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EYES ON THE FUTURE

Signals from recent reports on emerging technologies and breakthrough innovations to support European Innovation Council strategic intelligence

VOLUME 3

EU Policy Lab

JRC SCIENCE FOR POLICY REPORT

EMERGING TECHNOLOGIES

DISRUPTIVE INNOVATION

STRATEGIC FORESIGHT

Joint Research Centre

EUR 40424

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Volume 3

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This report is part of the project FUTURINNOV, (FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation), a collaboration between the European Commission's (EC) Joint Research Centre (JRC) and the European Innovation Council (EIC), the EC's flagship programme for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

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Contents

Abstract

This literature review is part of the FUTURINNOV project–a collaboration between the European Commission’s Joint Research Centre and the European Innovation Council and SMEs Executive Agency—, which aims at spotting signals of emerging technologies and some breakthrough innovations.

This literature review report presents the process and the results of a horizon scanning exercise, focusing on signals based of emerging technologies developed by non-EU countries. It summarises findings through a final selection of 30 signals and trends clustered according to the 10 critical technology areas defined by the European Commission, as well as through other frameworks such as the Strategic Technologies for Europe Platform and the EIC’s portfolios and specific taxonomy. The report identifies topics, including climate-adaption tech, neurotech, digital and network security and critical raw materials, as areas deserving of further research and development.

The report provides insights for the EIC and the readers to anticipate technological developments and address potential security concerns, ensuring the EU's position at the forefront of global innovation.

Executive summary

Project context

This report is developed in the context of the project FUTURINNOV (FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation), a collaboration between the European Commission's Joint Research Centre (JRC) and the European Innovation Council (EIC), aiming to support the EIC in building strategic intelligence capacity via foresight and other anticipatory approaches.

The report offers insights that can inform the prioritisation of funding for novel, emerging and close-to-market technologies for the EIC, the European Commission's flagship programme for emerging deep tech and breakthrough innovation, implemented by the EIC and SMEs Executive Agency (EISMEA).

As part of a workstream to surface cross-sector emerging technologies and breakthrough innovations the JRC carries out literature reviews. This report is the third literature review in the context of FUTURINNOV, centred on a new set of trends and signals, and with a region-specific context, focusing on non-EU developments. The report aims to provide actionable insights for funding decisions, particularly in areas of relevance to EU economic security, as well as technical domains of general high uncertainty and complexity.

Policy context

The literature review focusses on the EU's 10 critical technology areas, set out in the European Commission's Recommendation (EU) 2023/2113 of 3 October 2023 on critical technology areas for the EU's economic security for further risk assessment with Member States (see Annex 2 for more details). Moreover, in the context of recent geopolitical developments, the concept of technological sovereignty —referring to efforts to reduce Europe's reliance on technologies, services and products originating from the US, China and others— is gaining more attention. Thus, this report is particularly relevant because it focuses on emerging technologies in non-EU countries.

Methodology

Investing in technology, particularly in largely unexplored and uncertain domains, poses s challenge for many organisations. Technology foresight uses structured processes and gathers evidence to address this challenge. This report offers insights into areas where uncertainty often exceeds current knowledge.

The methodology used in this study is a six-step iterative process. It begins with a horizon scan and review of more than 50 reports and websites. Over 1300 technology signals were considered in this process, of which 80 were long-listed, 46 short-listed, and 30 selected for this report. The assessment was done internally and based on novelty and impact as criteria for selection.

Main findings and conclusions

The analysis of the 30 selected signals identifies key areas for potential EIC portfolio expansion or cross-domain challenges, notably in climate-adaptation, neurotechnology, digital security, and critical raw materials.

Many signals point to scaling existing technologies with high potential to enhance EU capabilities. Examples include drought-resistant crops, brain-swarm interfaces, federated AI, and quantum encryption. Advances in mineral exploration and material recovery also support supply resilience. These signals suggest that incremental innovation can drive strategic advantage and complement breakthrough efforts.

Investing in these domains could help address climate resilience, digital sovereignty, and technological autonomy, warranting further R&D&I and cross-thematic policy attention.

1 Introduction

1.1 Report context and goals

This report is developed in the context of the project FUTURINNOV - FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation. The project is a collaboration between the European Commission's Joint Research Centre (JRC) and the EIC, the European Commission's flagship programme for emerging deep tech and breakthrough innovation, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA). The JRC's mission is to provide evidence-based advice to policy, which includes anticipation and technology foresight.

FUTURINNOV is the second such collaboration between the JRC and the EIC[1]. It supports the EIC in building strategic intelligence capacity via foresight and other anticipatory approaches. In this way, it addresses activities focused on funding targets, programme design, policy feedback, and institutional governance.

The current report is the third literature review published in the context of the FUTURINNOV project. Volume 1 (Bailey, Farinha, Mochan, & Polvora, 2024) was published in June 2024 containing 34 signals and a brief qualitative analysis. Volume 2 (Farinha, Mochan, Riveong, Bailey, & Polvora, 2024) published in October 2024 is centred on 30 trends and signals which connect to the 10 critical technology areas set out by the EU (see Annex 2).

Following the publication of the two previous literature review volumes, the JRC and EIC agreed to capture signals from third-party reports outside the EU and connect them to the EU's 10 Critical Technology Areas (see Annex 2). The aim is not to provide a full illustration of the most significant developments expected in those areas, but rather to provide examples that highlight the current diversity of emerging technologies and some breakthrough innovations.

The analysis can inform priority-setting from novel (TRL[2] 1 to 3) to emerging (TRL 4-6) and close-to-market (TRL 7 to 9) deep tech and innovation. The authors' understanding is that novelty can occur at all maturity levels, in particular if we look at innovative combinations of established technologies or incremental innovation.

This report aims to support the EIC in answering questions such as:

— Which of these signals should be on the EIC's radar for anticipatory intelligence?

— Which signals imply a likely impact on and criticality for the EU's future?

— Which signals are indicative of strategic innovation being built up outside the EU?

Chapter 2 provides a complete explanation of the process. For the current report, the authors have:

— Continued to feed the project's internal database of more than 1300 signals signals via this literature review as well as the horizon scanning exercises. Out of

[1] The previous collaboration with the EIC was framed under the project ANTICIPINNOV - Anticipation and monitoring of emerging technologies and disruptive innovation. In this context three reports were published: a literature review on 3rd party reports (Farinha, Vesnic-Alujevic, Alvarenga, & Polvora, 2023); a summary of the horizon scanning exercises (Farinha, Vesnic-Alujevic, & Pólvora, 2023) and a report on methods and best practices for technology foresight (Dannemand Andersen, et al., 2023).

[2] Technology Readiness Levels (TRL) serve as a system for evaluating the development stage of a specific technology. Every technology project undergoes assessment according to the criteria established for each level, resulting in the assignment of a TRL score that reflects the project's advancement. The scale comprises nine levels, with TRL 1 indicating the earliest stage of development and TRL 9 representing the most advanced stage.

these signals, 80 were long-listed, 46 short-listed and 30 selected for this report.

- Reviewed reports and websites, ranging from general to sector-specific and specialised sources, supplemented by dozens of scientific articles.
- Connected the selected signals with the EU's list of 10 critical technology areas [3] (Commission Recommendation (EU) 2023/2113 of 3 October 2023 – see Annex 2 for more details); the three target investment areas of the Strategic Technologies for Europe Platform (STEP) initiative[4] (Regulation (EU) 2024/795 of the European Parliament and of the Council of 29 February 2024 - see Annex 3 for more details); the 11 EIC portfolios and the new EIC taxonomy.
- Analysed the signals and drawn conclusions to support the EIC's funding prioritisation and additionally, provide reflections on EIC portfolio setting.

1.2 Background

This literature review (1) draws on and evaluates reports on emerging technologies outside of the EU, (2) provides technology signals based on the 10 critical technologies area list and (3) analyses the impact, novelty, maturity, and significance of these technology signals. By analysing innovations beyond the EU, this review aims to highlight disruptive emerging technologies that could be relevant for the EU's strategic planning and security.

The review underscores the importance of scanning for global technological advancements outside the EU to maintain a competitive edge and attain technological sovereignty. Innovations in the 10 critical technology areas such as artificial intelligence, quantum computing, and advanced materials are rapidly evolving, with significant developments occurring in regions such as North America and Asia. These advancements not only drive economic growth but also have profound geopolitical implications, influencing global power dynamics and security landscapes.

By evaluating the novelty and significance of these technology signals, the review provides insights into their potential impact which could support discussions on the advancement of technological sovereignty in the EU. This analysis is crucial for the EIC to anticipate technological developments and address potential security concerns. Understanding the competitive landscape will enable the EU to prepare for and adapt to emerging technological trends, ensuring its position at the forefront of global innovation.

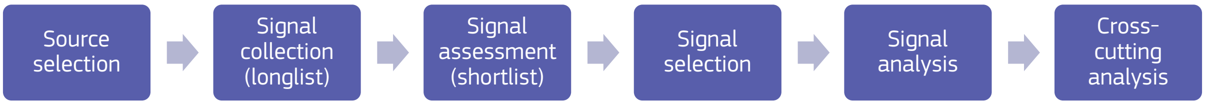
[3] The 10 critical tech areas are: advanced semiconductors technologies; artificial intelligence technologies; quantum technologies; biotechnologies; advanced connectivity, navigation and digital technologies; advanced sensing technologies; space & propulsion technologies; energy technologies; robotics and autonomous systems; and advanced materials, manufacturing and recycling technologies. See Annex 2 for more details.

[4] The 3 target investment areas are: digital technologies and deep tech innovation; clean and resource efficient technologies; and biotechnologies. See Annex 3 for more details.

2 Methodology

The methodology used in this literature review is a six-step iterative process, as outlined in Figure 1. Each of the six steps can be reiterated; however, the three initial steps were the most frequently iterated, as further explained and detailed in the decision tree (see Annex 4).

Figure 1. Simplified diagram of the method used in this literature review. See Annex 4 for more details regarding the collection, assessment, and selection steps.



Source: Authors.

2.1 Source selection and signal collection (longlist)

The literature review process began by gathering reports through online search engines and scientific and innovation news feeds that could provide signals, or a manifestation of novelty, covering all 10 critical technology areas (see Annex 2).

Beyond this main criterion, the signals were selected based on the following criteria:

— Stemming from technologies and innovations being developed *outside* of the EU.

— Relevance to the mission of the EIC and fitting within at least one of the 11 primary categories of the new EIC taxonomy (see Annex 1);

— Relevance to EIC funding mechanisms, namely Pathfinder, Transition and Accelerator[5], considering information on the TRL or an initial qualitative assessment of the maturity of the signal;

— Technology signals that demonstrate novelty or contain novel aspects which may enable or accelerate the development of other emerging technologies or innovations.

Preference was given to sources that contained/provided the following:

— Technology signals which had the potential to be strategically important to their region of origin;

— Recent publications, with an emphasis on sources published between 2022 and 2024;

— References to published scientific research that could attest the technological development or innovation breakthrough

The project's internal database of over 1300 signals[6] was also supplemented throughout this exercise. From this step, 80 long-listed signals were selected and added to this database. There were signals already in the database which were checked regarding their relevance for this literature review.

[5] For more information on the specificities of each mechanism, check: https://eic.ec.europa.eu/eic-funding-opportunities_en

[6] Approximate number of signals in the project database, collected between October 2023 and August 2024.

2.2 Signal assessment (shortlist)

The signals were then short-listed from 80 signals to 46 signals based on an internal evaluation[7] of impact and novelty. The impact and novelty of each signal was scored based on a score of 1-5, with 5 being the most impactful and novel. The novelty dimension refers to the signal's uniqueness, meaning the probability of containing developments that are unknown to the wider public, independent of the maturity level of the technologies behind it[8]. The novelty dimension was accorded lower priority than the impact dimension, as the emphasis was on spotting region-based strategic innovations.

Every signal collected for this literature review was entered into the internal database built specifically for FUTURINNOV and categorised according to several dimensions, with the following being particularly noteworthy:

- Connection with one or more critical technology areas;
- Connection with EIC PM Portfolios;
- Connection with the EIC Taxonomy;
- Region-based strategic importance;
- Maturity.

Regarding maturity, a signal was assigned 'novel' (TRL 1-3) status when it was mostly only referenced in a recent academic article. The signal was assigned 'emerging' (TRL 4-6) status when it was referenced in publications, with references to early pilots and still facing technology development challenges. The signal was assigned 'close-to-market' (TRL 7-9) status when examples of mature pilots or demonstrations were available. Overall, a signal was categorised based on Research, Development and Innovation (R&D&I) developments that were either mentioned in the sources or identified through additional research.

2.3 Signal selection

The sources for the final 30 selected technology signals (detailed in Chapter 3) were complemented by dozens of scientific articles or innovations, that were either quoted in those initial sources or were considered important by the authors for cross-checking and understanding certain aspects of the technologies and innovations.

