovative strategies.
  - Shortage of professionals trained in advanced manufacturing.
- **Risk Aversion:**
  - Hesitation to invest in new methods due to perceived uncertainties.
  - Preference for proven approaches over experimentation.

#### 4. Sustenance

##### **Sustenance**

##### **Goal:**

- **Provide Sustenance to Humans and Pets:**
  - Ensure the intake of energy, necessary nutrients, and trace elements.

##### **Qualitative Values:**

- **Perceived Quality:**
  - Taste preferences and sensory perceptions.
  - Enjoyment derived from food in social contexts.
- **Cost:**
  - Price of food items.
  - Effort required to acquire or prepare food.
- **Healthiness:**
  - Nutrient content and energy value.

- Absence of spoilage, allergens, or harmful substances.
- **Security of Supply and Sustainability:**
  - Reliable availability of food.
  - Sustainable production methods ensuring long-term supply.
- **Individual Needs and Preferences:**
  - Catering to personal dietary requirements and desires.
  - Accommodating increasing allergies and diverse ethnic backgrounds.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Agriculture:**
  - Cultivation of fields (crop farming) producing large quantities of raw food materials cyclically.
  - Animal husbandry and greenhouse farming with economies of scale.
- **Industrial Processing and Storage:**
  - Mass production of processed foods requiring industrial-scale storage.
  - Reliance on seasonal cycles and large-scale operations.
- **Distribution Channels:**
  - Grocery stores and institutional kitchens as primary points of food distribution.
  - Closed logistics chains controlled by a few major operators.
- **Regulation and Control:**
  - Emphasis on cleanliness, additive regulation, and labeling control.
  - Food production operating under subsidies allocated for tools and methods, not output.

### **Values:**

- **Compliance with Established Practices:**
  - Adherence to prevailing agricultural and food production models.
- **Economies of Scale:**
  - Maximizing efficiency through large-scale farming and processing.
- **Food Safety and Control:**
  - Ensuring safety through stringent regulations and oversight.
- **Preservation of Existing Structures:**
  - Maintaining current logistics chains and benefiting major operators.

## **Challenger Regime:**

## **New Opportunities Enabled by:**

- **Indoor Farming and Urban Agriculture:**
  - Aquaculture under artificial lighting in controlled environments.
  - Farming plants on shelves using nutrient solutions and LED lights.
  - Year-round production with minimal space and resource usage.
- **Biotechnological Food Production:**
  - Genetically modified organisms (GMOs) for safe, nutritious, and tasty food.
  - Culturing animal cells to produce artificial meat locally.
  - Development of plant and insect-based proteins mimicking meat.
- **Insect Husbandry:**
  - Raising insects as a sustainable and efficient protein source.
- **Robotized Food Preparation:**
  - Robot cooks capable of preparing individual meals.
  - Potential deployment in restaurants, institutional kitchens, shops, and residential buildings.
- **Advancements in Food Preservation:**
  - Vacuum-packaged food irradiated underwater for extended freshness.
  - Possibility of revolutionizing food e-commerce with long-lasting, shelf-stable products.

## **Values Promoting Change:**

- **Individualization:**
  - Catering to personal tastes, dietary needs, and preferences.
- **Sustainable Development:**
  - Reducing environmental impact through efficient resource usage.
- **Ethical Considerations:**
  - Addressing concerns over animal welfare and environmental sustainability.
- **Technological Innovation:**
  - Embracing new technologies in food production and preparation.
- **Health Consciousness:**
  - Increased awareness of personal health and nutrition.
  - Growing popularity of functional foods enhanced by measurement equipment and artificial intelligence.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**



- **Improved Public Health:**
  - Personalized nutrition leading to healthier diets.
  - Reduction in consumption of processed and preserved foods.
- **Environmental Sustainability:**
  - Lower environmental impact compared to traditional farming.
  - Significant reductions in water usage and elimination of fertilizer runoff.
- **Enhanced Quality of Life:**
  - Access to fresh, locally produced food that meets individual preferences.
- **Crisis Resilience:**
  - Localized production reduces reliance on long supply chains.
  - Increased food security in the face of global disruptions.
- **Economic Opportunities:**
  - Creation of new jobs in urban farming, biotechnology, and robotics.
  - Potential improvements in terms of trade due to innovative food products.

#### **Risks:**

- **Regulatory Challenges:**
  - Existing regulations designed for large operators may hinder small local producers.
  - Need for updated frameworks to accommodate new production methods.
- **Technological Uncertainty:**
  - Indoor farming and robot cooks are still in developmental stages.
  - Unpredictability in technological advancements and adoption rates.
- **Consumer Acceptance:**
  - Skepticism towards genetically modified foods and lab-grown proteins.
  - Uncertainty about the acceptance of robot-prepared meals.
- **Food Safety and Liability:**
  - Establishing safety standards and liability in decentralized food production.

#### **Inhibitors:**

- **Established Consumer Habits:**
  - Preference for traditional shopping experiences and familiar foods.
  - Resistance to changing long-standing purchasing behaviors.
- **Lack of Alternative Distribution Channels:**
  - Dependence on existing grocery stores and supply chains.
  - Challenges in creating new channels for personalized food delivery.

- **Integration of the Food Supply Chain:**
  - Strong control by a few operators makes structural change difficult.
  - Streamlined processes favor existing models over new entrants.
- **Regulatory and Control Systems:**
  - Current oversight mechanisms may not be suitable for decentralized production.
  - Potential overregulation hindering innovation at the local level.
- **Resistance from Major Operators:**
  - Large companies benefiting from the status quo may oppose changes.
  - Potential lobbying against new technologies and methods.

## 5. Energy supply

### Energy Supply

#### Goal:

- **Provide Need-Based Supply of Energy:**
  - Produce, refine, store, and distribute primary energy in suitable forms for various purposes, including buildings, transportation, machinery, and industrial processes.

#### Qualitative Values:

- **Cost-Effectiveness:**
  - Minimize procurement, distribution, and storage costs of energy.
- **Security of Supply:**
  - Ensure reliable and continuous availability of energy to meet demand.
- **Social Acceptability:**
  - Consider environmental impacts and societal preferences in energy production and consumption.
- **Sustainability:**
  - Utilize renewable and clean energy sources to reduce negative externalities.
- **Independence:**
  - Promote autonomy from centralized electricity grids where feasible.
- **Innovation and Experimentation:**

- Encourage the adoption of new technologies and practices in energy production and storage.
- **Flexibility and Elasticity of Consumption:**
  - Adapt energy usage patterns to optimize efficiency and reduce costs.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Centralized Energy Production:**
  - Reliance on fossil fuels and nuclear power for large-scale energy generation.
  - Centralized refining of primary energy in industrial processes.
- **Distribution Networks:**
  - Energy distributed through extensive electricity grids, heat networks, and fuel distribution systems.
- **Regulated Electricity Markets:**
  - Strong government regulation with cost-based pricing for transmission network operators.
  - Transmission costs standardized regardless of individual line costs.
- **Limited Incentives for Energy Storage:**
  - Low emphasis on energy storage solutions.
  - Transmission network operators often prevented from storing energy.

### **Values:**

- **Securing Inexpensive Energy:**
  - Focus on providing low-cost energy for centralized production structures and industries.
- **Uniform Regional Costs:**
  - Guaranteeing consistent energy prices across different regions.
- **Regulatory Control:**
  - Maintaining strict regulation to ensure stability and prevent rapid changes.
- **Resistance to Change:**
  - Existing structures and policies that effectively prevent the adoption of new technologies.

## **Challenger Regime:**

## **New Opportunities Enabled by:**

- **Renewable Energy Sources:**
  - Increasing use of solar and wind power for local energy production.
  - Decreasing costs making renewables competitive with traditional energy sources.
- **Advanced Energy Storage Technologies:**
  - Rapid advancements in battery technology increasing energy density and reducing costs.
  - Development of specialized batteries for various applications.
- **Conversion of Renewable Energy to Fuels:**
  - Technologies converting solar and wind energy into gaseous and liquid synthetic fuels.
  - Potential to store energy in forms that reduce reliance on electricity grids.
- **Integration of Energy Generation into Infrastructure:**
  - Thin-film solar technology allowing power generation to be integrated into building materials.
- **Fuel Cells and Local Energy Production:**
  - Decreasing prices and increased efficiency of fuel cells for heat and electricity generation at the household level.
- **Innovative Energy Production Methods:**
  - Use of metal-organic frameworks (MOFs) to convert solar energy directly into fuels.

## **Values Promoting Change:**

- **Sustainability:**
  - Commitment to reducing environmental impact and combating climate change.
- **Energy Independence:**
  - Desire for autonomy from centralized grids and external energy suppliers.
- **Cost Consciousness:**
  - Interest in reducing energy costs through efficiency and new technologies.
- **Security of Supply:**
  - Enhancing reliability and reducing vulnerabilities in energy provision.
- **Ethical and Environmental Awareness:**
  - Growing emphasis on ethical considerations and environmental stewardship.
- **Innovation Culture:**

- Spirit of experimentation and openness to adopting cutting-edge solutions.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Reduced Energy Costs:**
  - Lower production and operational costs, especially in regions with abundant sunlight.
- **Decreased Reliance on Central Infrastructure:**
  - Less need for extensive electricity grids and centralized systems.
- **Enhanced Security of Supply:**
  - Localized energy production increases resilience and reduces susceptibility to crises.
- **Environmental Advantages:**
  - Lower emissions and reduced environmental footprint from renewable sources.
- **Technological Advancement:**
  - Promotion of innovation and technological progress in energy sectors.

### **Risks:**

- **Stranded Assets:**
  - Potential financial losses from decommissioning existing energy production and distribution infrastructure.
- **Political and Regulatory Resistance:**
  - Possible intentional slowing of change due to political interests or regulatory barriers.
- **Investment Uncertainty:**
  - Long-term investments in energy infrastructure may face unpredictability in profitability.
- **Dependence on Technological Development:**
  - Success contingent on continued advancements in renewable and storage technologies.

### **Inhibitors:**

- **Established Expectations:**
  - Public accustomed to centralized energy supply and may resist changes.
- **Regulatory Barriers:**

- Existing regulations and taxation structures may discourage new entrants and technologies.
- **Economic Interests:**
  - Incumbent energy providers may oppose changes that threaten their business models.
- **Infrastructure Investment Cycles:**
  - Long life cycles of energy infrastructure slow down the adoption of new technologies.
- **Emotional and Political Factors:**
  - Irrational or emotional political decisions can hinder progress and adoption of innovations.

## 6. Materials

### Materials

#### Goal:

- **Provide Access to Materials for Manufacturing and Construction:**
  - Ensure the availability of materials used in the manufacturing of goods, chemical industry, and construction.

#### Qualitative Values:

- **Cost-Effectiveness:**
  - Secure raw materials at minimal cost to enhance operational efficiency.
- **Minimization of Adverse Effects:**
  - Reduce harm to people and the environment during production and use.
- **Adequate Quality:**
  - Maintain sufficient material quality for manufacturing, usage, and recycling processes.
- **Reliability of Supply:**
  - Ensure consistent access to necessary materials to prevent costly interruptions in production.
- **Sustainability:**
  - Promote the use of renewable and environmentally friendly materials.
- **Functionality:**

- Consider materials' performance in manufacturing, usage, and end-of-life recycling.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Reliance on Traditional Industries:**
  - Heavy dependence on mining, forestry, and energy-intensive process industries.
- **Mass Production:**
  - Utilization of large raw material streams for mass production of goods.
- **Global Supply Chains:**
  - Extensive logistics infrastructure transporting raw materials from extraction sites to refineries and production facilities.
- **Capital-Intensive Processes:**
  - Significant investments in infrastructure and machinery for large-scale production.
- **Established Educational and Economic Systems:**
  - Vocational training and economic policies supporting traditional material industries.

### **Values:**

- **Economic Stability:**
  - Preference for proven methods perceived as low-risk investments.
- **Preservation of Existing Structures:**
  - Support for long-term societal investments in current industrial and logistics infrastructures.
- **Resistance to Change:**
  - Hesitance to adopt new materials or processes that could disrupt established industries.
- **Regulatory Alignment:**
  - Regulations designed around traditional materials and methods, often hindering innovation.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Renewable and Efficient Materials:**



- Development of materials that are renewable and more efficient in processing and functionality.
- **Nanotechnology and Advanced Materials:**
  - Use of graphene, nanocarbons, and nanocellulose offering superior strength and versatility.
  - Potential to replace rare metals with advanced carbon-based materials.
- **Biotechnology and Biomimicry:**
  - Production of high-strength fibers and materials by mimicking natural processes.
  - Utilization of bacteria and molds to produce raw materials at room temperature.
- **Low-Temperature and Decentralized Processes:**
  - Adoption of processes requiring less energy and capital investment.
  - Shift towards localized production reducing reliance on massive logistics networks.
- **3D Printing and Additive Manufacturing:**
  - Creation of complex structures like honeycombs and laminates with enhanced properties.
  - Reduction in material usage and waste through precise manufacturing techniques.
- **Efficient Recycling and Circular Economy:**
  - Advanced robotics and AI for material recognition and recycling outside traditional systems.
  - Design of products optimized for recycling and resource recovery.

#### **Values Promoting Change:**

- **Environmental Protection:**
  - Commitment to reducing environmental impact from material extraction and processing.
- **Process Enhancement:**
  - Improving efficiency and reducing costs through innovative materials and methods.
- **Competitiveness:**
  - Gaining a market edge by offering superior products with new material properties.
- **Sustainability:**
  - Embracing sustainable practices to ensure long-term resource availability.
- **Innovation and Adaptability:**
  - Openness to adopting new technologies and flexible production models.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Reduced Environmental Impact:**
  - Less harm to nature and human environments by replacing traditional raw materials.
- **Lower Capital Requirements:**
  - New materials and processes often require less investment than traditional methods.
- **Improved Logistics:**
  - Decentralized production reduces the need for extensive raw material transportation.
- **Enhanced Product Competitiveness:**
  - Superior material properties can lead to better-performing products.
- **Local Economic Growth:**
  - Ability to manufacture or source materials locally boosts trade balance and employment.
- **Advancement of Circular Economy:**
  - Efficient recycling leads to sustainable resource utilization and waste reduction.

### **Risks:**

- **Economic Disruption:**
  - Investments and expertise tied to traditional materials may become obsolete.
- **Structural Unemployment:**
  - Rapid global demand shifts could lead to job losses in established industries.
- **Industry Resistance:**
  - Attachment to traditional materials may prevent timely recognition of necessary changes.
- **Intellectual and Cultural Challenges:**
  - Identity and pride in traditional industries may hinder adaptation.

### **Inhibitors:**

- **Existing Investments:**
  - Significant capital sunk into current infrastructure and technologies.

- **Educational and Policy Support for Status Quo:**
  - Training and policies favoring traditional industries over innovative approaches.
- **Regulatory Barriers:**
  - Regulations designed around old materials may restrict new, more sustainable methods.
- **Risk Aversion:**
  - Preference for low-risk investments discourages experimentation with new materials.
- **Limited Awareness and Expertise:**
  - Lack of knowledge and skills in new materials and decentralized processes.
- **Media and Attention Economy:**
  - Focus on traditional industry events overshadows emerging innovations.

## 7. Built environment

### Built Environment

#### Goal:

- **Provide Facilities for Mobility and Activity:**
  - Ensure that people, animals, equipment, and plants have the necessary facilities for their mobility and activities with respect to location and conditions.

#### Qualitative Values:

- **Location:**
  - Importance of geographic location in relation to traffic routes.
  - Proximity to services, workplaces, and social environments.
- **Cost:**
  - Emphasis on lifecycle costs, including service life, maintenance expenses, and environmental impact.
- **Compliance with Norms:**
  - Adherence to land use plans, construction regulations, and maintenance provisions.
- **Systemic Efficiency:**

- Efficient design, construction, and utilization of facilities and routes.
- **Individuality:**
  - Accommodating individual needs and preferences in facility design and construction.
- **Experiential Nature:**
  - Enhancing user experience within built environments.
- **Ease and Accessibility:**
  - Simplifying use and ensuring easy access to facilities and services.
- **Proximity of Services:**
  - Locating amenities and services close to users.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Construction Methods:**
  - Construction and maintenance carried out using human-operated machines and traditional materials.
  - Majority of work performed on-site with minimal automation.
- **Strict Norms and Regulations:**
  - Construction subject to stringent land use plans, building codes, and regulations.
  - Political decision-making controls locations, purposes, routes, materials, and appearance.
- **Centralized Decision-Making:**
  - Authorities decide on the construction and maintenance of routes, funded by public revenue.
- **Focus on Location and Cost:**
  - Builders and developers prioritize securing permissions in attractive locations.
  - Purchase price, location, and suitability for intended use are primary considerations for customers.
- **Quality Determined by Authorities:**
  - Regulatory bodies set construction quality standards.
- **Low Automation:**
  - Automation limited to certain components like building services engineering and prefabricated elements.

### **Values:**

- **Dependency on Motoring:**

- Built environments designed around personal vehicle use.
- **Conservatism and Risk Aversion:**
  - Reluctance to adopt new methods or technologies.
- **Significance of Location and Purchase Price:**
  - Emphasis on prime locations and affordability in decision-making.
- **Normativity:**
  - Strong adherence to established norms; slow to adapt to digitalization.

### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Automation and Robotization in Construction:**
  - Automating tasks such as casting, brickwork, painting, material transfer, installation, and finishing.
  - Use of 3D printing for buildings and robotic systems in construction processes.
- **Automated Maintenance:**
  - Deployment of robots for tasks like lawn mowing, floor cleaning, and maintenance of infrastructure.
- **Advancements in Transportation:**
  - Development of high-speed transport systems like Hyperloops connecting distant urban centers.
  - Mobility as a Service (MaaS) reducing reliance on personal vehicles.
- **Changing Facility Requirements:**
  - Impact of robot kitchens, virtual reality (VR), augmented reality (AR), and indoor farming on facility design and usage.
  - Shift towards adaptable and versatile spaces.
- **Innovative Construction Materials:**
  - Use of materials that enable buildings to produce energy and create lightweight, insulating structures.
- **Advanced Building Automation:**
  - Application of sophisticated building automation systems, including retrofitting older buildings with mobile robots.

#### **Values Promoting Change:**

- **Systemic Efficiency:**
  - Optimizing the efficiency of design, construction, and utilization of built environments.
- **Individuality:**

- Customization of facilities to meet individual preferences and needs.
- **Enhanced User Experience:**
  - Creating environments that offer engaging and improved experiences.
- **Ease and Convenience:**
  - Simplifying access to and use of facilities and services.
- **Proximity of Services:**
  - Locating amenities and services closer to users for improved accessibility.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Denser Urban Planning:**
  - Reduced dependency on personal vehicles allows for denser urban development and better traffic management.
- **Optimized Mobility:**
  - Enhanced use of routes and transportation options, freeing up space and improving mobility.
- **Adaptable Facility Usage:**
  - Increased versatility in facility design allows for repurposing spaces to meet changing needs.
- **Improved Accessibility in Remote Areas:**
  - Advancements in transport and telepresence technologies make living in sparsely populated areas more feasible.
- **Economic Growth and Equity:**
  - Expansion of commuting and service areas boosts economic activity and balances property values.
- **Environmental Sustainability:**
  - Energy-efficient buildings and reduced reliance on personal vehicles contribute to lower environmental impact.

### **Risks:**

- **Employment Disruption:**
  - Automation may lead to significant job losses in construction and maintenance sectors.
- **Economic Challenges:**
  - Importation of construction robots and new materials could negatively impact local industries and labor markets.
- **Resistance to Adoption:**

- Conservative attitudes within the sector may hinder the implementation of new technologies.

#### **Inhibitors:**

- **Slow Rate of Change:**
  - Long lifespans of buildings and infrastructure lead to gradual changes in the built environment.
- **Conservatism and Risk Aversion:**
  - Reluctance to embrace new methods due to fear of risks and attachment to traditional practices.
- **Regulatory Constraints:**
  - Strict regulations and slow adaptation to technological advancements impede innovation.
- **Focus on Traditional Priorities:**
  - Emphasis on location and purchase price over innovative features may slow demand for new solutions.

## 8. Exchange

### **Exchange**

#### **Goal:**

- **Facilitate the Transfer of Ownership and Access Rights:**
  - Enable the exchange of goods, services, and rights between parties.

#### **Qualitative Values:**

- **Low Transaction Costs:**
  - Minimize search costs, bargaining costs, and delivery costs.
- **Reliability:**
  - Ensure the ability to deliver, responsibility, and ethical compatibility.
- **Prevalence and Flexibility:**
  - Offer flexibility in delivery methods, delivery times, and means of payment.
  - Provide a wide range of products and services.
- **Locality and Cultural Relevance:**
  - Foster geographic and cultural closeness or shared group identity.



- **Individuality:**
  - Cater to individual needs and preferences.
- **Ease and Convenience:**
  - Simplify processes for users, making transactions effortless.
- **Peer Trust:**
  - Build trust through peer reviews, ratings, and transparent practices.
- **Time and Location Independence:**
  - Allow transactions to occur regardless of time and place.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Trade Practices:**
  - Goods and services are advertised through traditional media.
  - Trust is established through brands and directed at companies engaging in trade.
- **Physical Retail and Service Locations:**
  - Goods are picked up from shops or delivered by the seller or subcontractor.
  - Services are local and tied to the physical offices of sellers or customers.
- **Bank-Centric Payment Systems:**
  - Banks play a central role in payment transactions.
  - Authorities oversee verification of agreements and control of trade and services.
- **Hierarchical Structures:**
  - Trade and services are produced within hierarchical organizations.
  - Low degree of automation, except in financial services and large-scale warehousing.