For this selection process, in addition to the authors use of the internal qualitative review process to assess the short-listed signal's impact and novelty, each signal's impact was also framed in the context of geopolitical impact. The geopolitical dimension reflects the likelihood that a signal embodies technological advancements capable of giving a region a competitive edge—whether by enabling it to act as a first mover, achieve rapid scale, or reduce external dependencies.

To ensure a complete evaluation, it was important that each of the 10 critical technology areas had at least 1 signal. Finally, to ensure diversity, it was important to avoid where possible referring more than once to the same enabling technologies or combination of enabling technologies applied in the same field. Annex 4 contains a summary of the decision

[7] This evaluation was conducted by the authors that although not experts on specific technological and innovation fields have developed generalist know-how to qualitatively and preliminarily assess trends and signals of emerging technologies and breakthrough innovations. When needed to perform the assessment, the authors consulted additional references and external experts.

[8] As mentioned in the introduction, it's the authors understanding that novelty can appear at all stages of technology maturity, namely by combining through innovative means already known technologies and by expanding those to new application fields or through new business models.

tree and process flow.

2.4 Signal analysis and cross-cutting analysis

The last two steps of the methodology include:

- Signal analysis: additional background research of each individual signal, providing insights that highlight its geopolitical relevance;
- Cross-cutting analysis: an analysis of signals within each critical technology area as well as complementary information regarding some key technologies (see introductions to Chapters 3.1-3.10 and Boxes 1 to 10), complemented with a cross-cutting analysis across all selected signals (see Chapter 4).

2.5 Additional remarks and limitations

This methodology is qualitative and exploratory by design, reflecting an initial step in identifying promising trends and signals following the steps and criteria described above.

While systematic, it remains interpretative and dependent on further expert judgement. The results do not intend to be exhaustive, but rather to inform and invite further validation, refinement, and discussion by subject-matter experts and policy makers.

As mentioned in Volumes 1 and 2, it is worth noting that many of the types of 3rd party reports referenced in the first literature review conducted by the JRC for the EIC (Farinha, Vesnic-Alujevic, & Pólvora, 2023) have become too generic for the purposes of this project.

For this cycle of literature reviews, novelties were more effectively surfaced when investigating sector-specific reports (published with a focus on a single domain or industry) and, to a greater extent, journal articles and scientific studies.

This highlights the need to go beyond the numerous generic technology foresight reports (and most importantly beyond press releases) published by a significant number of organisations today, which often contribute to inflated hype cycles — a phenomenon certain technologies undergo. The authors acknowledge this risk and emphasise that their aim is to surface specific breakthrough applications that may not yet be widely known by most policymakers.

Therefore, and as mentioned before, in addition to the original sources, a significant number of scientific and news articles as well as other documented sources (all referenced in the section References) were used to verify and describe the signals and trends.

3 Selected signals

The following subsections present the 30 signals organised by the 10 critical technology areas. When a signal relates to more than one area, it has been filed under the most significant one.

The introduction to each subsection includes a brief summary of the novelties found across these signals, their potential geopolitical importance, as well as additional information (in boxes), that the authors consider important for a non-expert reader.[9]

Table 1. Summary list of key signals presented in the following pages.

Critical Tech Area (main)	Signal number and title	
Advanced semiconductors technologies	01	Researchers in China develop 12-inch one-atom thick (2D) wafers for more efficient, higher performance chips
	02	U.S.-based company aims to boost speeds of existing CPU and GPU through industry's first in-package silicon photonics chiplets
	03	Japan-based researchers develop highly energy efficient extreme ultraviolet (EUV) lithography
Artificial intelligence technologies	04	Researchers at Chinese university develop new AI-powered tool which can diagnose multiple cancers using a drop of dried blood
	05	U.S and South Korea employing federated approaches to AI for improved privacy and energy efficiency
Quantum technologies	06	China develops largest known integrated quantum key distributed (QKD) network, creating potentially unhackable encrypted communications
	07	Singaporean-researchers develops skyrmion-based memory technology for extremely low-power devices
	08	South Korean developer achieves first demonstration of chemical accuracy on commercially available quantum computers

[9] The AI-generated images accompanying each signal are conceptual illustrations, intended to provide an abstract visualisation of the technologies and ideas they represent. These images are in no way intended to depict precise or factual representations.

Critical Tech Area (main)	Signal number and title	
Biotechnologies	09	Organoid intelligence opens a new potential path in the computing race
	10	Developing industrial-scale microbiome mining for drug and material discovery in the U.S.
	11	Brazil develops natural nematicide from agriculture waste, reducing dependencies
	12	Israel-based researchers achieve more drought-resistant tomatoes using CRISPR
	13	U.S. based research achieves limb regeneration in adult frogs
Advanced connectivity, navigation and digital technologies	14	New battery-free technology from Singapore may power electronic devices using ambient radiofrequency signals
Advanced sensing technologies	15	Israeli study uncovers new light-magnetism interactions that may create better sensors and memory technology
	16	U.A.E. researchers exploring use of lasers to "shock" clouds into rainfall
Space & propulsion technologies	17	Space technology company in Turkey advances hybrid rocket development
	18	China-based firm launches first batch of 15,000 satellites to compete with SpaceX's Starlink with aims for global coverage by 2027
	19	SPADEX: India's autonomous spacecraft docking mission set for late 2024 launch
	20	India’s indigenous electric propulsion system for satellites
Energy technologies	21	U.S. pulsed fusion technology company may lead to first-ever commercially operating fusion plant
	22	South Korean researchers develop new stretchable solar cells with record efficiency
	23	U.S. institute makes fusion energy more economical via nanoporous foam targets
	24	U.S. start-up using enzymatic chemical synthesis to create carbon-negative petrochemical alternatives
Robotics and autonomous systems	25	U.S. university lab develops brain swarm interface

Critical Tech Area (main)	Signal number and title	
Advanced materials, manufacturing and recycling technologies	**26**	Researchers in U.S and China focus on elastocaloric materials for higher efficiency cooling without greenhouse causing hydrofluorocarbons (HFCs)
	27	U.S. based company leverages muon tomography used to find metal ores to relieve competition for critical metals
	28	Japanese university develops first diamond semiconductor powered device
	29	U.S. university researchers apply redox-mediated electrochemical liquid-liquid extraction for critical raw materials
	30	A “supersolid” material could replace helium, easing dependence amid the US-China tech war

Source: Authors.

3.1 Advanced semiconductors technologies

3.1.1 Introduction

Advanced semiconductors are crucial geopolitically because they underpin critical technologies in both civilian and military applications (dual-use), making them essential for national security and economic power. Moreover, control over semiconductor production and innovation may be decisive for who keeps a leading position in technologies such as artificial intelligence.

Signal 01 refers to the development of 12-inch, one-atom-thick wafers made from molybdenum disulfide (MoS_2) which offers superior semiconducting properties compared to traditional silicon, enabling the creation of smaller, more powerful, and energy-efficient chips. The smaller the transistors, the more can be put in the same package, which is economically more interesting.

Signal 02 refers to Ayar Labs' TeraPHY chiplet (box 1) which integrates silicon photonics with NVIDIA and Intel chips, achieving a 4-Tbps bidirectional connection using only 5 picojoules per bit. A picojoule is one trillionth (1/1,000,000,000,000) of a joule. To put this into perspective, the energy released by a single photon of visible light is in the order of 1-10 picojoules. This innovation significantly boosts data transfer speeds and reduces energy consumption in AI and high-performance computing.

Signal 03 developed by the Okinawa Institute of Science and Technology (OIST) pertains to a novel extreme ultraviolet lithography (EUV) technology. The crucial part of this technology is the light or EUV source. This technology by OIST simplifies the EUV lithography process by using only two mirrors, reducing costs and energy consumption significantly. This innovation could lower the exorbitant price of EUV machines and cut power usage to 100 kilowatts, compared to over 1 megawatt for conventional systems.

Box 1. What is lithography in semiconductors?

In semiconductor manufacturing, lithography, or photolithography, is a pivotal process that defines the intricate patterns of electronic circuits on silicon wafers, forming the foundation of microchips. This technique enables the mass production of complex integrated circuits essential for modern electronic devices.

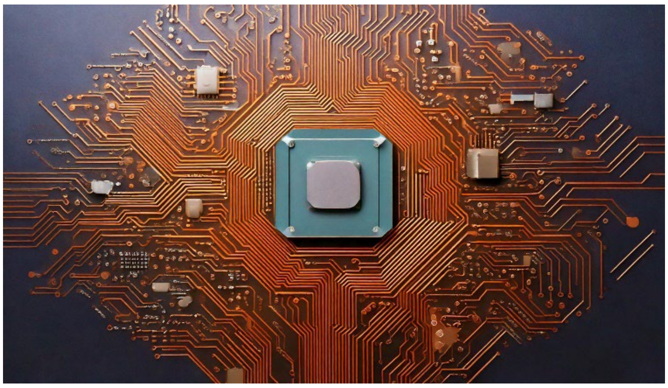
A photosensitive layer is first applied to the wafer, exposed to light through a pattern mask, and developed to remove specific areas. The exposed wafer is etched, transferring the design, and the remaining layer is removed. This process is repeated for each chip layer.

Lithography is central to the semiconductor fabrication process, directly impacting the performance, size, and cost of electronic devices. Advancements in lithography have been instrumental in adhering to Moore's Law, which predicts the doubling of transistors on a microchip approximately every two years. As the demand for smaller and more powerful microchips has increased, lithography techniques have evolved including Deep Ultraviolet (DUV) Lithography and Extreme Ultraviolet (EUV) Lithography. High Numerical Aperture (High-NA) EUV Lithography, a promising new method, is being tested by Advanced Semiconductor Materials Lithography (ASML).

Sources: (Semiconductor Engineering, 2024; Giannopoulos, Mochi, Vockenhuber, Ekinci, & Kazazis, 2024; Reuters, 2024)

01

Researchers in China develop 12-inch one-atom thick (2D) wafers for more efficient, higher performance chips



Researchers at Peking University have developed a novel semiconductor technology that allows for the production of 12-inch wafers from two-dimensional (2D) materials, specifically molybdenum disulfide (MoS_2), that are just one atom thick. Researchers believe that 2D wafers offer superior semiconducting properties compared to traditional silicon, potentially enabling the creation of smaller, more powerful, and more energy-efficient chips.

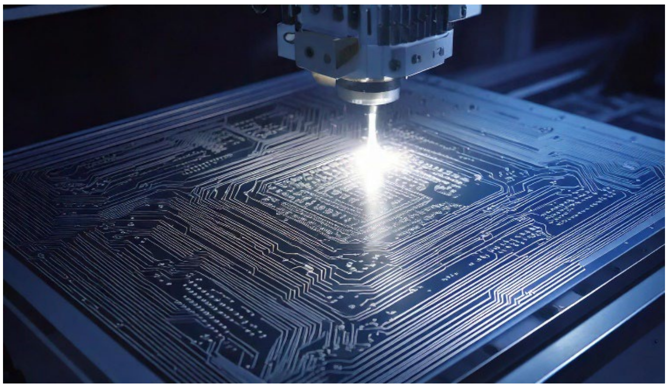
The novelty of this particular method lies in surface-to-surface supply method, which overcomes previous challenges in scaling up 2D materials to industry-standard 12-inch wafers. This makes it more compatible with existing machinery and designs. This new technique allows for uniform growth across the entire wafer, minimising defects and enabling high-volume production of up to 10,000 wafers per machine annually.

Further research is needed to transform these wafers into usable chips, including advancements in chip design and photolithography processes.

Sources	(Ezell, 2024; Tong, 2023; Hernandez, 2023)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Semiconductors Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation / Clean and Resource Efficient Technologies	
EIC portfolios	Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Semiconductors & Integrated Circuits / Energy Efficiency / Advanced Materials
	Verticals	Integrated Circuitry & Advanced Packaging / 2D & Nano-materials

02

US-based company aims to boost speeds of existing CPU and GPU through industry's first in-package silicon photonics chiplets



Ayar Labs, a US-based company, partly funded by the Singaporean government, has developed silicon photonic chiplets that integrate with existing chips from NVIDIA and Intel. Their flagship product, the TeraPHY chiplet, is designed to integrate in-package with GPUs or CPUs, enabling immediate conversion of electrical data to optical data using mirroring resonators. This innovation allows for high-speed data transfer between compute resources via optical fibre.

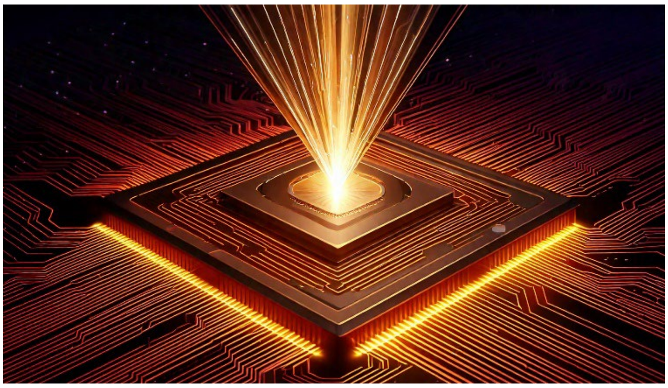
At Optical Fiber Communication Conference and Exhibition 2023, Ayar demonstrated a 4-Tbps bidirectional connection (2-Tbps each way) using only 5 picojoules per bit. This high throughput was achieved through wavelength-division multiplexing across eight fibre connections, each carrying eight wavelengths at 32 Gbps. The company later showcased a similar system integrated with Intel FPGAs.