### **Values:**

- **Desire for Safety and Stability:**
  - Preference for established, trusted brands and methods.
- **Paternalism and Hierarchical Ties:**
  - Reliance on structured organizations and authority oversight.
- **Salaried Work:**
  - Emphasis on traditional employment structures.
- **Resistance to Change:**
  - Unwillingness to try new things or adopt new technologies.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **E-Commerce and Globalization:**
  - Migration of purchase transactions to the web.
  - Traders becoming global, crossing national borders.
  - Online shops serving as their own marketing channels without relying on traditional advertising.
- **Platforms and Decentralization:**
  - Emergence of platforms as marketing and transaction channels.
  - Platforms offering services of trusted third parties.
  - Reduction of customer loyalty due to platform use.
- **Automation and Artificial Intelligence:**
  - Machine-to-machine transactions guided by data systems and AI.
  - AI assistants representing customers in finding and comparing products and services.
- **Sharing Economy and Crowdsourcing:**
  - Growth of sharing economy platforms with peer reviews and public complaint practices.
  - Crowdsourcing achieving economies of scale without formal organization.
- **Cryptocurrencies and Blockchain Technology:**
  - Electronic payment methods extending to cryptocurrencies.
  - Expansion of contractual practices using blockchain technology, reducing the need for trusted third parties.
- **Advanced Technologies:**
  - Use of virtual reality (VR) and augmented reality (AR) to enhance e-commerce experiences.
  - Robotics delivering physical services purchased online in real time.

### **Values Promoting Change:**

- **Individuality:**
  - Catering to personal preferences and needs.
- **Ease and Convenience:**
  - Simplifying transactions and processes for users.
- **Extensive Range of Products and Services:**
  - Access to a wide selection globally.
- **Peer Trust:**
  - Building trust through peer reviews, ratings, and transparent practices.

- **Time and Location Independence:**
  - Enabling transactions regardless of time and place.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Reduced Transaction Costs:**
  - Lower search, bargaining, and delivery costs.
- **Ease of Comparison and Access:**
  - Easier to compare products and services globally.
- **Expanded Product and Service Range:**
  - Access to a wider variety of offerings.
- **Increased Flexibility:**
  - Transactions less tied to specific locations or times.
- **Simplification of Crowdsourcing and Automation:**
  - Digitalization facilitates new models of service provision.
- **Potential Reduction in Income Inequality:**
  - Reduced hierarchy may level the economic playing field.

### **Risks:**

- **Loss of Control and Regulation:**
  - Difficulty in controlling transactions and ensuring compliance.
- **Increased Consumer Responsibility:**
  - Greater burden on consumers to assess trustworthiness and quality.
- **Employment Challenges:**
  - Traditional employment structures may be undermined.
- **Taxation and Public Revenue:**
  - Narrowing tax base due to digitalization and globalization.
- **Dependency on Global Platforms:**
  - Vulnerability due to reliance on international platforms, potentially weakening security of supply.

### **Inhibitors:**

- **Consumer Habits and Preferences:**
  - Preference for traditional purchasing methods and reluctance to adopt new ones.
- **Existing Urban and Infrastructure Designs:**
  - Structures favoring traditional trade and exchange.

- **Regulatory Barriers:**
  - Regulations not adapted to new forms of exchange and digital transactions.
- **Organizational Resistance:**
  - Established entities favoring current methods and resisting change.
- **Lack of Regulation for New Models:**
  - Sharing economy and crowdsourced services may lack appropriate regulation.

## 9. Remote impact

### Remote Impact

#### Goal:

- **Enable Remote Influence on Things and Events:**
  - Provide means for individuals and organizations to influence things and events without being physically present.

#### Qualitative Values:

- **Participation:**
  - Ability to engage and influence remotely, driven by empathy, earning opportunities, or the desire to affect change.
- **Location Independence:**
  - Opportunity to participate in situations occurring elsewhere without the need to travel, regardless of one's own location.
- **Ease and Accessibility:**
  - Simple, fast, and convenient access to tools and methods for remote influencing.
- **Safety and Security:**
  - Ensuring data protection and privacy.
  - Ability to influence without personal risk.
  - Capability to restrict unlawful remote influencing.
- **Efficiency:**
  - Effective use of resources to achieve desired outcomes through remote means.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Communication Channels:**
  - Centralized communication via media messages, advertisements, phone calls, emails, and social media.
  - Systematic influencing of target groups using established methods.
- **Physical Methods Used by Large Entities:**
  - Armies and large organizations employing physical means of remote influence.
  - Measurement and control of decentralized processes and devices through data networks.
- **Extensive Bureaucracy:**
  - Use of written instructions, required reports, norms, and regulations as methods of remote influence.
  - Reliance on diplomatic and economic tools like customs duties, trade agreements, and international policies to influence beyond borders.

### **Values:**

- **Appreciation for Physical Presence:**
  - Preference for in-person interactions and traditional methods of influence.
- **Adherence to Norms and Habits:**
  - Reliance on established practices and resistance to change.
- **Underestimation of Remote Efforts:**
  - Disregard for the effort undertaken by those who use remote means.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Advanced Global IT Platforms:**
  - Platforms allowing individuals and organizations to influence remotely through digital communication channels.
- **Emerging Channels of Influence:**
  - Use of viruses, social media, cryptocurrencies, and the dark web as new means of remote influence.
- **Remote-Controlled Robotics and Avatars:**

- Robots capable of moving and interacting in various environments, serving as tools for telepresence and remote work.
- Avatars enabling active participation and physical labor remotely.
- **Advancements in Machine Vision and AI:**
  - Improved perception and autonomous movement in robots, enhancing remote capabilities.
- **Virtual Reality (VR) and Augmented Reality (AR):**
  - Technologies providing natural user interfaces for remote control.
  - Creation of immersive experiences that blend virtual and real-world environments.
- **Enhanced Connectivity with 5G Networks:**
  - Increased bandwidth and reduced latency allowing more devices to connect wirelessly.
  - Improved user experience for remote operations.
- **Geopositioned Virtual Content:**
  - Placement of virtual information at real-world coordinates to create actual events.
  - Influence of virtual elements on real-world behaviors (e.g., location-based games affecting customer footfall).
- **Synthetic Media and Deepfakes:**
  - Creation of realistic but false information, making remote interactions more convincing.

### **Values Promoting Change:**

- **Efficiency:**
  - Seeking more effective methods of remote influence.
- **Ease and Accessibility:**
  - Desire for user-friendly tools and platforms.
- **Safety and Security:**
  - Influencing others without personal risk.
  - Protecting data and privacy in remote interactions.
- **Innovation and Technological Advancement:**
  - Embracing new technologies to expand remote capabilities.

### **Benefits, Risks, and Inhibitors of Change:**

#### **Benefits:**

- **Reduced Need to Travel:**

- Decreases travel costs and time, reducing delays and environmental impact.
- **Expanded Participation and Interaction:**
  - Enhances virtual expansion of commuting and service areas.
  - Increases participation and improves regional equality.
- **Improved Quality of Influence:**
  - More versatile methods lead to better outcomes and fewer mistakes.
  - Natural-feeling telepresence replaces impersonal communication methods.

#### **Risks:**

- **Increased Cybersecurity Threats:**
  - Higher risk of cyberattacks, hybrid warfare, and terrorism as remote tools become more accessible.
- **Privacy Concerns:**
  - Decreased protection of privacy due to advanced remote capabilities.
- **Abuse of Remote Influence:**
  - Potential misuse of technology to spread false information or conduct malicious activities.
- **Job Displacement:**
  - Professional tasks being handled remotely from anywhere, impacting local employment.

#### **Inhibitors:**

- **Fragmented Communication Practices:**
  - Existing diverse and complex communication methods.
- **Symbolic Meanings of Traditional Communication:**
  - Difficulty in replacing established methods that hold cultural or symbolic value.
- **Technological Limitations:**
  - Limited mobility and functionality of robots and avatars.
  - Need for physical setup in some cases.
- **Legal and Regulatory Barriers:**
  - Legal requirements for physical presence in certain situations.
  - Regulated environments slowing down adoption.
- **Contradictory Motives:**
  - Receiver's need to invest in new technology while the initiator saves costs may hinder adoption.



## 10. Automation of work

### Automation of Work

#### Goal:

- **Replace Human Labor with Machines:**
  - Utilize machines to perform tasks traditionally done by humans.

#### Qualitative Values:

- **Functionality:**
  - Ease of use and operational reliability of machines.
  - High-quality results that meet desired standards.
- **Acceptability:**
  - Reduction of danger, physical strain, and unpleasant aspects of work.
  - Positive impact on job status and privacy protection.
- **Cost-Effectiveness:**
  - Minimization of fixed and variable costs associated with machinery.
  - Consideration of risks and externalities from manufacturing and use.
- **Efficiency:**
  - Ability to perform tasks faster and more consistently than human labor.
- **Versatility:**
  - Machines capable of adapting to new tasks and environments quickly.

#### Means and Values of the Dominant Regime:

##### Current Means:

- **Repetitive Automation and Human-Controlled Machinery:**
  - Machines performing specific, repetitive tasks in mass production lines.
  - Tools like excavators and chainsaws requiring constant human operation.
- **Enhancement of Human Work:**
  - Machines serving as aids (e.g., word processors, calculators) to enhance human productivity.
  - Information technology systems compiling and sorting data under human supervision.
- **Human-Centric Skill Requirements:**
  - Professional expertise focused on operating and controlling machines.

- Training centered around human interaction with machinery.

#### **Values:**

- **Emphasis on Human Control:**
  - Preference for machines that require human oversight.
  - Belief in the superiority of human judgment over machine autonomy.
- **Preservation of Professional Identity:**
  - Protecting jobs and roles traditionally performed by humans.
  - Valuing human labor as essential to work and society.
- **Fear of Autonomous Machines:**
  - Concerns about safety and unpredictability of machines acting independently.
  - Resistance to machines that could replace human interaction.

#### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Advanced Autonomous Machines and Robots:**
  - Machines with versatile capabilities operating without constant human control.
  - Robots that can move independently, process materials, and make decisions based on detected needs.
- **Artificial Intelligence and Machine Learning:**
  - Systems capable of learning from data and experiences (deep learning).
  - Machines adapting to new situations without explicit programming.
- **Mobile Robotics and 3D Printing:**
  - Robots performing logistics, environmental maintenance, and complex tasks.
  - 3D printers manufacturing a wide range of customized items.
- **Shared Use and Sharing Economy:**
  - Decreased costs and increased autonomy facilitating the shared use of machines.
  - Crowdsourcing development and utilization of machinery.
- **Decentralization of Production:**
  - Localized manufacturing reducing logistics costs and delays.
  - Customized production competing with economies of scale.