The TeraPHY chiplet's novel approach could significantly boost data transfer speeds in AI and high-performance computing applications, potentially alleviating bandwidth bottlenecks and reducing energy consumption in data centres.

Sources	(Lanford, Sender, & Wills, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Semiconductors Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation / Clean and Resource Efficient Technologies	
EIC portfolios	Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Photonics & Optoelectronics / Semiconductors & Integrated Circuits
	Verticals	n/a

03

Japan-based researchers develop highly energy efficient extreme ultraviolet (EUV) lithography



The Okinawa Institute of Science and Technology (OIST) in Japan has developed a novel Extreme Ultraviolet (EUV) lithography technology that could lead to a vastly more energy and cost-efficient approach to manufacturing advanced semiconductors, the basis for microchips.

The novel approach simplifies the EUV lithography process by using only two mirrors in its optical projection system, compared to the conventional six or more. The simplified design dramatically lowers the cost of EUV lithography machines, currently priced at up to USD 380 million each. The technology also consumes less than one-tenth of the power required by conventional EUV systems, using only 100 kilowatts instead of over 1 megawatt.

The technology is still in the development stage. OIST has verified the system's performance using optical simulation software, with aims to test a working system by 2026. If successful, the technology would provide a more cost- and energy-efficient alternative to existing EUV lithography processes used by dominant players such as Netherlands-based ASML.

Sources	(AleksandarK, 2024; Okinawa Institute of Science and Technology, 2024; Shintake, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Advanced Semiconductors Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation / Clean and Resource Efficient Technologies	
EIC portfolios	Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Photonics & Optoelectronics / Semiconductors & Integrated Circuits / Energy Efficiency
	Verticals	n/a

3.2 Artificial intelligence technologies

3.2.1 Introduction

Developments in AI can play a supportive role in advancing other emerging technologies, such as quantum computing and biotechnology, which together may enhance a nation's strategic position. In the artificial intelligence race, China and the US are competing for the lead. The U.S. government has effectively banned Nvidia and advanced semiconductor equipment makers from exporting to China. But that hasn't stopped the Chinese from investing in AI technology. Signal 04 depicts China's advancement in AI-driven healthcare and biotechnologies with its foray into AI-powered tools for diagnostics, potentially increasing its influence in global health initiatives. This development could lead to significant economic benefits through both the commercialisation of the technology and reduced healthcare costs.

Federated learning described in Signal 05 can enhance global security by ensuring that AI technologies are developed in a secure and privacy-preserving manner. This is one of the approaches can reduce the misuse of AI and protect against cyber threats.

Box 2. What are the differences between various modes of federated learning?

Federated learning is a decentralised machine learning approach that allows multiple devices or data centres to collaboratively train models without sharing their private data. This method addresses challenges related to data privacy and security, making it particularly useful in scenarios where data cannot be centralised due to privacy concerns. Federated learning encompasses various modes, each tailored to specific needs and challenges. Asynchronous, decentralised and vertical are just three examples.

Asynchronous federated learning allows participants to update the global model at different times, rather than waiting for all participants to synchronise. This approach is beneficial in environments with unbalanced computation and communication resources, as it can improve efficiency by reducing idle times and allowing faster nodes to contribute more frequently.

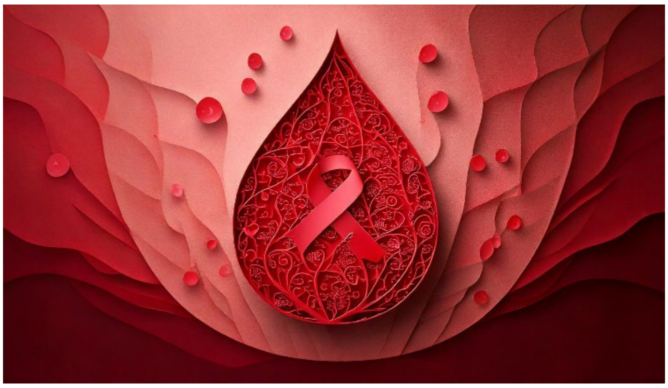
Decentralised federated learning removes the need for a central server, instead relying on a peer-to-peer network for model updates. This approach enhances privacy and reduces the risk of a single point of failure. It is particularly useful in environments where trust in a central server is a concern, and it can improve resilience in unstable network conditions.

Vertical federated learning is used when different parties hold different features of the same set of users. It is particularly useful in scenarios where organisations want to collaborate without sharing raw data, such as in financial or healthcare sectors. This mode requires specific techniques to handle the disjointed feature sets and ensure privacy.

Sources: (Gu, Xu, Huo, Deng, & Huang, 2021; Zhao, et al., 2022; Wu, Cai, Xiao, Chen, & Ooi, 2020; Zhou, et al., 2023; El-Hindi, Zhao, & Binnig, 2022; Wu & Xing, 2023; Khan, Thij, & Wilbik, 2022)

04

Researchers at Chinese university develop new AI-powered tool that can diagnose multiple cancers using a drop of dried blood



Researchers at Shanghai Jiao Tong University report having developed an innovative AI-powered diagnostic tool that can detect colorectal, gastric, and pancreatic cancers using a single drop of dried blood. This paper-based test combines nanoparticle-enhanced laser desorption/ionisation mass spectrometry (NPELDI MS) with machine learning to analyse dried serum spots (DSS) to detect multiple cancers within minutes. This novel approach analyses metabolic profiles in blood samples, achieving high accuracy (82-100%) in identifying colorectal, gastric, and pancreatic cancers.

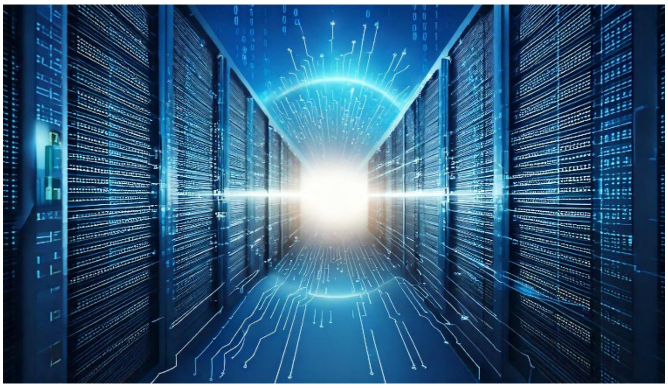
The test uses DSS, which are easier to collect, store, and transport than liquid blood samples, making it particularly valuable for resource-limited areas. By leveraging AI, this method offers a non-invasive and cost-effective alternative to traditional diagnostic techniques that could democratise early cancer detection worldwide, especially in resource-limited regions.

While further research and clinical trials are needed to demonstrate its full potential, this technology represents a promising step towards more accessible and efficient cancer diagnostics, potentially improving survival rates and reducing healthcare costs.

Sources	(Wang, 2024; Cooke, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Artificial Intelligence Technologies / Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Health and Biotechnology / Medical Technologies and Medical Devices / Artificial Intelligence	
EIC taxonomy	**Sector (Primary)**	AI, Data & ICT
	Sub-sector (Secondary)	Artificial Intelligence / Non-implantable devices & In-Vitro Medical Diagnostics
	Verticals	Digestive System

05

US and South Korea employing federated approaches to AI for improved privacy and energy efficiency



The explosion of interest in large-language models (LLM) like ChatGPT and Claude.ai has brought concern about energy usage and data privacy. Companies like NVIDIA and Google as well as start-ups like South Korea-based DEEPX are exploring using collaborative AI approaches, called 'Federated Learning' and 'Federated Operation of LLM' to distribute computation and the training-of-datasets thereby reducing energy and improving data privacy.

'Federated Operation of LLM' employs a collaborative distribution of AI processing between servers and edge devices equipped with low-power AI chips. Lighter AI-related tasks are handled locally on low-power chips, while servers handle more resource-intensive tasks. As with 'Federated Learning', data privacy is improved by processing sensitive information on local, edge devices instead of a centralised server.

Both of these federated approaches balance data privacy with the need for large-scale, collaborative AI training. Geopolitically, they offer a way for countries to collaborate on AI advancements without compromising national data sovereignty. This is particularly relevant in an era when data privacy regulations like GDPR are becoming stricter, and geopolitical tensions around data-sharing are rising. By enabling secure, decentralised AI development, these federated learning approaches can foster international cooperation while respecting local data governance laws.

Sources	(DigiTimes Asia, 2024; Yuan, Wang, Sun, Yu, & Brinton, 2024; Frost & Sullivan, 2024; McMahan & Ramage, 2017)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Artificial Intelligence Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Artificial Intelligence	
EIC taxonomy	**Sector (Primary)**	AI, Data & ICT
	Sub-sector (Secondary)	Artificial Intelligence / Cybersecurity & Privacy
	Verticals	n/a

3.3 Quantum technologies

3.3.1 Introduction

Quantum technologies promise new breakthroughs in computing, potentially revolutionising fields from chemistry to secure communication. The selected signals in quantum technologies illustrate how these technologies are critical components of geopolitical strategy, impacting the EU's security, economic power, and international influence. China and South Korea are making significant technological advancements in the quantum computing space.

China has developed the largest known integrated quantum key distribution (QKD) network, which represents a significant leap in secure communications, potentially revolutionising data security. China is sometimes referred to as the 'world's workshop' as it develops global leadership in scaling up technologies. Signal 06 describes the addition of thousands of kilometres to this QKD network as a perfect example of scaling up and building out infrastructure, which has the potential to secure, long-distance communication, a crucial issue for national or global security.

Singapore's work, depicted in Signal 07, can increase cybersecurity: skyrmion-based memory can enhance the security of data storage and processing, making it harder for adversaries to breach systems.

Finally, quantum computing can simulate molecular structures and chemical reactions with high precision thanks to South Korean research. Signal 08 describes how this newfound accuracy can lead to the discovery of new materials and new medicines which have the potential to enhance innovation beyond biochemistry and material science.

Box 3. What is a skyrmion?

A skyrmion is a small, stable, swirling structure found in magnetic materials, characterised by its topological properties. These structures are essentially tiny, particle-like formations that can be manipulated using electric currents, making them highly promising for various technological applications. Skyrmions are particularly notable for their potential in the field of spintronics (see Box 6), which involves the use of electron spin in electronic devices.

Skyrmions can be used in high-density, low-power memory devices. Their ability to be created, moved, and annihilated with minimal energy makes them ideal for non-volatile memory applications, such as racetrack memory, which promises exceptional capacity and performance. They can be also employed in reconfigurable logic gates, enabling ultra-low-energy and high-density computing. They can perform various logic functions like AND, OR, and NOT by manipulating their movement and interactions within nanotracks. Skyrmions are being explored for quantum computing applications due to their quantised helicity excitations. They offer a pathway to develop quantum operations by controlling their quantum states, potentially leading to skyrmion-based quantum computers.

In summary, skyrmions are promising for future technologies due to their stability, small size, and low energy requirements, with applications ranging from memory storage to quantum computing.

Sources: (Luo & You, 2021; Fert, Reyren, & Cros, 2017; Kang, Huang, Zhang, Zhou, & Zhao, 2016; Yu, et al., 2017; Luo, et al., 2018; Tokura & Kanazawa, 2020; Psaroudaki, Peraticos, & Panagopoulos, 2023)

06

China develops largest known integrated quantum key distributed (QKD) network, creating potentially unhackable encrypted communications

China has established the world's first integrated quantum communication network, combining over 700 optical fibres on the ground with two ground-to-satellite links to achieve quantum key distribution (QKD) over a total distance of 4,600 kilometres. The network integrated originally the Micius satellite, launched in 2016, which has demonstrated long-distance entanglement and secure key exchange between ground stations 2,600 km apart. Micius has been in the meantime decommissioned but superseded by Jinan-1, that is ten times lighter, 45 times cheaper and much more efficient than its predecessor. Jinan-1 allowed Chinese researchers to break previous distance records allowing a secret message to be sent from China to South Africa, more than 13,000 km apart.

QKD uses quantum states of particles, such as photons, to create unhackable encryption keys. Any eavesdropping attempt alters the quantum state, immediately alerting the communicating parties. This technology promises unbreakable security for banks, power grids, and government communications. This advancement paves the way for a global quantum communication network, offering unprecedented security against cyber threats and potential quantum computer attacks.

Sources	(Parker, et al., 2022; Chen, et al., 2021; Gibney, 2025	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Quantum Technologies / Space & Propulsion Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Quantum Technologies / Space	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Quantum Technologies / Satellite Communications & Space-based Connectivity / Cybersecurity & Privacy
	Verticals	n/a

07

Singaporean researchers develops skyrmion-based memory technology for extremely low-power devices

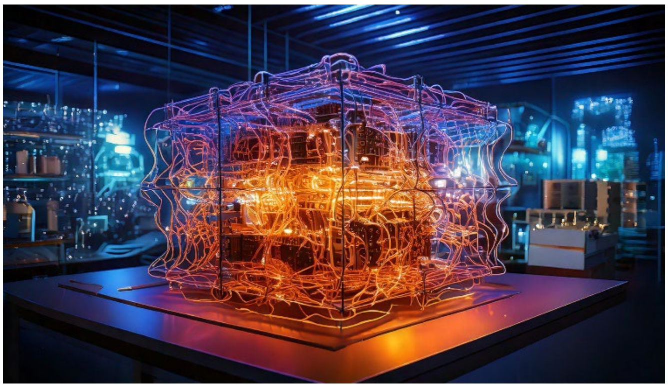
Researchers from A*STAR and the National University of Singapore have developed a groundbreaking skyrmion-based memory technology that marks a significant advancement in low-power computing devices. This innovative microelectronic device achieves electrical readout and switching of skyrmion states, a feat previously unattained. Skyrmions, which are tiny magnetic whirls 10,000 times smaller than a human hair, form the basis of this technology (see box 3).

The device operates using a tunnel junction, allowing it to function under ambient conditions. Remarkably, it consumes 1,000 times less power than commercial memory technologies, addressing the growing energy demands of AI and edge computing. The technology's novelty lies in its ability to achieve multiple states within a single device, eliminating the need for further size reduction to enhance performance. This breakthrough paves the way for more efficient and sustainable AI computing, particularly in edge devices with limited power and computing capacity. In addition, researchers in France have postulated that these skyrmions can be used to advance quantum computing.

Sources	(National University of Singapore, 2024; Chen, et al., 2024; Psaroudaki, Peraticos, & Panagopoulos, 2023; National University of Singapore, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Quantum Technologies / Advanced Semiconductor Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation / Clean and Resource Efficient Technologies	
EIC portfolios	Quantum Technologies	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Quantum Technologies
	Verticals	n/a

08

South Korean developer achieves first demonstration of chemical accuracy on commercially available quantum computers



Qunova Computing, a South Korean quantum software developer, has claimed to be the first in the field to achieve significant breakthroughs in quantum chemistry simulations by demonstrating chemical accuracy (below 1.6 millihartrees) on commercially-available NISQ-era quantum computers.

Noisy Intermediate-Scale Quantum (NISQ) computers are devices that, while commercially available today, are subject to significant levels of quantum noise and error, which presents challenges for the practical applications of these devices. Qunova claims that they are the first to use NISQ quantum computers to achieve 'chemical accuracy'. This means they can use commercially- available quantum computing platforms to model molecular properties and reactions accurately as well as for other real-world chemistry applications.

The technology is at an advanced development stage, with successful demonstrations on multiple platforms and plans for further experiments to confirm its potential for industrial applications. IBM for example has integrated Qunova's algorithm into its open-source Qiskit library, signalling external interest and reuse. If their work is further confirmed, Qunova's achievement would bring quantum computing closer to real-world applications in chemistry, potentially revolutionising various industries that rely on molecular modelling and simulation.

Sources	(Qunova, 2024; Davies, 2024; Swayne, Qunova Reports Achieving 'Chemical Accuracy' on Commercial Quantum Computers With Hardware Agnostic Algorithm, 2024; Paleja, 2024; Quantum Zeitgeist, 2025)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Quantum Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Quantum Technologies	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Quantum Technologies
	Verticals	n/a

3.4 Biotechnologies

3.4.1 Introduction

The selected signals illustrate the breadth of potential applications and research areas available in biotechnologies, which range from organoids to microbiome mining to drought-resistant tomatoes. Many nations such as China, U.S. and Australia are exploring the advent of organoid intelligence (OI) which is demonstrated in Signal 09. OI can provide a sort of biological hardware, offering significant advances in computational power, with application in national defence systems and cybersecurity.

The U.S. initiative to scale up microbiome mining (Signal 10), highlights the potential for existing technologies to benefit from iterations of existing technologies. As mentioned in the section on Quantum Technologies, many of the innovations in this study refer to advances in scaling existing technologies as a way to remain or become strategically competitive. Signal 11 refers to Brazilian research which is innovating to help the government support agriculture without relying on imported petrochemical fertilizers and pesticides. The ability for countries to decouple from the petrochemical industry is a strategic imperative for some countries.

Research coming from Israel on applying CRISPR to make food drought-resistant not only addresses immediate food security challenges but also could position itself to be more competitive in the global agricultural market by driving innovation, sustainability, and efficiency. This is demonstrated in Signal 12. Finally, research coming from U.S. on the development and implementation of limb regeneration technologies depicted in Signal 13 can drive further innovation in regenerative medicine and related fields. This has overlap with organ regeneration and has a strategic relevance in terms of maintaining the heath (and employability) of an aging population. A population with increased healthy lifespan can lead to increased productivity, innovation, and entrepreneurship, driving economic growth and competitiveness. This can be particularly beneficial for nations with aging populations, as it can help offset the economic impacts of demographic change.

Box 4. What is an organoid?

An organoid is a 3D in-vitro tissue construct that mimics the structure and function of real organs. These miniaturised models are derived from stem cells, either pluripotent or adult, and are used to study organ development, disease, and for applications in drug discovery and regenerative medicine.

Achieving consistent and complex organoid structures remains a challenge, requiring advances in engineering and bioengineering to improve their physiological relevance. While organoids offer great potential, translating these models into clinical applications requires overcoming limitations such as variability and limited maturation.

Sources: (Hofer & Lutolf, 2021; Rossi, Manfrin, & Lutolf, 2018; Schutgens & Clevers, 2020; Souza, 2018; Andrews & Kriegstein, 2022)

09

Organoid intelligence opens a new potential path in the computing race

A groundbreaking field known as Organoid Intelligence (OI) emerged recently, marking a significant shift in biocomputing and AI. This new domain moves away from the traditional Von Neumann architecture and embraces more innovative approaches like neuromorphic computing, which mimics the brain's structure to efficiently manage simultaneous information storage and processing.

Johns Hopkins researchers pioneered OI, using biological materials—predominantly human brain cells—for information processing. This leverages their inherent capabilities, surpassing traditional silicon-based systems and harnessing the brain's natural efficiency for AI applications.

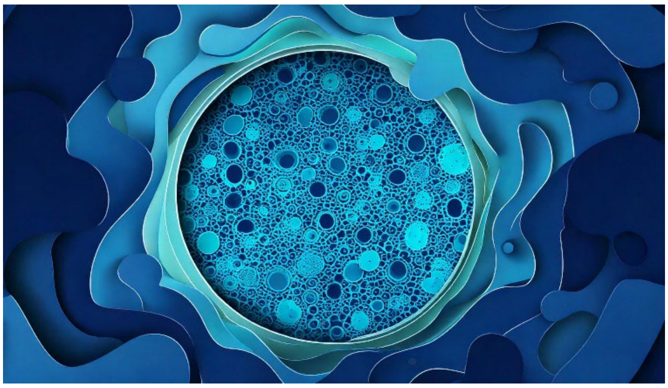
A notable achievement in this field was a biocomputing system using living brain cells that learned to identify a person's voice from 240 audio clips featuring eight people pronouncing Japanese vowels. The organoids processed these clips as sequences of spatial signal patterns. Similarly, in 2021, Cortical Labs in Australia successfully taught brain cells to play the game Pong.

This development has significant geopolitical implications. The US and China are already competing for dominance in areas like quantum computing, semiconductors, and 5G/6G technologies. The advent of biological computing could add a new dimension to this race. The political sensitivities surrounding biology in the US further complicate this scenario, suggesting that OI could become a contentious and strategically critical field.

Sources	(Webb, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Health and Biotechnology / Responsible and Sustainable Electronics	
HeEIC taxonomy	**Sector (Primary)**	Health Biotechnology
	Sub-sector (Secondary)	Cell, tissue and other regenerative therapies / Artificial Intelligence / Hybrid & High Performance Computing
	Verticals	Biomass & Bio-based Materials, incl. Engineered Living Materials

10

Developing industrial-scale microbiome mining for drug and material discovery in U.S.



Biosortia, a US-based company, has pioneered industrial-scale microbiome mining, the extraction and study of microbial life forms previously inaccessible due to culturing limitations. Their novel technology allows for the collection of microbiomes from vast water volumes while preserving their integrity, typically harvesting ~1,000 kg of dry weight microbiome from 20 million litres of water. This approach enables access to the "dark matter" of biology, uncovering a treasure trove of novel compounds and potential drug leads.

In a single recovery, Biosortia claims to have identified 73,000 unknown novel small molecules used in cellular signalling pathways, far surpassing the approximately 36,000 known small molecules from microbes listed in the Encyclopedia of Natural Products. This technology has immense potential for accelerating drug discovery, agrichemicals, cosmetics, material, and life sciences.

Sources	(Polyplexus, 2024; Youngs, 2023)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Health and Biotechnology	
EIC taxonomy	**Sector (Primary)**	Health and Biotechnology
	Sub-sector (Secondary)	Drug & Biologics
	Verticals	n/a

11

Brazil develops natural nematicide from agriculture waste, reducing dependencies

Embrapa Agroenergia has developed a novel natural nematicide derived from agro-industrial waste, specifically residues from oilseed extraction. This innovative product targets phytonematodes, particularly the Meloidogyne genus, which cause significant crop losses estimated at R$35 billion annually in Brazil. The nematicide uses plant-based extracts that demonstrate both nematicidal and nematostatic effects, offering a more environmentally friendly alternative to synthetic pesticides.

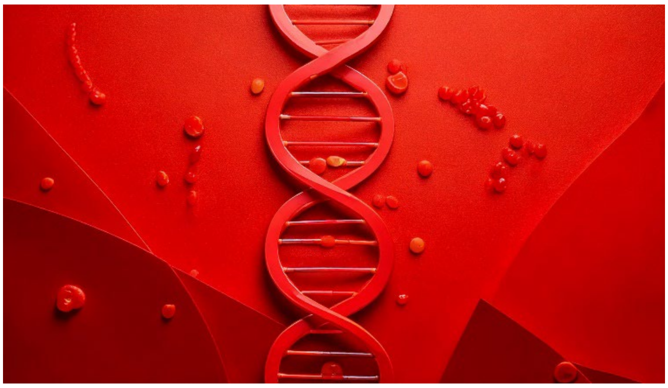
This research supports the current government's push to find ways to support its agricultural industry without relying on imported petrochemical-based fertilizers and pesticides. In 2022, Brazil was the world's largest imported of pesticides, majority coming from China, the United States, and India. In addition, bio-based nematicides, compared to traditional petrochemical-based methods, typically help reduce environmental impact and potentially help preserve beneficial soil microbiota.

Researchers are exploring ways to enhance the efficacy of this nematicide through chemical modifications of the active compounds.

Sources	(Embrapa, 2022; Observatory of Economic Complexity, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Agriculture & Food	
EIC taxonomy	**Sector (Primary)**	Agriculture & Food
	Sub-sector (Secondary)	Agrifood Biotechnology
	Verticals	Biomass & Bio-based Materials, incl. Engineered Living Materials

12

Israel-based researchers achieve more drought-resistant tomatoes using CRISPR



Researchers at Tel Aviv University have developed a novel method for creating CRISPR-edited tomatoes that consume significantly less water while maintaining yield, quality, and taste. By targeting the ROP9 gene, which regulates stomatal function, the modified tomatoes can partially close their stomata during peak water loss periods. This adaptation allows for efficient carbon dioxide uptake without compromising photosynthesis, making these tomatoes particularly valuable in drought-prone regions.

The importance of this innovation lies in its potential to address global food security challenges exacerbated by climate change. As water scarcity becomes increasingly pressing, crops that require less water while still producing high yields are essential for sustainable agriculture.

The study's findings indicate that the CRISPR-edited tomatoes perform comparably to traditional varieties, marking a significant step forward in the use of biotechnology for environmental sustainability. Currently, the project is at the research stage, with ongoing studies needed to evaluate the long-term effects and broader applications of this technology across different crops.

Sources	(ISAAA, 2024; Seed World, 2024; Technology Networks, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Health and Biotechnology / Agriculture and Food	
EIC taxonomy	**Sector (Primary)**	Agriculture & Food
	Sub-sector (Secondary)	Agrifood Biotechnology
	Verticals	n/a

13

US based research achieves limb regeneration in adult frogs

Researchers at Tufts and Harvard University achieved limb regeneration by successfully regrowing functional legs in adult African clawed frogs, a species that normally lacks this ability.

The novel approach involved applying a five-drug cocktail to the amputation site for just 24 hours using a silicone cap called "BioDome." This brief treatment triggered a sustained regenerative response, resulting in the growth of new legs with bones, nerves, and toe-like structures over 18 months.

The study demonstrates that it's possible to reactivate dormant regenerative capabilities in animals that typically cannot regrow complex limbs. The regenerated limbs, while not perfect, allowed frogs to swim and respond to touch stimuli.