#### **Values Promoting Change:**

- **24/7 Service Availability:**
  - Machines operating continuously without the limitations of human work hours.
- **Efficiency and Productivity:**
  - Higher output and consistency compared to human labor.
- **Cost Reduction:**
  - Lower operational costs through automation and reduced need for human labor.
- **Innovation and Adaptability:**
  - Embracing new technologies for competitive advantage.
  - Willingness to overcome social inhibitions regarding machine use.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Increased Production Flexibility:**
  - Ability to produce smaller batches without increased costs.
  - Enhanced customization and local production capabilities.
- **Reduced Costs and Competence Requirements:**
  - Lower costs of goods and services due to decreased human involvement.
  - Less need for specialized human skills in certain tasks.
- **Easier Sharing and Access to Machines:**
  - Shared economy models expanding to autonomous machines.
  - Broader access to machinery for various tasks.
- **Enhanced Efficiency and Lower Hierarchies:**
  - Streamlined production processes with fewer managerial layers.
  - Faster adaptation to market demands.

### **Risks:**

- **Job Market Disruption:**
  - Significant changes in professions and potential job losses.
  - Challenges in retraining and workforce adaptation.
- **Misuse of Autonomous Machines:**
  - Potential for machines to be used for harmful purposes.
  - Security vulnerabilities in AI-controlled equipment connected via networks.
- **Liability and Ethical Issues:**
  - Unclear responsibility in cases of machine errors or accidents.

- Legal challenges in assigning blame and encouraging safety improvements.
- **Reduction in Tax Base:**
  - Decreased employment leading to lower income tax revenues.
  - Shift towards self-reliance and crowdsourcing affecting traditional economic models.

#### **Inhibitors:**

- **Resistance to Change and Fear of the Unknown:**
  - Comfort with traditional methods hindering adoption of new technologies.
  - Fear of losing human connection and value in work.
- **Lack of Investment and Vision:**
  - Insufficient resources allocated to exploring new opportunities.
  - Educational systems not keeping pace with technological advancements.
- **Technical Limitations:**
  - Current limitations in mobile robotics and machine adaptability.
  - Challenges in integrating machines into environments designed for humans.
- **Regulatory Barriers:**
  - Laws restricting the use of autonomous machines in public spaces.
  - Regulations not yet adapted to address new technological realities.
- **Skill Gaps in Business and Services:**
  - Decline in local business skills needed to leverage mechanization.
  - Service industries unprepared for robotization of services.

## **11. Work and income**

### **Work and Income**

#### **Goal:**

- **Enable Individuals to Secure Well-Being and Promote Important Matters:**
  - Provide means for people to earn income, save resources, and exercise social influence to secure their own well-being and that of family and friends.

#### **Qualitative Values:**

- **Earnings and Savings:**
  - Compensation for work performed.
  - Access to benefits and opportunities for advancement.
  - Ability to save resources through self-service and subsistence activities without spending previous means of exchange.
- **Suitability of Work:**
  - Alignment of job roles with personal abilities and value systems.
  - Engagement in work that is meaningful and fulfilling.
- **Social Significance:**
  - Recognition and appreciation from society for one's work.
  - Building relationships and networks through professional activities.
- **Equitable Access:**
  - Fair distribution of opportunities for work and earning among all members of society.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Specialized Paid Employment:**
  - Dominance of regular, specialized, paid work organized through hierarchical structures.
  - Clear distinction between paid work and free time or personal activities.
- **Large-Scale Production and Economies of Scale:**
  - Work tied to large-scale production due to natural economies of scale and repetitive automation.
  - Regulation and policies promoting interests of established power structures and hierarchies.
- **Ownership and Capital Orientation:**
  - Significant impact of ownership, capital, and privileges such as intellectual property rights.
  - Influence of states and politics on business economics at national and global levels.
- **High Taxation on Paid Work:**
  - Substantial tax-like fees on the exchange of work performances.
  - Taxation supports transfer payments and public services, relying on high work productivity differences.

### **Values:**

- **Desire for Safety and Stability:**

- Preference for secure employment and predictable income.
- Reliance on established employment structures.
- **Acceptance of Hierarchical Structures:**
  - Comfort with hierarchical organizations and authority oversight.
  - Identification with professional roles within established systems.
- **Comfort and Familiarity:**
  - Preference for known routines and resistance to change.
  - Cultural emphasis on paid work as a defining aspect of identity.

### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Artificial Intelligence and Robotization:**
  - Easy access to tools and expertise required for productive work.
  - Reduction in differences in work productivity and specialization needs.
- **Sharing Economy and Platform Economy:**
  - Facilitation of occasional employment relationships, crowdsourcing, and communal work.
  - Data systems organizing activities by matching needs and resources, handling monitoring and transactions.
- **Crowdsourcing and Collaborative Work:**
  - Scaling services regionally with wide specialization.
  - Platforms leveraging user-provided resources without owning significant assets.
- **Economy of Smallness and Self-Sufficiency:**
  - Decrease in the need for large-scale production due to digital tools and AI guidance.
  - Individuals producing their own goods, energy, food, and knowledge.
- **Remote Work and Telepresence:**
  - Use of avatars, augmented reality (AR), and virtual reality (VR) to perform work remotely.
  - Reduction of geographical limitations in professional activities.

#### **Values Promoting Change:**

- **Self-Reliance and Freedom:**
  - Desire for autonomy and control over one's work and resources.
  - Emphasis on personal responsibility and initiative.
- **Willingness to Take Risks:**
  - Openness to experimentation and embracing new opportunities.

- Flexibility in adapting to changing work environments.
- **Desire for Innovation:**
  - Pursuit of new methods and technologies to enhance work and income.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Increased Meaningfulness of Work:**
  - Less hierarchical and more comprehensive work tasks enhance job satisfaction.
  - Greater alignment with personal values and abilities.
- **Enhanced Self-Sufficiency:**
  - Individuals and regions becoming more self-reliant, reducing vulnerability to external disruptions.
  - Decreased dependence on centralized structures.
- **Reduced Transaction Costs:**
  - Platform economies increase openness and efficiency by eliminating intermediaries.
  - Easier access to markets and resources.
- **Rapid Societal Transformation:**
  - Ability to produce goods and services independently leads to significant societal changes.
  - Empowerment of individuals to control their economic destinies.

### **Risks:**

- **Diminishing Tax Base:**
  - Sharing economy, self-reliance, and crowdsourcing moving labor away from the monetary economy.
  - Challenges in funding public services and social welfare systems.
- **Challenges to Transfer Payments:**
  - Difficulty in maintaining social welfare mechanisms when standard of living is less dependent on traditional earned income.
  - Potential strain on pension systems, unemployment benefits, and public services.
- **Negative Economic Cycles:**
  - Increasing tax burdens may exacerbate economic issues.
  - Risk of creating disincentives for participation in the formal economy.

### **Inhibitors:**



- **Strong Social and Psychological Ties to Paid Work:**
  - Cultural and symbolic value placed on traditional employment.
  - Resistance to changing long-held perceptions of work identity.
- **Inadequate Infrastructure for Self-Sufficiency:**
  - Homes and communities not equipped for independent manufacturing or remote work.
  - Lack of access to necessary tools and technologies.
- **Educational Systems:**
  - Education focused on preparing individuals for traditional paid work in hierarchical organizations.
  - Insufficient emphasis on skills needed for self-reliance and adaptability.
- **Regulatory Barriers:**
  - High regulation in many industries makes exchange difficult outside existing organizations.
  - Legal and bureaucratic obstacles to new forms of work and income generation.

## 12. Health care

### Health Care

#### Goal:

- **Enable People to Lead Healthy Lives for as Long as Possible:**
  - Provide prevention and treatment of diseases affecting the mind and body.
  - Maintain physical and mental health.
  - Correct problems related to appearance and behavior that affect social relationships.

#### Qualitative Values:

- **Functionality of Mind and Body:**
  - Optimal physical and cognitive functioning.
- **Longevity:**
  - Extended lifespan with good health.
- **Well-Being:**
  - Overall quality of life, including mental and emotional health.

- **Appearance:**
  - Satisfaction with physical appearance, including correction of issues impacting social interactions.
- **Individuality and Personalization:**
  - Tailoring health care to individual needs and characteristics.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Centralized, Bureaucratized Health Care Systems:**
  - Health care guided by official guidelines, regulations, and population-level recommendations.
  - Treatment provided by licensed professionals within officially monitored institutions.
- **General Recommendations and Norms:**
  - Influence on lifestyle choices through general health recommendations based on statistical population studies.
  - Regulations affecting food industry practices, institutional kitchens, mobility, and behaviors such as alcohol and tobacco use.
- **Strict Regulation and Control:**
  - Tight control over the development, marketing, and distribution of medicines.
  - Diagnostics and treatments are the exclusive domain of licensed medical professionals.
  - Distribution of medicine based on prescriptions issued by doctors.

### **Values:**

- **Trust in Institutions and Professionals:**
  - Reliance on established medical authorities, institutions, and standardized guidelines.
- **Uniformity and Equality:**
  - Commitment to providing standardized care where everyone is bound by the same rules.
- **Public Health Ideology:**
  - Emphasis on population health and prevention strategies over individual preferences.
- **Privacy Concerns:**
  - Protection of personal health data and privacy.
- **Paternalism:**

- Authorities guiding individual behaviors for the perceived benefit of public health.

### **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Personalized Medicine and Self-Care Technologies:**
  - Use of artificial intelligence (AI), self-care measurement devices, and biomarkers for proactive care and early symptom recognition.
  - Household equipment for advanced health monitoring, including genome and cell metabolism analysis.
- **Wearable and Smartphone Diagnostics:**
  - Devices allowing individuals to perform diagnostic tests and send data to professionals or AI for analysis.
  - Approval and use of smartphone accessories for diagnostic purposes.
- **Advancements in Artificial Intelligence:**
  - AI capable of providing medical statements, personalized recommendations, and automatic diagnoses.
- **Biotechnology and Genomics Advances:**
  - Affordable DNA sequencing enabling detailed personal health data.
  - Ability to correct health issues at their root causes through genetic and metabolic interventions.
- **Personalized Nutrition and Lifestyle Medicine:**
  - Individualized dietary recommendations monitored at the cellular level.
  - Use of gamification, digital tattoos, and self-diagnostic implants to integrate health monitoring into daily life.
- **Biohacking and Self-Experimentation:**
  - Individuals adjusting lifestyles and experimenting with treatments based on self-diagnostics.
  - Peer-to-peer sharing of experiences and collaborative patient communities.
- **Mental Health Innovations:**
  - Utilization of AI, virtual agents, peer assistance, and gamification to provide new methods for improving mental health.
- **Research into Lifespan Extension:**
  - Emerging methods potentially extending healthy human lifespan, leading to increased voluntary treatments.