The scientists believe that similar applications for humans could be possible within decades. While still in early stages, this technology represents a major step forward in understanding and manipulating the biological processes underlying limb regeneration in vertebrates.

Sources	(Wetzel, 2022; Murugan, et al., 2022)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Biotechnologies	
STEP categories	Biotechnologies	
EIC portfolios	Health and Biotechnology	
EIC taxonomy	**Sector (Primary)**	Health Biotechnology
	Sub-sector (Secondary)	Drugs & Biologics / Cell, tissue and other regenerative therapies
	Verticals	Musculoskeletal / Connective Tissue

3.5 Advanced connectivity, navigation and digital technologies

3.5.1 Introduction

The selected signal in advanced connectivity and navigation technologies (Signal 14) highlights the importance on technological sovereignty in the digital space. Research from Singapore demonstrates the potential of using radiofrequency (RF) signals to power devices instead of relying on traditional batteries. This technology involves harvesting ambient RF energy from sources like Wi-Fi and cellular networks to generate electricity. By harnessing ambient RF energy, regions can reduce their reliance on imported batteries and other energy sources. This can lead to greater self-sufficiency in powering electronic devices and IoT networks.

Box 5. What is ambient radiofrequency energy?

Ambient radiofrequency (RF) energy refers to the electromagnetic energy emitted by various communication sources such as radio, television, and mobile phone signals. This energy is omnipresent in urban and semi-urban environments due to the widespread use of wireless communication technologies.

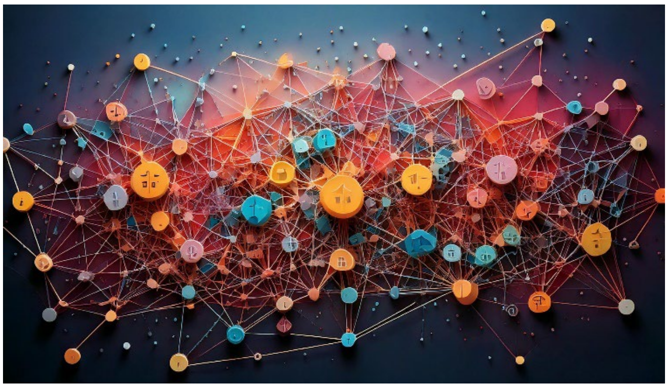
The concept of using ambient RF energy as a new energy source involves capturing and converting these RF signals into usable electrical power. This process is known as RF energy harvesting. It typically involves a device called a rectenna, which is a combination of an antenna and a rectifier circuit. The antenna captures the RF signals, and the rectifier converts them into direct current (DC) electricity.

RF energy harvesting is particularly appealing for powering low-power devices such as wireless sensors and Internet of Things (IoT) devices, which require minimal energy to operate. This technology can potentially enable battery-free devices, reducing the need for frequent battery replacements and contributing to more sustainable energy solutions. However, challenges such as low power density and efficiency need to be addressed to make RF energy harvesting a viable alternative energy source.

Sources: (Mekid, Qureshi, & Baroudi, 2017; Piñuela, Mitcheson, & Lucyszyn, 2013; Balachandra, Kulkarni, & Kattimani, 2022; Gu, Hemour, & Wu, 2018; Kitazawa, Ban, & Kobayashi, 2012; Yathavi, Maunasree, Meenakshi, Malika, & Santhoshini, 2021; Flint, Lu, Privault, Niyato, & Wang, 2015)

14

New battery-free technology from Singapore may power electronic devices using ambient radiofrequency signals



A team led by scientists from the National University of Singapore has developed a novel energy harvesting module that converts ambient radiofrequency (RF) signals into DC voltage, capable of powering small electronic devices. This technology addresses the challenges of low ambient RF signal power by using nanoscale spin-rectifiers (SRs) to efficiently convert RF signals below -20dBm to DC voltage.

The innovation lies in its ability to operate at extremely low power levels. This compact and sensitive rectifier technology offers advantages over traditional methods, which struggle with efficiency at low power levels. Currently, the team has successfully powered a commercial temperature sensor at -27dBm using their SR-array integrated energy harvesting module.

Researchers are focusing on further integrating different parts of the energy harvesting module and exploring connecting multiple modules together to power a broader range of low-power devices, such as wireless sensors, IoT devices, and small communication modules, without the need for batteries or with significantly extended battery life.

Sources	(The Engineer, 2024; Sharma, et al., 2024; NUS News, 2024; Critical Comms, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Connectivity, Navigation and Digital Technologies / Energy Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Energy Systems / Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	AI, Data & ICT
	Sub-sector (Secondary)	Telecommunications / Energy Generation & Conversion
	Verticals	Other Sources of Energy

3.6 Advanced sensing technologies

3.6.1 Introduction

Advanced sensing technologies go beyond traditional sensors by offering enhanced sensitivity, selectivity, miniaturization, and the ability to operate in challenging environments enabling high-resolution, often real-time measurement of physical, chemical, or biological parameters. Signal 15 describes the development of an "all-optical" magnetic memory device. In this device, a laser pulse is used to manipulate the magnetic properties of a material, allowing data to be written and stored. This is done by exploiting the newly discovered connection between light and magnetism, where the magnetic field of the light (known as the "magnetic part of light") is used to control the magnetic properties of the material. Countries that develop and deploy these technologies may be better equipped to protect their critical infrastructure and intellectual property, giving them a strategic advantage.

For the mobile high-power pulsed laser demonstrators, autonomous operation is used to direct high-power lasers for various applications to induce rainfall. Signal 16 illustrates a strategic innovation for U.A.E. as it’s a water scarce region. As other parts of the world deal with climate change mitigation technologies, the fact that U.A.E. is working on climate adaption technology to address water shortages make sense as for the environmental issues affecting this region. However, if this type of technology is not built up further in regions outside of UAE, then it could leave regions as such as EU behind in climate adaption technology.

Box 6. What is spintronics?

Spintronics, short for spin electronics, is a field of technology that focuses on the manipulation of the electron's spin, in addition to its charge, to create new electronic devices. Unlike traditional electronics that rely solely on the charge of electrons to transmit information, spintronics exploits the intrinsic spin of electrons, which can be thought of as a tiny magnetic moment. This approach allows for potentially faster, more efficient, and smaller devices.

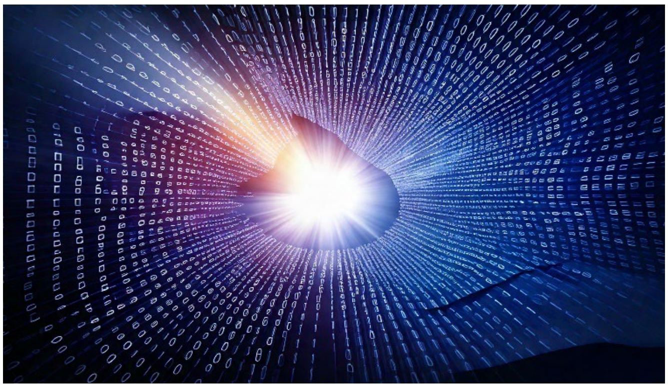
The key advantage of spintronics is its ability to enhance data storage and processing capabilities. For instance, spintronic devices can be used to develop magnetic memories and sensors, which are more energy-efficient than conventional electronic devices. Additionally, the use of two-dimensional (2D) materials, such as graphene, in spintronics has shown promise. This is due to their unique properties, like long spin relaxation times, which are beneficial for maintaining spin information over longer periods.

Overall, spintronics represents a promising direction for future electronics, offering the potential for low-power, high-speed, and multifunctional devices that could revolutionise the microelectronics industry.

Sources: (Žutić, Fabian, & Sarma, 2004; Feng, et al., 2017; Liu, et al., 2020; Hu & Xiang, 2020; Sanvito, 2011; Diény, et al., 2020; Lin, Yang, Wang, & Zhao, 2019; Joshi, 2016)

15

Israeli study uncovers new light-magnetism interactions that may create better sensors and memory technology



A new study at Hebrew University uncovered a previously unknown connection between light and magnetism. This discovery could lead to super-fast light-controlled memory technology and innovative sensors that detect the magnetic part of light.

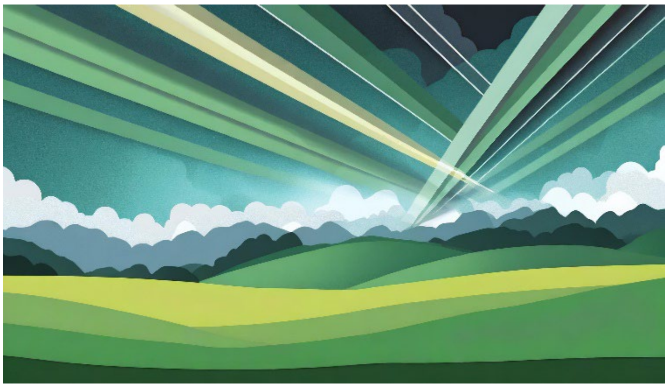
The team's unexpected discovery reveals a mechanism wherein an optical laser beam controls the magnetic state in solids, promising tangible applications in various industries. The researchers arrived at this understanding by using principles that are well established within the quantum computing and quantum optics communities but less so in the spintronics and magnetism communities.

Moreover, in tandem with this discovery, the team introduced a specialised sensor capable of detecting the magnetic part of light. Unlike traditional sensors, this cutting-edge design offers versatility and integration across various applications, potentially revolutionising sensor and circuit designs using light in diverse ways.

Sources	(Swayne, 2024; Siegel-Itzkovich, 2024; Hilson, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Advanced Sensing Technologies / Advanced Semiconductors Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	Quantum, Advanced Computing & Semiconductors
	Sub-sector (Secondary)	Semiconductors & Integrated Circuits
	Verticals	n/a

16

UAE researchers explore use of lasers to "shock" clouds into rainfall



Starting in 2023, Dr. Guillaume Matras at the Technology Innovation Institute (TII) in the UAE has led a team of researchers exploring laser-induced rain triggering as an alternative to current rain-inducing methods that rely on cloud seeding. The research team is testing a Mobile High-Power Pulsed Laser Demonstrator (MHPPLD) to target clouds and create shockwaves that coalesce cloud droplets into rainfall.

This research builds upon earlier studies led by the University of Geneva and the University of Florida that tested how high-powered lasers can increase water condensation in clouds.

Work on developing and testing the Mobile High-Power Pulsed Laser Demonstrator (MHPPLD) is part of the UAE's larger efforts to increase rain precipitation through the UAE Research Program for Rain Enhancement Science and to locally design and develop high-energy lasers at the UAE's Directed Energy Research Centre (DERC).

Sources	(Wired, 2024; Technology Innovation Institute, 2024; CORDIS, 2023; Chopkar & Chakrabarty 2023)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Advanced Sensing Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	n/a	
EIC taxonomy	**Sector (Primary)**	Climate & Environmental Tech
	Sub-sector (Secondary)	Water Management & Resilience / Photonics & Optoelectronics
	Verticals	n/a

3.7 Space & propulsion technologies

3.7.1 Introduction

A key underlining trend in the space and propulsion technology domain is more countries are developing space and propulsion capabilities, and potentially at a lower cost than historically, established players being the United States, European Union, and Russia. For example, Signal 17 demonstrates Turkey's entry into advanced hybrid propulsion technologies and growing capabilities in the space and propulsion sector.

Along similar lines, Chinese space companies are also becoming increasingly involved in space technology development. Signal 18 refers to China's launch of a similar network to Starlink to be able to compete with the U.S. space industry. While Starlink might be a pioneer in this area, the key novelty is that these capabilities and ambitions are quickly appearing in different geographies. In a world where major regional players have access to the same cutting-edge technologies—each aiming to create chains of space sensors networked with broadband—the advantage is likely to favour the nation that can more quickly apply and upscale these technologies.

India's national space agency, Indian Space Research Organisation (ISRO), is outsourcing some of its space integration activities as way to boost India's private players in the space sector (Signal 19). India also continues to grow its capabilities, such as recently manufacturing more of its own rocket electric propulsion systems, which no longer relies on foreign (Russian) parts (Signal 20).

Box 7. What is the relevance of dual use technologies in space?

Dual use in space refers to the application of space technologies and systems for both civilian and military purposes. This concept is significant because many space technologies, such as satellites and launch vehicles, can serve peaceful purposes like communication and weather monitoring, as well as military functions like surveillance and reconnaissance. The dual-use nature of these technologies raises concerns about the potential for weaponisation of space.

For instance, space situational awareness systems, which track objects in space to prevent collisions, are crucial for both civilian safety and military strategy. Similarly, technologies developed for civil applications, such as telecommunications (e.g. the EU's Infrastructure for Resilience, Interconnectivity and Security by Satellite - IRIS^2) and Earth observation, can be repurposed for defence needs, highlighting the blurred lines between peaceful and military uses of space.

The dual-use concept is essential for efficient resource utilisation, as it allows for shared infrastructure and technology development between civil and defence sectors. However, it also necessitates careful management and international cooperation to prevent the escalation of space-based conflicts and ensure the peaceful use of outer space.

Source: (Pražák, 2021; Czyzak, Idell, & Crawford, 2000; Otani, Ohkami, Kohtake, & Sakurai, 2012; Otani, Kohtake, & Ohkami, 2013; European Commission, 2025)

17

Space technology company in Turkey advances hybrid rocket development

Delta V Space Technologies, a Turkish company, has made significant strides in developing hybrid rocket technologies. Their Sonde Rocket System (SORS) successfully surpassed 100 km altitude in November 2023, marking the first time a hybrid rocket using paraffin and liquid oxygen reached space. This achievement coincided with the 100th anniversary of the Turkish Republic.

The company's hybrid rocket technology offers a safer and more cost-effective alternative, at up to 3 times lower in cost, compared to traditional solid and liquid rocket propulsion systems. The technology is at an advanced stage of development, with 17 successful SORS launches to date.

Delta V is now focusing on further improving this technology to make it more competitive globally and potentially usable as a stage in future launch systems. They are also collaborating with Fergani Space Technologies to develop cost-effective technologies for satellite placement and orbital transfer.

Sources	(Railly News, 2023; TRT World, 2021; Daily Sabah, 2021)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Space & Propulsion Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Space	
EIC taxonomy	**Sector (Primary)**	Space
	Sub-sector (Secondary)	Launch vehicles
	Verticals	n/a

18

China-based firm launches first batch of 15,000 satellites to compete with SpaceX's Starlink with aims for global coverage by 2027

In 2024, Shanghai Spacecom Satellite Technology (SSST) launched their first batch of Qianfan satellites as part of the Spacesail Constellation project. SSST plans to deploy 600 satellites by the end of 2025 and provide global internet coverage by 2027. In December 2024, SSST signed an agreement with Brazilian state-owned group Telebrás to provide satellite communications and broadband internet services by 2026.

The Qianfan satellites represent the development by China of stackable flat satellite platforms, also used by Starlink, which enable faster, modular manufacturing of satellites and more efficient launches through stacking multiple satellites in a single launch vehicle.

The Spacesail Constellation project is one of three efforts in China to build a Starlink-like network. China's other Starlink-like projects include Guowang and Honghu-3 with plans for 13,000 and 10,000 satellites, respectively. In contrast, as of September 2024, Starlink's constellation consists of over 7,000 satellites with the goal of reaching 12,000 satellites.

Sources	(Feldstein, 2024; Jones, 2024; Kuhr, 2024; South China Morning Post, 2024)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Space & Propulsion Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Space	
EIC taxonomy	**Sector (Primary)**	Space
	Sub-sector (Secondary)	Satellite Communications & Space-based Connectivity
	Verticals	n/a

19

SPADEX: India achieves unmanned space docking operations

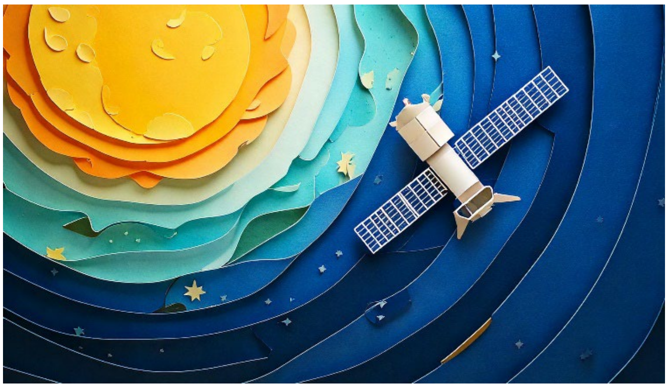
SPADEX (Space Docking Experiment) by the Indian Space Research Organisation (ISRO) aims to develop an autonomous docking technology for spacecrafts. The mission is a key step towards India's long-term space exploration goals, including manned spaceflight, satellite maintenance, and the construction of the proposed Bharatiya Antariksha Space Station.

As of October 2024, the two satellites for SPADEX had been assembled, integrated, and tested by Ananth Technologies Private Limited (ATL), marking the first time ISRO has outsourced complete satellite integration to a private company, and showcasing the growing capabilities of India's private space industry.

Sources	(Singh A. , 2024; Ray, 2024; MP, 2024; Manorama Yearbook, 2022)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Space & Propulsion Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Space	
EIC taxonomy	**Sector (Primary)**	Space
	Sub-sector (Secondary)	In-Space Servicing, Assembly, and Manufacturing
	Verticals	n/a

20

India's domestic electric propulsion system for satellites



Indian Space Research Organisation (ISRO)'s domestically-built Electric Propulsion System (EPS) is an advanced technology for satellite propulsion that uses electrical power to ionise and accelerate propellant gases, such as argon, instead of traditional chemical propellants. The EPS will be demonstrated with the Technology Demonstrator Satellite (TDS-1), originally scheduled for launch in late 2024, but in the meantime postponed for late 2025.

Although EPS is not a new technology in it-self, the fact that all components have been developed in India, - marking a departure from previous systems that relied on imported technology from Russia - is a development worth highlighting.

EPS allows for lighter satellites with the same power capabilities as larger ones, potentially reducing launch costs and increasing payload capacity. While a traditional 4-tonne communication satellite carries about 2 tonnes of liquid fuel, an EPS-based satellite only needs about 200 kg of propellant.

Sources	(Indian Defence News, 2024; Singh S. , 2024; Singh N. , 2024)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Space & Propulsion Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Space	
EIC taxonomy	**Sector (Primary)**	Space
	Sub-sector (Secondary)	Launch vehicles
	Verticals	n/a

3.8 Energy technologies

3.8.1 Introduction

The push to advance on the nuclear fusion area is seen as more and more important in a geopolitical context: achieving nuclear fusion is often compared to achieving energy independence due to its potential to provide a virtually limitless and clean source of energy. In U.S., there are considerable developments in pulsed fusion which is a method of achieving nuclear fusion by using short, intense bursts of energy to compress and heat the fusion fuel. In pulsed fusion, energy is stored in capacitors and released in rapid pulses. These pulses create high magnetic pressures and temperatures, which compress the fusion fuel (in the case of signal 21 it is deuterium-tritium) to the point where nuclear fusion occurs.

On the topic of energy security, signal 22 refers to South Korea's development of stretchable solar cells which allow them to harness renewable energy sources more efficiently. Through this innovation, South Korea could reduce their dependence on fossil fuels and other sources of energy from other nations by deploying stretchable solar cells which can provide energy in diverse environments, including remote or off grid locations.

With regards to deployment, nuclear fusion suffers from economic challenges which a U.S. institute is investigating. Signal 23 depicts not a technology per se but a model which helps determine the best fuel targets. For nuclear fusion energy targets are critical components that hold the fusion fuel. These targets must meet stringent specifications to ensure successful fusion reactions. For the signal related to pulsed fusion, the important point is how the fuel is *diffused* but if there's no fuel in the first place then energy security cannot be ensured. Thus Signal 23 is relevant to selecting the fuel targets which are most (economically) viable.

The last signal in the energy technologies domain, Signal 24, is related to enzymatic process for biobased materials to create chemicals. This enzymatic process is not new but represents a renewed effort to take an existing technology to scale up.

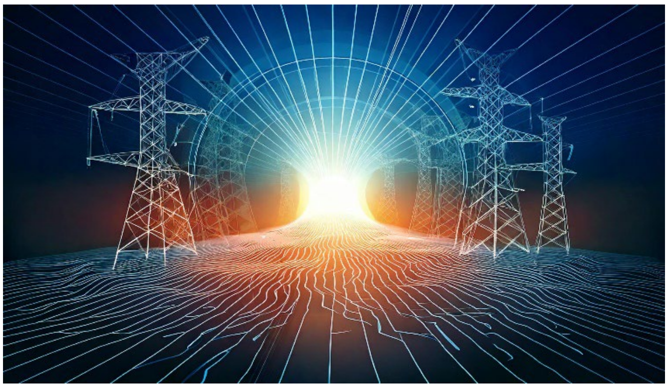
Box 8. What are nuclear fusion targets?

> Nuclear fusion targets are specially designed materials or structures used in fusion experiments to achieve the conditions necessary for nuclear fusion reactions. These targets are crucial in both inertial confinement fusion (ICF) and magnetic confinement fusion (MCF) approaches.
>
> In ICF, targets are typically small spherical shells filled with fusion fuel, such as deuterium-tritium (DT) gas. These shells are imploded using high-energy lasers or ion beams to create the extreme temperatures and pressures needed for fusion. For example, laser-direct-drive fusion targets use a high-Z gradient-density pusher shell to improve stability and energy gain during implosion. Indirectly driven targets, known as hohlraum targets, use X-rays generated in a cavity to compress the fusion capsule.
>
> In MCF, targets are often in the form of plasma confined by magnetic fields, but solid targets can also be used in experiments involving laser-driven fusion reactions. For instance, silicon targets enriched with hydrogen and boron are used in laser-driven fusion to initiate proton-boron reactions.

Sources: (Hu, et al., 2023; Murakami & Meyer-Ter-Vehn, 1991; Liu, et al., 2023; Picciotto, et al., 2017; Li, Lindley-Start, Porch, & Barrow, 2017)

21

US pulsed fusion technology company may lead to first-ever commercially operating fusion plant



Nuclear fusion has been a goal for more than 80 years and some are doubtful that the technology is around the corner. A new development by Helion Energy is a pulsed approach that repeatedly produces small amounts of fusion energy without needing to achieve steady-state operations. Helion's latest prototype, Polaris, aims to achieve significant milestones, such as increasing the pulse rate to one pulse per second and heating fusion plasma to temperatures greater than 100 million degrees Celsius. These advancements are crucial steps towards achieving commercial viability and moving to higher TRLs.

Pacific Fusion uses fast-rising, high-current pulses to magnetically compress and heat deuterium-tritium fuel, aiming to achieve net facility gain (more energy output than input). The U.S. Department of Energy (DOE) will publish its first fusion science and technology roadmap aligned with industry in 2025. That roadmap will include guidance on how the industry can make progress and measure its success, as China works to corner the fusion energy supply chain by securing the market for critical materials needed to build fusion power plants.

Among the many reasons to develop it, particular attention should be given to the potential role of fusion in powering energy-intensive AI applications and data centres, as the AI race also depends on securing the necessary energy to operate these systems.

Sources	(McKenzie, 2024; Hiller & Hua, 2024; Lerner, Hassan, Karamitsos-Zivkovic, & Fritsch, 2023)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Energy Technologies / Artificial Intelligence Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Energy Systems	
EIC taxonomy	**Sector (Primary)**	Energy
	Sub-sector (Secondary)	Energy Generation & Conversion / Water Management & Resilience
	Verticals	Nuclear

22

South Korean researchers develop new stretchable solar cells with record efficiency

Researchers at the Korea Advanced Institute of Science & Technology (KAIST) have developed a groundbreaking stretchable organic solar cell with exceptional performance and elasticity. This novel organic polymer potentially allows for unprecedented flexibility and efficiency in solar energy conversion.

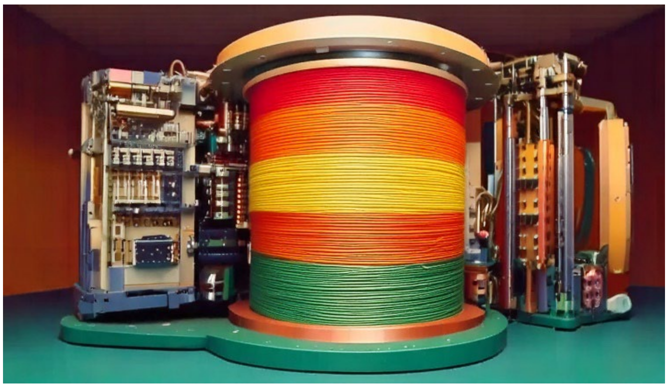
The researchers claim a photovoltaic conversion efficiency of 19%, which is the highest reported level for stretchable organic solar cells. It can be stretched up to 40% during operation, making it ten times more stretchable than comparable devices. This combination of high efficiency and flexibility makes it particularly suitable for wearable electronic devices.

If successful, this development can help addresses the challenge of creating stretchable solar cells that maintain strong electrical performance. The new polymer is lighter and more flexible than previous materials, opening up possibilities for various malleable electronic applications, such as enabling versatile energy harvesting in portable and wearable devices.

Sources	(Kazmer, 2024; KAIST, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Energy Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Energy Systems / Advanced Materials	
EIC taxonomy	**Sector (Primary)**	Energy
	Sub-sector (Secondary)	Energy Generation & Conversion / Advanced Materials
	Verticals	Solar

23

US institute makes fusion energy more economical via nanoporous foam targets



One of the hurdles facing nuclear fusion as a clean abundant energy source is the economic challenge. Recent advancements in nanoscale additive manufacturing have demonstrated a 100-fold increase in printing speed, yet achieving economic viability requires an additional 100-fold improvement in either production rate or printer cost reduction.