### **Values Promoting Change:**

- **Individuality and Self-Reliance:**
  - Desire to take personal initiative in managing health.
- **Desire for Control and Experimentation:**
  - Willingness to experiment with new treatments, technologies, and lifestyles.
- **Concern for Personal Well-Being and Aging:**
  - Focus on optimizing personal health and longevity.
- **Distrust in General Recommendations:**
  - Skepticism towards one-size-fits-all guidelines and desire for personalized care.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Enhanced Personalization of Health Care:**
  - Tailored treatments and recommendations based on individual characteristics and needs.
- **Empowerment and Better Health Outcomes:**
  - Individuals have greater understanding and control over their health, leading to improved decision-making.
- **Proactive Health Management:**
  - Early detection and prevention of diseases through self-monitoring and personalized interventions.
- **Potential Reduction in Health Care Costs:**
  - Decreased burden on public health systems due to early interventions and self-care.
- **Innovation in Mental Health Care:**
  - New methods addressing mental health challenges, improving access and effectiveness.

### **Risks:**

- **Spread of Misinformation and Unproven Treatments:**
  - Risk of harm from reliance on incorrect information or alternative medicine without scientific validation.
- **Conflict with Medical Professionals:**
  - Potential opposition between self-informed patients and traditional medical practitioners.
- **Errors in Self-Diagnosis and Treatment:**

- Inaccurate self-measurements leading to unnecessary or harmful actions.
- **Privacy and Data Security Concerns:**
  - Personal health data may be exposed, misused, or compromised.
- **Unregulated Synthesis of Pharmaceuticals:**
  - Potential for individuals to produce harmful substances, posing risks to themselves and others.

#### **Inhibitors:**

- **Trust in Established Institutions and Practices:**
  - Reluctance to move away from centralized health care systems and reliance on professionals.
- **Regulatory Barriers:**
  - Existing regulations not accommodating self-care technologies and personalized medicine.
- **Cultural and Social Norms:**
  - Preference for traditional practices, processed foods, and institutional care.
- **Lack of Infrastructure and Capabilities:**
  - Limited access to necessary technologies and expertise for personalized self-care.
- **Privacy and Ethical Concerns:**
  - Worries about data privacy, ethical implications, and potential misuse of health information.

### 13. Redressing disabilities

#### **Redressing Disabilities**

##### **Goal:**

- **Compensate Functional Deficiencies and Optimize Functional Ability:**
  - Provide assistive devices and facilitate living environments to enhance individuals' functional abilities in everyday life.

##### **Qualitative Values:**

- **Functional Ability in Everyday Life:**
  - Achieving independence or receiving continuous care to perform daily activities.
- **Cost and Societal Benefit:**
  - Balancing the costs of interventions with the benefits to society, such as improved functional ability and increased years of life.
- **Preservation of Life:**
  - Prioritizing keeping people alive, especially in cases of severe illness.
- **Quality of Life:**
  - Enhancing overall well-being and life satisfaction.
- **Personal Initiative and Proactivity:**
  - Encouraging individuals and their families to take an active role in managing disabilities.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Institutional Care and Home Care:**
  - Reliance on society-supported institutional care, home care, and informal caregiving.
- **Simple Assistive Devices:**
  - Use of basic prostheses, wheelchairs, rollators, and other traditional assistive devices.
- **Limited Adoption of New Technologies:**
  - New methods and advanced assistive devices are not widely known or adopted.
- **Guideline-Based Measures:**
  - Interventions based on established guidelines, primarily financed by public funds.
- **Focus on Accessibility Features:**
  - Significant funding allocated to accessible construction and personal assistance, with less emphasis on innovative assistive devices.

### **Values:**

- **Paternalism and Protection:**
  - Emphasis on safeguarding individuals through controlled measures.
- **Equal Treatment Over Need-Based Treatment:**
  - Prioritizing uniform solutions rather than tailoring to individual needs.

- **Preservation of Life Over Enabling Functionality:**
  - Focusing on keeping people alive rather than enhancing their abilities.

### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Advancements in Robotics and AI:**
  - Development of robotized prosthetics connected to the nervous system, allowing control through thoughts.
  - Wearable robotic exoskeletons assisting those with muscle weakness or paralysis.
- **Artificial Organs and Implants:**
  - Artificial organs like pancreases and hearts improving bodily functions.
  - Neural implants bypassing damaged nervous systems.
- **Enhanced Assistive Technologies:**
  - Machine vision applications for the visually impaired, enabling recognition of objects and environments.
  - Advanced hearing aids and middle ear implants for the hearing impaired.
- **Personal AI Assistants:**
  - AI devices monitoring actions, warning of dangers, and providing reminders.
- **Crowdsourcing and Community Support:**
  - Leveraging collective efforts to develop and distribute assistive technologies.

#### **Values Promoting Change:**

- **Idea of a Good Life:**
  - Striving for improved quality of life and independence.
- **Personal Initiative and Proactivity:**
  - Encouraging individuals to take charge of their functional abilities.
- **Active Aging:**
  - Promoting staying active in old age through technological assistance.
- **Awareness of Institutional Care Costs:**
  - Recognizing the high costs of institutional care and seeking alternatives.

### **Benefits, Risks, and Inhibitors of Change:**

#### **Benefits:**



- **Increased Independence:**
  - Empowering individuals to cope independently in daily life.
- **Improved Quality of Life:**
  - Enhancing life satisfaction and reducing reliance on institutional care.
- **Restoration of Working Capacity:**
  - Enabling individuals to return to work or remain productive.
- **Reduced Need for Accessible Construction and Personal Assistance:**
  - Decreasing societal costs associated with infrastructure adaptations.
- **Benefits to Society as a Whole:**
  - Extending advantages to all groups requiring assistance.

#### **Risks:**

- **Rapid Pace of Change:**
  - Potential challenges adapting to new technologies quickly.
- **Experimental Artificial Organs:**
  - Uncertainties associated with new medical devices and implants.
- **Surprising Effects of Artificial Intelligence:**
  - Unanticipated AI behaviors that could pose risks.
- **Cybersecurity Threats:**
  - Vulnerability of essential devices to cyberattacks, risking users' health.
- **Data Security Concerns:**
  - Privacy issues related to personal health data collected by devices.

#### **Inhibitors:**

- **Conservative and Regulated Operating Culture:**
  - Strict regulations and conservative practices within healthcare institutions.
- **Submissiveness and Social Stigma:**
  - Individuals may resist using visible or new assistive devices due to fear of social reactions.
- **Lack of Professional Identity Alignment:**
  - Medical professionals may be more familiar with pharmaceuticals than with assistive technologies.
- **Paternalistic Focus on Care Over Empowerment:**
  - Emphasis on care provision rather than enabling independence.
- **Limited Awareness and Accessibility of New Technologies:**
  - New methods are not widely known or accessible to those in need.

## 14. Acquiring information

### Acquiring Information

#### Goal:

- **Provide Reliable Information to People on Topics of Interest:**
  - Enable access to accurate observations and interpretations from various sources, including direct observations and information acquired from others directly or via media.

#### Qualitative Values:

- **Relevance:**
  - Usefulness of information for the specific situation or need.
  - Ability of information to help create situational awareness or assist in achieving objectives.
- **Credibility:**
  - Trustworthiness based on the source's authority, presentation, or experience.
  - Information trusted due to its practical nature or rhetorical effectiveness.
- **Surprising Nature:**
  - Element of novelty that stimulates curiosity.
  - Information prompting re-examination of threats and opportunities.

#### Means and Values of the Dominant Regime:

##### Current Means:

- **Organizational Gathering and Media Publication:**
  - Information is collected by organizations and published by traditional media outlets.
  - Trustworthiness is based on the reputation of organizations or individuals conveying the information.
- **Limited Direct Observations:**
  - Individuals rely primarily on their immediate sensory perceptions, mainly visual.
  - Acceptance of images and reports from media as if personally witnessed.
- **Certified Information Paradigm:**

- Emphasis on information verified and certified by authorities, experts, and institutions.
- Reliance on traditional media, research institutions, and bureaucratic sources.

#### **Values:**

- **Faith in Authorities:**
  - Trust placed in institutions, experts, and official sources.
- **Dependency on Established Sources:**
  - Habitual reliance on traditional media and official channels for information.
- **Information as Entertainment:**
  - Consumption of news and information as a form of leisure, focusing on distant problems not directly affecting daily life.

#### **Challenger Regime:**

##### **New Opportunities Enabled by:**

- **Digital Platforms and Peer-to-Peer Media:**
  - Immediate and widespread sharing of information through social media and online platforms.
  - Ability to reach others directly and compare observations.
- **Advanced Search Engines and Artificial Intelligence:**
  - Tools that help evaluate the truthfulness of messages.
  - Provision of localized and interest-specific search results.
- **Evolving Measurement Devices:**
  - Development and commercialization of advanced measurement tools accessible to individuals.
  - Optical, biomechanical, and electronic devices identifying materials, substances, and even DNA.
- **Artificial Intelligence in Interpretation:**
  - AI systems interpreting facial expressions, gestures, and emotions.
  - Crowdsourcing of images and data contributing to vast online resources.
- **Crowdsourced Information and Experiences:**
  - Sharing of observations, experiences, and peer reviews on services, goods, and environments.
  - Mapping and sharing of local resources like natural sites or routes.

#### **Values Promoting Change:**

- **Social Curiosity and Local Interest:**
  - Desire to learn about one's immediate environment and social circle.
- **Distrust Towards Authority Figures:**
  - Skepticism of official sources leading to independent information seeking.
- **Desire to Be Useful:**
  - Motivation to contribute by sharing information and assisting others.
- **Caution and Vigilance:**
  - Proactive seeking of information to mitigate risks and uncertainties.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Increased Relevance and Personalization:**
  - Access to current, localized information highly relevant to individuals.
- **Enhanced Understanding and Interaction:**
  - Direct information about others facilitating better social interactions.
- **Improved Quality and Credibility:**
  - Access to original sources, observations, and peer experiences.
- **Reduced Information Manipulation:**
  - Ability to choose information sources and methods reduces the impact of biased intermediaries.

### **Risks:**

- **Spread of False Information:**
  - Ease of creating and sharing misinformation, including fabricated content.
- **Echo Chambers and Information Bubbles:**
  - Risk of forming groups reinforcing inaccurate beliefs due to selective exposure.
- **External Interference:**
  - Potential for external parties to manipulate information flow for malicious purposes.
- **Difficulty in Interpretation:**
  - Individuals may lack skills to interpret observations correctly or assess source reliability.
- **Faulty Tools and Falsified Sources:**
  - Use of poor-quality devices or access to falsified "original" sources.

## **Inhibitors:**

- **Dependency on Existing Sources:**
  - Habitual reliance on established information channels.
- **Social and Cultural Norms:**
  - Pressure from social networks to conform to mainstream views.
- **Established Methods and Regulations:**
  - Standardized practices for information gathering and dissemination supported by authorities and public funding.
- **Technological Barriers:**
  - Limitations in access to advanced AI tools or language barriers in certain regions.