A novel quantitative framework introduced in this research provides a roadmap for enabling cost-effective inertial fusion energy by linking manufacturing capabilities with economic feasibility through the concept of energy budget per target. Drawing on data from the 2022 Lawrence Livermore National Laboratory scientific breakeven milestone, this approach highlights actionable goals for fusion power plant designers, funding agencies, and policymakers. The findings underscore the need for sustained investment and innovation in target manufacturing technologies to unlock fusion's transformative potential for the global energy landscape.

Sources	(Saha, 2024; International Atomic Energy Agency, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Energy Technologies / Advanced Materials, Manufacturing and Recycling Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Energy Systems / Advanced Materials	
EIC taxonomy	**Sector (Primary)**	Energy
	Sub-sector (Secondary)	Energy Generation & Conversion / Nanofabrication, Microfabrication & Foundries
	Verticals	Nuclear

24

US start-up using enzymatic chemical synthesis to create carbon-negative petrochemical alternatives

Solugen is a Houston-based start-up developing a novel approach to manufacturing chemicals using plant-derived substances instead of fossil fuels.

The company combines computationally-engineered enzymes and metal catalysts to convert bio-based feed-stocks, such as corn syrup, directly into various chemicals and materials. This chemical enzymatic process is claimed to be highly efficient, producing minimal emissions and waste while achieving higher yields compared to traditional petrochemical manufacturing.

Solugen claims that their process not only replace chemicals traditionally made using petroleum and natural gas, but can produce carbon-negative chemicals for use in agriculture, construction, energy, and more.

The company's Houston factory can produce about 10,000 tons of chemicals annually. U.S. Department of Energy has committed $200 million to help Solugen achieve commercial-scale production with a new facility that can produce 75,000 tons of chemicals annually when it opens in 2025.

Sources	(Crownhart, 2024)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Energy Technologies / Advanced Materials, Manufacturing and Recycling Technologies / Bio-technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Renewable Fuels and Chemicals	
EIC taxonomy	**Sector (Primary)**	Climate & Environmental Tech
	Sub-sector (Secondary)	Natural Resources & Biodiversity
	Verticals	Biomass & Bio-based Materials, incl. Engineered Living Materials / Metals & Alloys

3.9 Robotics and autonomous systems

3.9.1 Introduction

The selected signal for robotics and autonomous systems represents some of the most cutting-edge science and engineering.

Brain swarm interfaces (BSI) have regional strategic implications as they could be used for both civilian and defence purposes (i.e. dual use). In general, robots operate independently, without the need for human intervention or centralised control. However, the lack of human control can be a disadvantage as one needs precise control over swarms of robots or drones, allowing for more complex and nuanced behaviours. BSIs allow for improved situational awareness and can provide real-time feedback to the human operator about the swarm's behaviour and performance. However, BSIs need to be designed with safety and (digital) security in mind, to prevent accidents or unauthorised access.

Box 9. What is swarm robotics?

Swarm robotics is a field of robotics that focuses on the coordination of large groups of robots, drawing inspiration from natural systems like ant colonies and bird flocks. In swarm robotics, each robot operates autonomously without a central control system, relying on local interactions with other robots and the environment to achieve complex collective behaviours. This decentralised approach allows for high redundancy, fault tolerance, and scalability, making swarm robotics suitable for tasks such as exploration, search and rescue, and environmental monitoring.

The robots in a swarm are typically simple and inexpensive, which makes the system cost-effective and robust against individual robot failures. The key to swarm robotics is the use of distributed algorithms that enable cooperation among robots, allowing them to perform tasks collectively that would be difficult for a single robot. These systems are designed to be flexible and adaptable, capable of functioning in dynamic and unpredictable environments.

Overall, swarm robotics represents a promising approach to solving complex problems through the collective efforts of simple robotic agents, leveraging principles of self-organisation and distributed control.

Sources: (Sahin, Girgin, Bayindir, & Turgut, 2008; Bayindir, 2016; Chung, Paranjape, Dames, Shen, & Kumar, 2018; Dorigo, Theraulaz, & Trianni, 2020; Dorigo, Birattari, & Brambilla, 2014; Tan & Zheng, 2013; Kolling, Walker, Chakraborty, Sycara, & Lewis, 2016; Shahzad, et al., 2023) (Dias, et al., 2021; Webster, Garattoni, & Birattari, 2016)

25

US university lab develops brain swarm interface

The Multi-robot Systems Lab's Brain-Swarm Interface (BSI) project innovatively combines Swarm Robotics and Brain-Computer Interface (BCI) technology. This interface allows users to control a swarm of robots using thoughts and eye movements, recorded via an EEG headset. Signal processing and Hidden Markov Models (HMM) decode these signals to control the swarm's dynamics through a potential field-based controller. This method was tested with a human controlling both a small swarm of three robots in a lab and a larger swarm of 128 robots in simulation. The BSI holds promise for aiding individuals with disabilities by offering a flexible, thought-based control mechanism for robotic swarms, potentially surpassing traditional joystick interfaces in versatility and degrees of freedom. This technology could revolutionise how mobility-impaired individuals interact with their environment, providing new possibilities for interaction.

Sources	(Chen S. , 2024; McFadden, 2024; Saballa, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Robotics and Autonomous Systems / Advanced Sensing Technologies	
STEP categories	Digital Technologies and Deep-Tech Innovation	
EIC portfolios	Medical Technologies and Medical Devices	
EIC taxonomy	**Sector (Primary)**	Medical Technologies
	Sub-sector (Secondary)	Non-implantable devices & In-Vitro Medical Diagnostics
	Verticals	n/a

3.10 Advanced materials, manufacturing, and recycling technologies

3.10.1 Introduction

In the area of advanced materials, the highlighted signals underscore the significance of recovering critical raw materials and their underlying geopolitical impact. For instance, helium is essential for cooling superconducting quantum computers, which require extremely low temperatures (near absolute zero) to operate. Liquid helium is used to cool the quantum processors. The global helium supply is limited, as the majority of the world's helium reserves are located in the United States, Qatar, and Algeria. Countries that rely heavily on imported helium, such as China, might be vulnerable to supply chain disruptions or diplomatic tensions that could impact their quantum computing programmes.

Signals 26 and 30 refer to the development of alternative materials such as elastocalorics and supersolid materials. Elastocaloric cooling is a technology which uses shape-memory alloys to achieve cooling and could potentially replace liquid helium in some quantum computing applications. Electrocalorics have then the potential to bring down resource dependence but also eventually global warming potential as they can avoid the use of greenhouse gases such as HFCs.

Another innovative technology referred to in Signal 27 which is helping secure critical materials and helping mitigate the effects of climate change is muon tomography which uses cosmic-ray muons to image the subsurface of the Earth, helping to identify and map (critical) mineral deposits.

The benefits of diamonds are well known in the advanced materials world as they are attractive materials in surface chemistry. In Signal 28, a Japanese university is developing diamond semiconductors. However, these materials are more expensive than the traditional silicon materials found in semiconductors. Moreover, diamond mining occurs in various countries like Russia, Canada, and Australia but also Botswana, the Democratic Republic of the Congo (DRC) and South Africa. Thus, the recovery of these materials should also be in focus to reduce dependencies.

Finally, Signal 29 exemplifies a novel metals recovery process developed in the U.S.

Box. 10 What are supersolids?

Supersolids are fascinating states of matter that uniquely combine properties of both solids and superfluids. They exhibit crystalline order, similar to a solid, which is characterised by a periodic modulation of particle density. This means that the particles are arranged in a regular, repeating pattern, much like the atoms in a crystal lattice. However, unlike typical solids, supersolids also possess superfluid properties. This is due to the coherent delocalisation of particles across the system, allowing them to flow without viscosity, a hallmark of superfluidity.

The concept of supersolidity was initially proposed in the context of solid helium, but despite extensive research, it has not been observed in this material. Instead, recent studies have successfully demonstrated supersolid states in ultracold atomic gases, particularly with dipolar atoms, which have shown supersolidity in one or two dimensions. These systems allow for the exploration of rich excitation properties, such as vortex formation and varied ground-state phases, in a highly controllable environment.

Sources: (Norcia, et al., 2021; Li, et al., 2016)

26

Researchers in US and China focus on elastocaloric materials for higher efficiency cooling without greenhouse-causing HFCs

Elastocaloric technologies employ advanced materials that release heat under mechanical stress and absorb it upon relaxation. These emerging technologies offer a promising alternative to traditional cooling and heating systems, offering significant energy savings and environmental benefits.

Separately, researchers from the University of Maryland and the Hong Kong University of Science and Technology have both recently developed memory alloys (SMAs) that create elastocaloric cooling without the use of hydrofluorocarbons (HFCs), a greenhouse gas used in the current dominant refrigeration technologies.

The researcher team in Hong Kong prototyped an electrocaloric cooling device made of nickel-titanium (NiTi) shaped memory alloys. The device broke the record for its cooling performance, claiming to be 48% more efficient than previous attempts.

The importance for finding alternatives to cooling systems is underlined by the Kigali Amendment to the Montreal Protocol. Per the protocol, most HFCs will be prohibited in new air conditioners and refrigerators by 2030. However, the eventual dependence on sourcing critical materials such as nickel and titanium may limit the development and adoption of such solutions.

Sources	(World Economic Forum, 2024; University of Maryland, 2024; Ghoshal, 2024; Refindustry, 2024; Hong Kong University of Science and Technology, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Materials, Manufacturing and Recycling Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Advanced Materials	
EIC taxonomy	**Sector (Primary)**	Advanced Manufacturing & Advanced Materials
	Sub-sector (Secondary)	Advanced Materials
	Verticals	Metals & Alloys

27

US based company leverages muon tomography used to find metal ores to relieve competition for critical metals

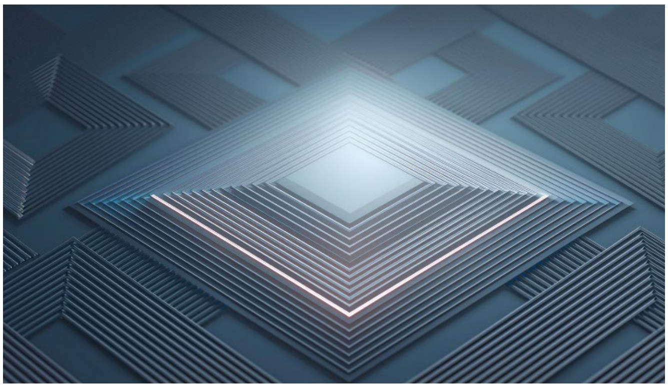
Muon tomography is an innovative technology that uses cosmic-ray muons to image the subsurface of the Earth, helping to identify and map (critical) mineral deposits. This technique is particularly valuable for finding critical metals needed for the clean energy transition. Muons are subatomic particles that are naturally produced when cosmic rays interact with the Earth's atmosphere. They can penetrate deep into the Earth, and by measuring the absorption and scattering of muons as they pass through different materials, scientists can create detailed images of the subsurface. KoBold Metals is an investment company founded in California, U.S. which bases its operation on a technology that identifies muons underground and sends back density readings of the hidden underground world.

This a new approach to identifying potential mines in a context of fast-growing demand and geopolitical competition for critical metals. By improving the efficiency and accuracy of mineral exploration, muon tomography can play a crucial role in meeting the growing demand for critical metals and supporting the transition to clean energy. Researchers have also studied its potential for pinpointing illegal cross-border tunnels.

Sources	(Bearak, 2024; Ideon, 2025)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Materials, Manufacturing and Recycling Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Advanced Materials / Responsible and Sustainable Electronics	
EIC taxonomy	**Sector (Primary)**	Climate & Environmental Tech
	Sub-sector (Secondary)	Natural Resources & Biodiversity / Advanced Materials
	Verticals	Metals & Alloys

28

Japanese university develops first diamond semiconductor powered device



Saga University in Japan has claimed to have developed the world's first diamond semiconductor power device. Diamond semiconductors could potentially offer superior performance compared to traditional materials, particularly in high-frequency and high-power applications. Diamond semiconductors can handle up to 50,000 times more electricity than silicon, operate in environments 5 times hotter, and offer 33 times stronger electrical insulation.

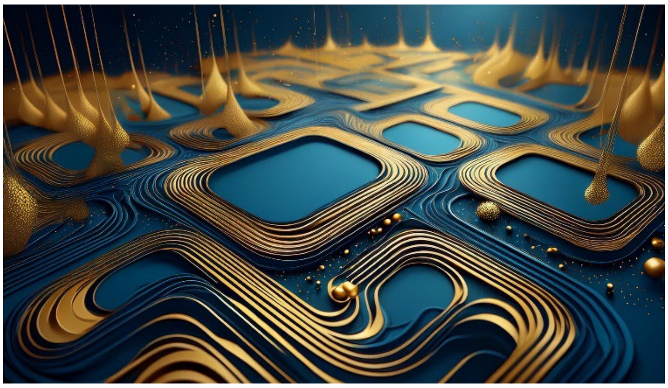
Researchers claim that these properties of diamond semiconductors could be valuable in high-radiation environments like in nuclear waste removal and in space communications, as well as electric vehicles and "beyond 5G communications".