## 15. Proficiency and its proof

### **Proficiency and Its Proof**

#### **Goal:**

- **Ensure Required Proficiency and Its Demonstration:**
  - Provide individuals with the necessary procedural and systemic skills, the ability to see the big picture, and methods to prove their proficiency to others.

#### **Qualitative Values:**

- **Recognizability of Proficiency:**
  - Clear demonstration and acknowledgment of skills, knowledge, and understanding.
- **Understanding of Meanings:**
  - Comprehension of larger contexts, interactions, and the significance of tasks and information.
- **Procedural and Systemic Skills:**
  - Mastery of methods, processes, and systems through extensive practice and tendencies.
- **Contextuality:**
  - Ability to apply skills and knowledge effectively in various contexts as complexity increases.

- **Learning to Learn:**
  - Developing the capability to acquire new skills and adapt to changing knowledge requirements.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Educational Institutions:**
  - Education focusing on teachers, reading, and writing as primary providers of skills and understanding.
  - Emphasis on textbooks, lectures, exercises, and discussions as teaching methods.
- **Authorized Evaluation of Formal Learning:**
  - Degrees and qualifications issued by educational institutions as proof of proficiency.
  - Assessment of students by teachers, lecturers, and professors who are considered authorities in their fields.
- **Silo-Based and Reductionist Teaching:**
  - Specialized teaching methods focusing on specific disciplines without integrating broader contexts.
- **Dependence on Established Structures:**
  - Hiring practices heavily reliant on degrees and qualifications from recognized institutions.
  - Proficiency gained outside formal education often not formally recognized.

### **Values:**

- **Appreciation for Titles and Credentials:**
  - High value placed on degrees, titles, and formal qualifications.
- **Authority of Educational Institutions:**
  - Trust in traditional institutions to provide and assess proficiency.
- **Resistance to Change:**
  - Preference for established teaching methods and curricula.
  - Reluctance among educators to adopt new technologies or methods.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Information Technology and Online Learning:**
  - Access to learning materials and teaching situations regardless of time and location.
  - Availability of lectures, exercises, and courses online, both free and paid.
- **Simulation and Gamification:**
  - Use of simulators and gamified learning environments to facilitate trial-and-error learning.
  - AI providing feedback, correcting performance, and motivating learners.
- **Flipped Learning Models:**
  - Replacing traditional lectures with instructional videos for independent viewing.
  - Classroom time dedicated to exercises and group work under supervision.
- **Virtual and Augmented Reality (VR and AR):**
  - Enhancing understanding through immersive experiences and visual aids.
  - AR glasses facilitating hands-on learning by overlaying guidance in real time.
- **Competence-Based Qualifications:**
  - Assessing proficiency through demonstrated skills rather than course completions.
  - Use of certificates, peer evaluations, customer feedback, portfolios, and competitions.
- **Learning to Learn and Tool Proficiency:**
  - Emphasizing the importance of adaptability and the use of tools that reduce unnecessary learning.

#### **Values Promoting Change:**

- **Individual Advancement:**
  - Catering to students' interests and learning styles.
- **Direct Feedback and Motivation:**
  - Immediate responses from AI and simulations enhancing the learning process.
- **Flexibility and Accessibility:**
  - Learning opportunities available anytime and anywhere.
- **Modernization and Relevance:**
  - Rapid updating of content to keep pace with technological and societal changes.
- **Recognition of Diverse Proficiencies:**
  - Valuing skills acquired from various sources and contexts.



## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Enhanced Learning:**
  - Improved outcomes through personalized, engaging, and interactive methods.
- **Rapid Content Modernization:**
  - Ability to update educational content more quickly than traditional methods allow.
- **Diversification of Skills Learned:**
  - Exposure to a wider range of subjects and practical tools.
- **Elimination of Barriers:**
  - Reducing reliance on entrance exams and traditional degrees as life-determining factors.
- **Inclusion of Private Sector and On-the-Job Learning:**
  - Integrating real-world experience and industry practices into education.

### **Risks:**

- **Educators' Resistance or Lack of Skills:**
  - Potential unwillingness or inability among teachers to adopt new methods.
- **Quality Assurance Challenges:**
  - Ensuring the validity and reliability of competence-based qualifications and alternative assessments.
- **Potential Inequality in Access:**
  - Disparities in access to technology and resources required for new learning methods.
- **Overemphasis on Technology:**
  - Risk of neglecting foundational skills and critical thinking in favor of tool proficiency.

### **Inhibitors:**

- **Institutional Resistance:**
  - Deeply rooted educational cultures and structures resistant to change.
- **Location-Based Limitations:**
  - Physical institutions tied to specific locations may hinder widespread adoption of new methods.
- **Regulatory Barriers:**

- Regulations and accreditation processes favoring traditional educational pathways.
- **Value of Traditional Degrees in Hiring:**
  - Employers' continued preference for conventional qualifications.
- **Lack of Adequate Funding and Pedagogical Skills in Private Sector:**
  - Challenges in scaling private education efforts without necessary support.

## 16. Producing experiences

### Producing Experiences

#### Goal:

- **Provide People with Experiences:**
  - Offer intentionally created experiences for financial, political, military, ideological benefits, or social relationship purposes.

#### Qualitative Values:

- **Emotional Experiences:**
  - Evoking emotions through empathy or personal situations, sourced from stories, music, food, or other sensory perceptions and stimuli.
- **Joy of Realization and Self-Exceeding:**
  - The satisfaction from realizing something new or surpassing one's own limits.
- **Shared Experiences:**
  - Strengthening bonds by sharing experiences with important others, providing substance for interaction.
- **Creativity and Desire to Influence:**
  - Innovative creation of experiences and aspiration to impact others.
- **Sociability and Desire for Experiences:**
  - Human inclination towards social interaction and seeking new experiences.
- **Escapism:**
  - The appeal of virtual realities allowing individuals to escape real-life worries and limitations.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Traditional Entertainment and Art Forms:**
  - Production of experiences through cinema, literature, music, theater, architecture, design, and other arts.
- **Producer-Consumer Structure:**
  - Clear division between producers and consumers, relying on established methods of conveying experiences.
- **Institutional and Organizational Involvement:**
  - Organizations, political parties, companies, and other entities producing experiences for entertainment or ideological purposes.
- **Emphasis on Authenticity and Physical Presence:**
  - Valuing genuine, traditional experiences and physical engagement.
- **Inactivity and Consumer Passivity:**
  - Consumer passivity resulting from the producer–consumer divide.

### **Values:**

- **Preservation of Traditional Methods:**
  - Preference for established forms of experience production.
- **Resistance to Technological Integration:**
  - Reluctance to mix teaching and work with technologically based experiences.
- **Emphasis on Elite and Popular Content Division:**
  - Distinction between content for the general public and for the elite.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Technological Advancements:**
  - Time and location independence of experiences due to technological progress.
- **Digitalization and Democratization of Experiences:**
  - Access to experiences becoming more widespread and equitable.
- **Virtual Reality (VR) and Augmented Reality (AR):**
  - VR creating immersive virtual worlds with powerful experiences.
  - AR adding realistic illusions to the user's actual environment, enhancing real-world experiences.

- **Artificial Intelligence and Robotics:**
  - AI recognizing human emotions and preferences to tailor experiences.
  - Robots producing physical experiences such as gourmet cooking, art creation, massage, or playing musical instruments.
- **Interactive and Participatory Media:**
  - Computer games offering shared environments and stimuli for shared experiences globally.
- **Mission Experiences and Ethical Engagement:**
  - Experiences achieved through ethical missions, mobilizing people for shared purposes.

#### **Values Promoting Change:**

- **Creativity and Innovation:**
  - Desire to create novel experiences and influence others.
- **Desire for Sociability and Experiences:**
  - Human drive for social interaction and seeking diverse experiences.
- **Escapism and Self-Transformation:**
  - Utilizing virtual realities to transcend real-life limitations and worries.
- **Desire to Stand Out:**
  - Seeking unique, authentic experiences to differentiate oneself.

#### **Benefits, Risks, and Inhibitors of Change:**

##### **Benefits:**

- **Increased Participation and Activity:**
  - Participatory experiences inspire greater engagement and activity.
- **Skill Development:**
  - Simulation-based experiences enhance proficiency and turn passive knowledge into active skills.
- **Enhanced Social Skills and Planning Ability:**
  - Cooperation-oriented online games improve social interactions and planning capabilities.
- **Reduced Need for Physical Travel:**
  - Virtual reality immersion decreases the necessity for travel while increasing familiarity with distant places.
- **Expanded Job Opportunities:**
  - Experiences produced with robotized avatars and augmented reality lower transaction costs, creating new employment possibilities.

## **Risks:**

- **Addiction to Virtual Experiences:**
  - Powerful virtual experiences may lead to addictive behaviors.
- **Social Alienation:**
  - Forming strong bonds in virtual groups may lead to detachment from physical social environments, increasing the risk of conflict.
- **Manipulation and Misuse:**
  - AI and virtual technologies may influence desires and preferences without individuals' awareness, posing significant potential for misuse.

## **Inhibitors:**

- **Established Social Structures and Norms:**
  - Society's maintenance of traditional myths and valorization of conventional experiences.
- **Conservative Media and Education Systems:**
  - Media and educational institutions promoting appreciation for traditional forms of experiences, such as sports and classic arts.
- **Emphasis on Authenticity and Physical Presence:**
  - Preference for genuine experiences and physical engagement over technologically mediated experiences.

## 17. Safety and security

### **Safety and Security**

#### **Goal:**

- **Ensure Regularity of the Operating Environment:**
  - Provide freedom from external threats and enable individuals to pursue their goals within known and predictable ground rules.

#### **Qualitative Values:**

- **Due Care:**
  - Willingness to sacrifice some personal freedom and resources to minimize future risks.

- Accumulating wealth or resources as a precaution against unexpected events.
- **Fairness:**
  - Upholding material and intangible integrity.
  - Establishing shared ground rules and a balanced exercise of power.
- **Predictability:**
  - Need for regularity and stability.
  - Importance of planning and understanding potential outcomes.
- **Individual Responsibility:**
  - Proactive steps taken by individuals to ensure their own safety and security.
- **Awareness of Risks:**
  - Understanding and recognizing potential threats to mitigate them effectively.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Centralized Authorities and Institutions:**
  - Reliance on police, fire departments, defense forces, hospitals, and regulatory agencies.
  - Control measures targeting clear interfaces like borders, manufacturers, service providers, and standardized processes.
- **Periodic and Reactive Control Measures:**
  - Safety and security managed through periodic inspections and interventions.
  - Systems designed for stability in environments with slow or predictable changes.
- **Hierarchical Control Structures:**
  - Top-down approaches where authorities dictate safety protocols and responses.

### **Values:**

- **Normativity:**
  - Adherence to established norms, regulations, and procedures.
- **Trust in Authorities and Institutions:**
  - Dependence on public entities to provide safety and security.
- **Expectation of Societal Support:**
  - Belief that society will offer assistance and protection when needed.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Decentralization of Safety and Security Measures:**
  - Shifting responsibility closer to individuals due to changing threat landscapes and increased personal production capabilities.
- **Advanced Technologies and Artificial Intelligence:**
  - AI systems monitoring personal environments and warning of potential dangers.
  - Protection of personal data and devices from unauthorized access or manipulation.
- **Self-Diagnostics and Personal Monitoring Tools:**
  - Individuals accessing detailed information about personal health risks and the quality of consumed products.
- **Peer-to-Peer Information Sharing and Crowdsourcing:**
  - Real-time sharing of information about risks, threats, and regional dangers through collaborative networks.
- **Increased Individual Proactivity:**
  - Empowerment of individuals to take control of their safety through accessible technology and information.

### **Values Promoting Change:**

- **Heightened Risk Awareness:**
  - Growing understanding of diverse and emerging threats.
- **Desire for Experimentation and Innovation:**
  - Openness to adopting new technologies and methods to enhance personal security.
- **Distrust in Traditional Systems:**
  - Skepticism regarding the effectiveness of centralized authorities in addressing modern threats.
- **Empowerment and Autonomy:**
  - Seeking greater control and self-reliance in managing safety and security.

## **Benefits, Risks, and Inhibitors of Change:**

### **Benefits:**

- **Enhanced Individual Control Over Safety:**



- Ability to manage personal risks effectively using advanced tools and technologies.
- **Continuous and Proactive Protection:**
  - Ongoing safety measures implemented during actual use of products or services, rather than periodic checks.
- **Improved Situational Awareness:**
  - Access to real-time information through crowdsourced data, enhancing responsiveness to threats.
- **Adaptation to Dispersed and Evolving Risks:**
  - Decentralized approaches better suited to handle a wide range of emerging and dispersed threats.

#### **Risks:**

- **Increased Dependency on Technology:**
  - Reliance on technological solutions that may be vulnerable to failures or cyberattacks.
- **Privacy Concerns:**
  - Extensive monitoring and data collection potentially infringing on individual privacy.
- **Erosion of Trust in Institutions:**
  - Possible decrease in confidence towards authorities and societal structures.
- **Regulatory Challenges:**
  - Existing regulations may hinder the adoption of new safety measures or obstruct individual initiatives.
- **Overburdening Individuals:**
  - Placing excessive responsibility on individuals without adequate support or resources.

#### **Inhibitors:**

- **Continued Trust in Established Authorities:**
  - Reluctance to shift away from dependence on centralized institutions for safety.
- **Perception of Manageable Risks:**
  - Belief that new threats are not severe enough to necessitate significant changes.
- **Shared Responsibility Leading to Inaction:**
  - Diffusion of responsibility causing delays in addressing emerging risks.
- **Regulatory and Legal Barriers:**

- Laws and regulations not keeping pace with technological advancements, limiting innovation.
- **Lack of Awareness and Understanding:**
  - Insufficient recognition of the changing nature of threats and the need for structural adjustments.

## 18. Collaboration and trust

### Collaboration and Trust

#### Goal:

- **Increase Cooperativeness to Achieve Synergy Benefits:**
  - Enable individuals and organizations to collaborate effectively, producing greater outcomes than working alone.

#### Qualitative Values:

- **Transparency:**
  - Making needs, opportunities, and activities visible to all parties.
  - Strengthening faith in promised actions through openness.
- **Trust:**
  - Belief in shared benefits and mutual advantage.
  - Building trust based on transparency, shared goals, and mechanisms like reputation systems.
- **Risk Management:**
  - Coordinating inputs and outputs to mitigate risks associated with collaboration.
  - Implementing measures to minimize potential losses from breaches of trust.

#### Means and Values of the Dominant Regime:

##### Current Means:

- **Hierarchical Trust and Cultural Norms:**
  - Reliance on authorities to control production and trade.

- Use of contracts, guarantees, and legal systems to enforce agreements.
- Belief in products and services as described due to regulatory oversight.
- **Monitoring by Public Authorities:**
  - Regulatory compliance enforced by governmental agencies.
  - Financial sector monitoring solvency and credit practices.
  - Public authorities controlling and certifying collaborations, identifying needs for sanctions.

#### **Values:**

- **Justice System and Hierarchical Decision-Making:**
  - Trust placed in formal institutions and legal frameworks.
  - Emphasis on top-down control and decision-making processes.
- **Nationalism and Privacy Protection:**
  - Preference for national regulations and protection of personal data.
  - Limitation on the accumulation of trust-impacting information due to privacy concerns.

#### **Challenger Regime:**

#### **New Opportunities Enabled by:**

- **Digital Platforms and Globalization:**
  - Purchasing products and services through online platforms from international entities and individuals.
  - Engaging in projects with diverse people online, sharing information across platforms.
  - Funding collaborative projects through crowdfunding instead of traditional financial avenues.
- **Peer-to-Peer Trust Mechanisms:**
  - **Reputation Economy:**
    - Parties use their reputation as collateral, increasing trust based on successful interactions.
    - Feedback systems like customer evaluations, ratings, and reviews enhancing credibility.
  - **Transparency and Feedback Systems:**
    - Open operating methods, including real-time updates and quality certifications.
    - Platforms providing credible feedback to potential customers (e.g., customer reviews).
  - **Blockchain Technology:**

- Decentralized systems certifying transactions, removing the need for trusted third parties.
  - Enhancing transparency and trust by allowing verification of authenticity and origin.
- **Crowdfunding and Crowdsourcing:**
  - Funding collaborative projects through collective contributions from interested individuals.
  - Emergence of alternative financing methods beyond traditional banking and investment activities.

### **Values Promoting Change:**

- **Globalization:**
  - Openness to cross-border collaboration and embracing a global community.
- **Communality and Openness:**
  - Desire for shared experiences and transparent interactions.
- **Desire for Innovation and Ease:**
  - Embracing new technologies and methods that simplify collaboration and foster innovation.

### **Benefits, Risks, and Inhibitors of Change:**

#### **Benefits:**

- **Reduced Transaction Costs:**
  - Automation and peer-to-peer trust reduce costs associated with hierarchical and traditional trust structures.
  - Decreased need for intermediaries lowers expenses in collaborative efforts.
- **Improved Quality and Incentives:**
  - Reputation systems incentivize higher quality from sellers, collaborators, and customers.
  - Enhanced accountability leads to better overall performance.
- **Increased Transparency:**
  - Easier identification and assessment of potential collaborators.
  - Open access to information builds confidence in collaborative relationships.
- **Access to Funding and Resources:**
  - Crowdfunding allows innovative ideas to secure funding without reliance on traditional financial institutions.

- Greater opportunities for projects that might not fit conventional funding criteria.
- **Enhanced Collaboration:**
  - Crowdsourcing improves the quality and diversity of information and solutions.
  - Large-scale participation leads to more productive and innovative outcomes.

#### **Risks:**

- **Fraud and Scams:**
  - Potential for pyramid schemes and untrustworthy operators misrepresenting their activities.
  - Increased vulnerability to fraudulent practices in decentralized systems.
- **Conflicts with Regulations:**
  - International platform activities may conflict with national laws and regulations.
  - Legal uncertainties can hinder the adoption of new collaborative methods.
- **Lack of Systematic Control:**
  - Decentralized trust mechanisms may lack oversight, leading to errors and misuse.
  - Absence of centralized authority can result in difficulties in enforcing agreements.

#### **Inhibitors:**

- **Slow Trust Building:**
  - Trust in new platforms and systems develops gradually over time.
  - Reluctance to engage with unfamiliar entities slows adoption.
- **Preference for Familiar Organizations:**
  - Tendency to trust established organizations over new or unknown ones.
  - Comfort with traditional methods inhibits willingness to try new approaches.
- **Customs and Habits:**
  - Resistance to adopting new practices due to ingrained habits and cultural norms.
  - Established routines and expectations favor existing systems.
- **Regulatory Barriers:**
  - Existing laws and regulations favor traditional methods and may impede innovation.

- Compliance requirements can be challenging for new platforms to navigate.
- **Privacy Regulations:**
  - Data protection laws complicate the decentralization of trust structures.
  - Restrictions on information sharing can limit transparency and collaboration.

## 19. Existential meaning

### Existential Meaning

#### Goal:

- **Enable Individuals to Experience Meaningfulness in Their Existence and Actions:**
  - Foster a sense of purpose and significance in one's life and contributions.

#### Qualitative Values:

- **Self-Realization:**
  - Pursuit of personal growth through external appreciation, pleasures, or status.
  - Engaging in actions aligned with one's calling or passions.
- **Serving Others:**
  - Contributing to the well-being of others and feeling useful within a greater entity.
- **Participation in a Grand Narrative or Mission:**
  - Identifying with group identities that provide a larger purpose.
  - Feeling part of a story or mission that transcends individual existence.
- **Sense of Belonging:**
  - Building connections within local or online communities.
  - Sharing experiences and achievements with like-minded individuals.
- **Achievements and Exceeding Limits:**
  - Experiencing joy from realizing new accomplishments or surpassing personal boundaries.

## **Means and Values of the Dominant Regime:**

### **Current Means:**

- **Work and Professional Identity:**
  - Defining existence through professional roles rather than family, religion, or locality.
  - Motivation through job titles, degrees, and financial compensation.
- **Hierarchical and Specialized Work Structures:**
  - Work that is narrow in scope, tied to specific locations, and influenced by hierarchy.
  - Limited opportunities to influence work content or see its broader impact.
- **Peer Appreciation and Status Seeking:**
  - Seeking validation and significance through professional peer groups.
  - Emphasis on external markers of success and status.
- **Hedonistic and Individualistic Values:**
  - Finding meaning in personal pleasures and immediate social circles.
  - Manifesting self-centeredness and potential intolerance.
- **Voluntary Work in Traditional Organizations:**
  - Participation in associations, political parties, recreational groups, and religious institutions.
  - Deriving meaning from communal activities and causes.

### **Values:**

- **Fear of Change:**
  - Resistance to altering established roles and structures.
- **Desire for Comfort and Stability:**
  - Preference for maintaining the status quo to avoid uncertainty.
- **Pursuit of Achieved Status:**
  - Valuing current positions and societal recognition.
- **Societal Pressure and Conformity:**
  - Adherence to societal expectations and norms.

## **Challenger Regime:**

### **New Opportunities Enabled by:**

- **Digitalization and Robotization:**



- Creation of comprehensive work roles focused on meaningful contributions.
- Performing work for one's own community via digital networks or locally.
- **Measurement and Gamification of Work:**
  - Increasing meaningfulness through clear performance metrics and engaging methods.
- **Shift Towards Local and Online Communities:**
  - Re-establishing the local community as a primary peer group.
  - Facilitating meaningful connections through the internet.
- **Virtual and Augmented Reality:**
  - Constant contact with important individuals as if sharing the same space.
  - Enhancing social interactions and shared experiences.
- **Social Media and Global Sharing Platforms:**
  - Allowing individuals to share achievements and creations with a worldwide audience.
  - Easily finding and connecting with like-minded people.
- **New Forms of Self-Expression and Purpose:**
  - Engaging in activities like developing artificial intelligence, building virtual worlds, or achieving recognition in online communities.
- **Participation in Global Causes:**
  - Involvement in solving global problems with visible impacts.
  - Collaborating with others who share similar values and methods.

#### **Values Promoting Change:**

- **Rebelliousness and Innovation:**
  - Challenging traditional structures and embracing new ideas.
- **Desire for Achievements:**
  - Seeking personal accomplishments and recognition beyond traditional metrics.
- **Participation in a Grand Story:**
  - Engaging in meaningful narratives that provide a sense of purpose.
- **Community Building:**
  - Forming connections in online or local communities irrespective of geographical constraints.
- **Desire for Personal and Collective Growth:**
  - Pursuing self-improvement and contributing to larger goals.

#### **Benefits, Risks, and Inhibitors of Change:**

## Benefits:

- **Increased Meaningfulness of Work:**
  - Enhanced satisfaction when work benefits and is appreciated by those within one's group identity, including customers or beneficiaries.
- **Enhanced Motivation and Fulfillment:**
  - Clearer performance metrics and comprehensive roles leading to greater personal fulfillment.
- **Greater Autonomy and Choice:**
  - Ability to choose communities and activities that align with personal values and interests.
- **New Avenues for Self-Expression:**
  - Opportunities to share creativity and achievements on a global scale through digital platforms.
- **Strengthened Community Bonds:**
  - Building deeper connections with like-minded individuals, fostering a sense of belonging.

## Risks:

- **Difficulty in Transitioning:**
  - Rigid structures and uncertainties in the job market making it challenging to shift to more meaningful positions.
- **Unfulfilled Expectations:**
  - Potential for disappointment if new roles or communities do not meet personal expectations, leading to frustration.
- **Potential for Negative Influences:**
  - Risk of individuals being drawn into destructive communities or ideologies when seeking purpose.
- **Misalignment with Societal Norms:**
  - Pursuits of meaning that may not align with broader societal values, leading to conflict or isolation.

## Inhibitors:

- **Fear of Losing Stability:**
  - Reluctance to give up current positions and income for uncertain future opportunities.
- **Attachment to Existing Structures:**
  - Deep-rooted symbolic meanings associated with traditional roles and identities.
- **Need for Systemic Change:**

- Challenges in creating new meanings without widespread shifts in societal structures.
- **Support of Traditional Models by Dominant Regime:**
  - Existing systems favoring established hierarchies and resisting change.

## 20. Power structures

### Power Structures

#### Goal:

- **Optimize Joint Decision-Making Within Organizations:**
  - Combine diverse interest groups' objectives to function purposefully in decision-making processes.

#### Qualitative Values:

- **Productivity:**
  - Efficient relationship between the objectives and sacrifices of interest groups.
- **Cooperativeness:**
  - Ability of decision-making to organize productive joint activities.
- **Equality:**
  - Fair consideration and treatment of all interest groups' needs and objectives.

#### Means and Values of the Dominant Regime:

##### Current Means:

- **Hierarchical Organizational Structures:**
  - Power organized through delegation of responsibilities within financial hierarchies or control matrices.
- **Geographically-Based Public Authority:**
  - Governance divided into municipalities, regions, states, and unions based on geography.
- **Structural Power Held by Elite Groups:**

- Political parties, management elites of large companies, bureaucracies, advocacy groups, and media wield significant power.
- **Extensive Legislation and Control Mechanisms:**
  - Complex regulations and control systems increase management requirements, often favoring larger organizations.
- **Emphasis on Traditional Decision-Making Processes:**
  - Focus on centralized authority figures and established norms in making decisions.

#### **Values:**

- **Conservatism:**
  - Preference for traditional structures and resistance to change.
- **Normativity:**
  - Adherence to established norms, regulations, and procedures.
- **Focus on Hierarchical Authority:**
  - Belief in centralized decision-making and top-down control.

#### **Challenger Regime:**

##### **New Opportunities Enabled by:**

- **Digitalization and Automation:**
  - Freeing decision-making from time and location constraints.
  - Automating routine administrative tasks and simple decision-making processes.
- **Decentralization and Subject-Based Administration:**
  - Applying the subsidiarity principle based on subject matter rather than geography.
  - Establishing independent, competing administrations for tasks not tied to a specific location.
- **Platform Cooperatives and Networks:**
  - Member-managed bodies organizing joint administration and services through data networks.
  - Platforms handling assignments, feedback, communication, accounting, and supervision.
- **Revised Demarcation Between Markets and Hierarchies:**
  - Managing natural monopolies hierarchically and competitive matters through markets.
  - Technological advancements altering the suitability of matters for market or hierarchical management.

- **Utilization of Artificial Intelligence and Crowdsourcing:**
  - Implementing administrative regulations via AI, gamified systems, simulation, and crowdsourcing.
  - Enhancing efficiency and customization in administration.

#### **Values Promoting Change:**

- **Comparativeness:**
  - Encouraging comparison between different administrative approaches.
- **Interchangeability:**
  - Flexibility to choose between different service providers or administrative bodies.
- **Openness:**
  - Transparency in decision-making processes and structures.
- **Choice and Competition:**
  - Allowing stakeholders to select among competing administrations, fostering innovation and efficiency.

#### **Benefits, Risks, and Inhibitors of Change:**

##### **Benefits:**

- **Increased Expertise in Decision-Making:**
  - Subject-based decision-making enhances relevance and quality of decisions.
- **Democratization and Subsidiarity:**
  - Empowering those directly affected by decisions to participate more fully.
- **Improved Quality of Decisions:**
  - Better information gathering through crowdsourcing and automation.
- **Flexible Control Mechanisms:**
  - AI and interactive platforms enabling more responsive administration.
- **Freedom of Choice and Innovation:**
  - Competing administrations encourage experimentation and higher quality services.

##### **Risks:**

- **Increased Costs:**
  - Potential duplication of administrative efforts leading to higher expenses if economies of scale are present.
- **Confusion and Complexity:**

- Voters may be overwhelmed by having to elect multiple decision-makers for different sectors.
- **Inequality:**
  - Uneven implementation of competing administrations could lead to disparities.
- **Resistance to Change:**
  - Long-standing traditions and legal frameworks may hinder adoption of new structures.

#### **Inhibitors:**

- **Administrative Tradition:**
  - Deep-rooted practices and difficulty in conceptualizing alternative systems.
- **Legal and Structural Barriers:**
  - Existing laws and regulations embedding current divisions of responsibility.
- **Lack of Awareness and Discussion:**
  - Alternative models not well-known or debated at a conceptual level.
- **Comfort with Existing Systems:**
  - Preference for familiar democratic processes and reluctance to embrace new models.

## Attachment 6. Maturity and impact scoring criteria

This attachment presents the scoring rubrics used in the present report for assessing the maturity of anticipated radical technologies (ARTs) and their impacts across global value-producing networks (GVNs). The rubrics below reproduce, in operational form, the scoring logic used in the project's AI-assisted analysis: a seven-level maturity scale for ARTs and a logarithmic impact scale for ART–GVN pairings.

A more comprehensive account of the conceptual background of this scoring logic can be found in the 2022 *European Journal of Futures Research* article on the Radical Technology Inquirer methodology (Linturi et al. 2022). This article explains in greater detail how ARTs and GVNs are defined, how ART maturity is assessed on a seven-step scale, how GVN-specific impact scores are assigned on a strongly logarithmic basis, and how total ART significance is formed by combining impacts across GVNs with maturity.

Linturi *et al.* Radical Technology Inquirer: a methodology for holistic, transparent and participatory technology foresight. *Eur J Futures Res* **10**, 18 (2022).  
<https://doi.org/10.1186/s40309-022-00206-6>

### Maturity score

Assign ONE maturity score from 1 to 7 for the ART as a whole, using the following definitions:

- 1) The scientific principle enabling the breakthrough has been proven possible as a theoretical model, published by a reliable research institute; the observation is recent and there is academic interest.
- 2) The scientific model has been verified with concrete laboratory testing; the operating principle is demonstrated in a peer-reviewed publication; research groups are funded; progress is occurring.



3) A laboratory prototype has been demonstrated; it shows a key previously-blocking material/technical problem has been solved and necessary functionality achieved; production cost/durability issues may remain; academic or commercial motivation is clear.

4) PoC (Proof of Concept): A functional prototype has been scientifically or commercially demonstrated as meeting commercialization requirements in functionality and viability for production. It clearly exceeds previous solutions in benefit OR is plausibly lower-cost at scale. Progress is recent and clear.

5) Several well-capitalised market actors are competing to develop a production prototype post-PoC, OR a production prototype is clearly in the finishing phase with investments made to launch production; progress is fast-paced.

6) Products are being delivered to customers in increasing amounts; economies of scale are expected to reduce prices considerably; application areas are expanding; R&D is at least partly internally financed; expansion of production has been clearly financed; progress is recent.

7) Competing products are being delivered and customer demand is rising; competition is significantly internally financed; growth is financed by major industrial companies, wide clientele, or venture capitalists; product-property development has significant known potential.

If the ART comprises multiple technologies at different stages:

- If their areas of application deviate significantly and the benefit is divided among different technologies, use an average-based score and explain it.

- If the functionality is largely the same across variants, you may use the maximum value, and explain why.

# Impact scoring

## RUBRIC ANCHORS (LOOSE, ORDER-OF-MAGNITUDE)

0 = No plausible or meaningful impact on this GVN's goal/operating model (or no clear linkage).

1 = Concrete, non-trivial impact that makes the ART worth considering for this GVN (limited scale; could be beneficial or harmful).

3 = Material impact on a value related to the GVN's goal OR materially shifts goal attainment.

Anchor (annual, for ~5.5M society): ~€10–100 million OR ~5–50 million person-hours affected.

5 = Significant impact on a value related to the GVN's goal OR an important part of a whole that changes goal attainment substantially.

Anchor (annual, for ~5.5M society): ~€100–1,000 million OR ~50–500 million person-hours affected.

10 = Transformative impact (as described in the GVN text) on HOW the GVN goal is realised (including transformative disruption).

Anchor (annual, for ~5.5M society): >~€1 billion OR impacts the weekly everyday life of hundreds of thousands of people.

20 = Keystone impact: the ART is a necessary part of, or drastically increases, the most important transformative shift (or disruption) of the GVN operating model.

Anchor (annual, for ~5.5M society): >~€1 billion OR impacts the weekly everyday life of hundreds of thousands of people.

Use 20 sparingly (only if it is a linchpin, not just helpful).

## SCORING DISCIPLINE

- If uncertain between adjacent scores, pick the LOWER and state the key assumption needed to justify the higher score.
- Avoid invented precision. If you use € or person-hours, keep it rough and clearly assumption-based.



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