While still in the R&D stage, practical applications are expected between 2025 and 2030, with full commercialisation likely in the 2030s. This advancement positions Japan as a leader in diamond semiconductor research, potentially reshaping the global semiconductor landscape.

Sources	(Chiang & Hsiao, 2024; Sagasaki, 2023; Mitchell, 2024)	
Technology maturity	Close to market (TRL 7-9)	
10 Critical Tech Areas	Advanced Materials, Manufacturing and Recycling Technologies / Advanced Semiconductor Technologies	
STEP categories	Digital Technologies and Deep-Tech innovation	
EIC portfolios	Advanced Materials	
EIC taxonomy	**Sector (Primary)**	Advanced Manufacturing & Advanced Materials
	Sub-sector (Secondary)	Advanced Materials / Semiconductors & Integrated Circuits
	Verticals	Glass & Ceramics

29

US university researchers apply redox-mediated electrochemical liquid–liquid extraction for critical raw material recovery



Electrochemical separations are processes that use electrical energy to separate different components in a mixture and are important for recovering critical raw materials. Traditional methods suffer from inconsistent operation. This research presents a new method using a special liquid that can change its properties with electricity to continuously separate materials. This method doesn't need extra chemicals and can selectively recover precious metals like gold and platinum from complex mixtures, such as electronic waste and mining streams.

This new approach is very efficient, recovering over 90% of the target metals and being highly selective. It can concentrate gold and platinum 16 times more than traditional methods. This innovation is crucial for national interests, offering a scalable and industrially applicable solution for separating valuable metals.

Sources	(Cotty, Faniyan, Elbert, & Su, 2024)	
Technology maturity	Emerging (TRL 4-6)	
10 Critical Tech Areas	Advanced Materials, Manufacturing and Recycling Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Advanced Materials	
EIC taxonomy	**Sector (Primary)**	Climate & Environmental Tech
	Sub-sector (Secondary)	Circular Economy & Recycling
	Verticals	Metals & Alloys

30

A "supersolid" material could replace helium, easing dependence amid the US-China tech war

In response to the helium shortage, researchers from a Chinese Academy of Sciences laboratory in Beijing, embarked on a quest for a solid material capable of achieving significant energy changes by transitioning between states.

After extensive experimentation, they uncovered a cobalt-based quantum magnetic material termed "supersolid." This material exhibits solid and fluidic characteristics, showcasing promise as an alternative coolant.

As the scientists observed, the "supersolid" material demonstrated cooling to below one Kelvin, holding the potential to achieve ultra-low temperatures. In physics, ultra-low temperatures fall between – 273.15 and – 268.95 degrees Celsius, a crucial range for advancing technologies such as quantum computing.

Professor Sun Peijie from the Beijing National Laboratory for Condensed Matter Physics emphasised the emerging frontier of using solid-state to achieve ultra-cold temperatures.

Sources	(Emir, 2024)	
Technology maturity	Novel (TRL 1-3)	
10 Critical Tech Areas	Advanced Materials, Manufacturing and Recycling Technologies / Quantum Technologies	
STEP categories	Clean and Resource Efficient Technologies	
EIC portfolios	Advanced Materials / Energy Systems / Quantum Technologies	
EIC taxonomy	**Sector (Primary)**	Advanced Manufacturing & Advanced Materials
	Sub-sector (Secondary)	Advanced Materials
	Verticals	Metals & Alloys

4 Conclusions

4.1 Signal distribution

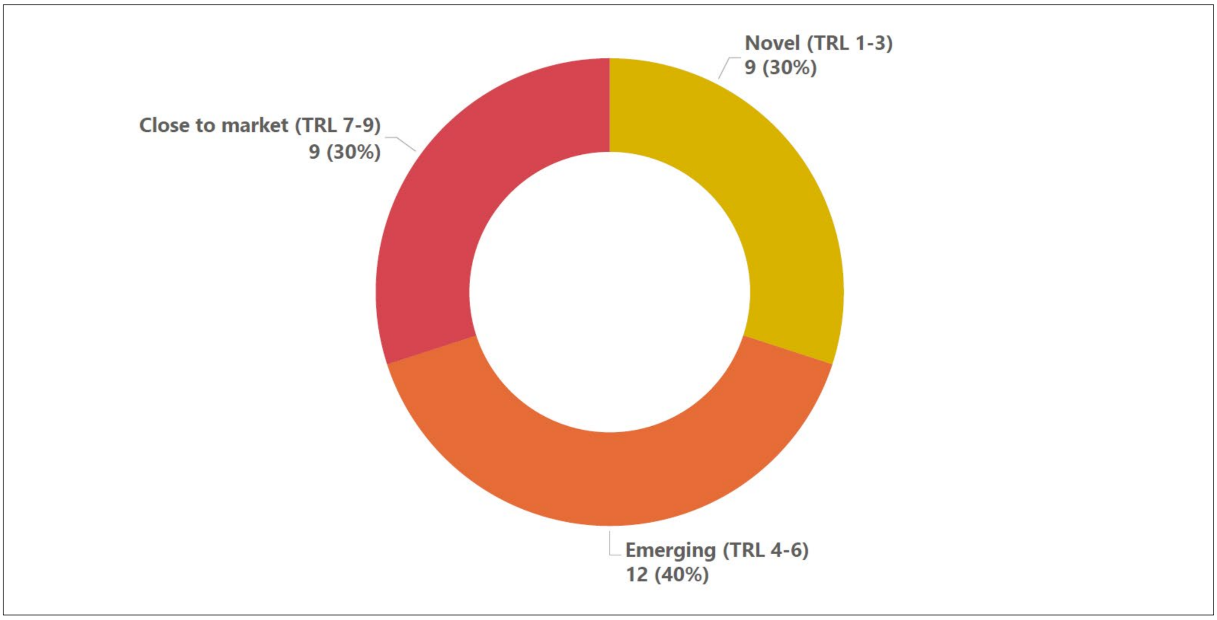
The sample size of 30 signals is small and it is difficult to justify broad conclusions. Nevertheless, some analysis is insightful, regarding in particular innovation hotspots and areas for further consideration for the EIC's strategic intelligence. To achieve this, the authors used several frameworks: the EIC’s own taxonomy and portfolio domains, the European Commission’s 10 critical technology areas (see Annex 2) and its Strategic Technologies for Europe Platform initiative (STEP – see Annex 3). The signals were assessed according to impact and novelty and maturity as explained in Sections 4.1.1 and 4.1.2.

4.1.1 Maturity

It is the authors’ understanding that novelty in the context of technology development can emerge at all TRLs. For the EIC, considering their broad range of financing mechanisms, capturing a wide scope of signals is of strategic interest. The programme supports initiatives from the earliest stages of scientific, technological, or deep-tech R&D to more mature innovative, game changing products, services, or business models that could create new markets or disrupt existing ones. Additionally, and regardless of the maturity level of the technology behind them, both disruptive and incremental innovations (Christensen, 1997) are of relevance.

However, in this literature review, and as the result of the application of the decision tree and the signal selection criteria (see Annex 4), slightly fewer signals were in TRL 1 to 3 and TRL 7 to 9 (see Figure 2), compared to the number of signals found in TRL 4 to 6. This is because the signals included in this review were selected based on their potential for geopolitical significance and not necessarily for their sheer novelty.

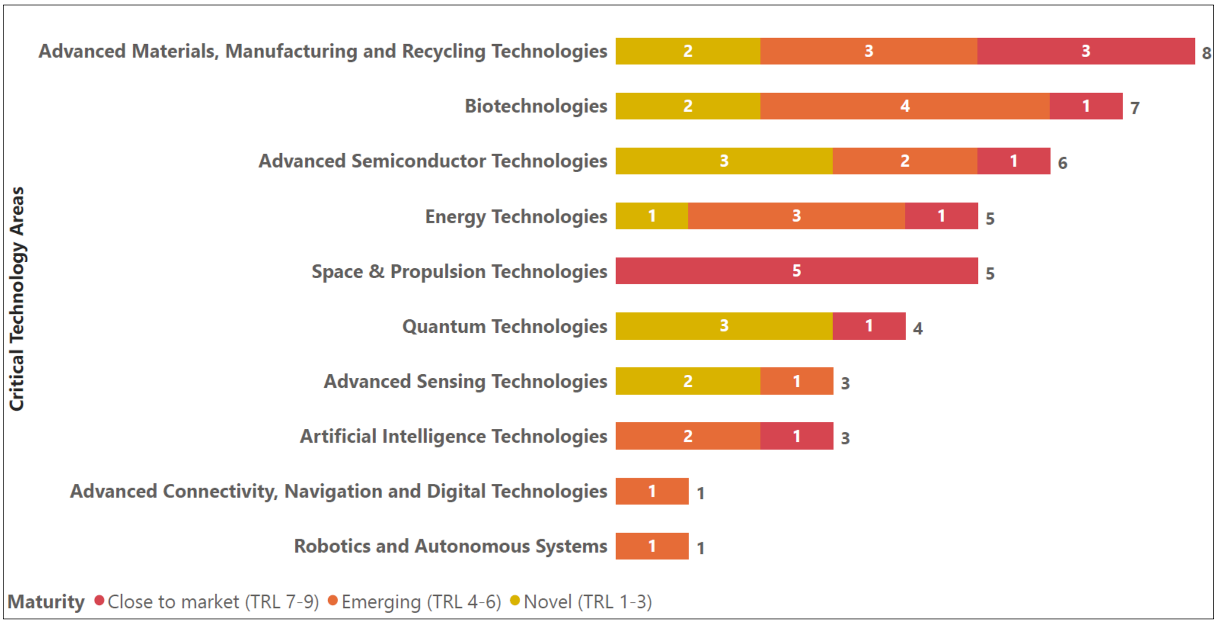
Figure 2. Distribution of the 30 selected signals according to their maturity.



Source: Authors.

The technology signals' maturity is evaluated according to available information. The distribution of technology signals within each critical technology area is demonstrated in Figure 3. The technology signals' maturity varies, with some areas encompassing more early-stage (TRL 1-3) technologies than others (see Figure 3). Nevertheless, the small number of signals does not allow for definitive conclusions from this, other than highlighting the need to continuously monitor developments that are still at the concept or lab stage, as well as innovations already being tested in pilot projects.

Figure 3. Distribution of the 30 selected signals according to their critical technology area and maturity.



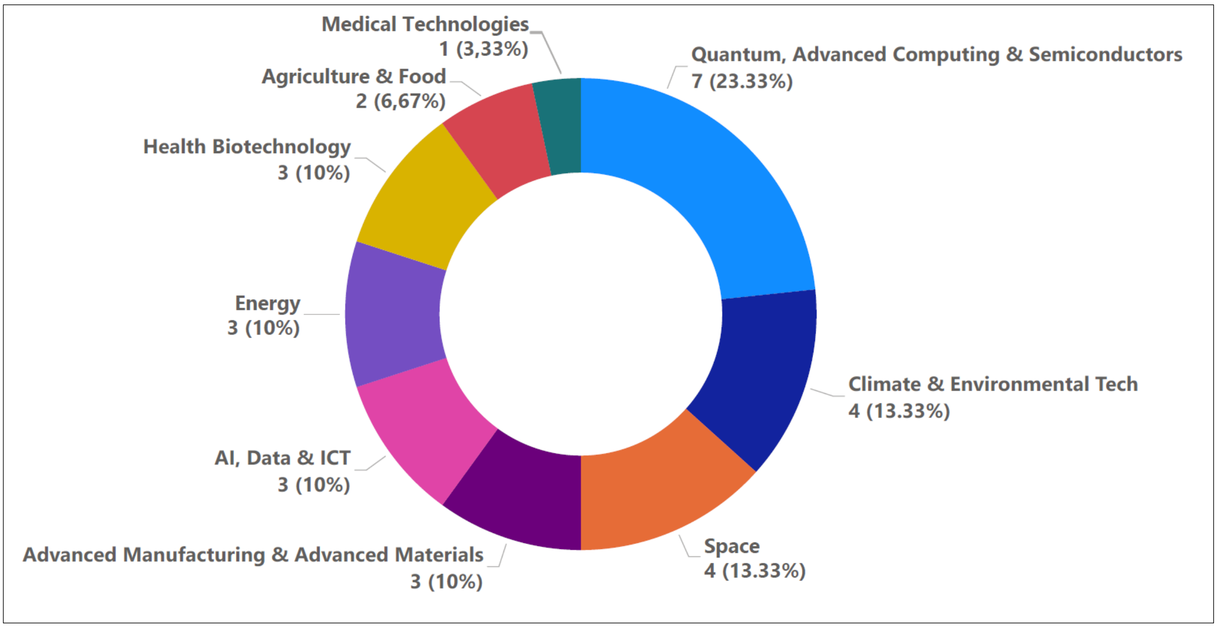
Source: Authors.

4.1.2 Critical Technology Areas

The 10 critical technology areas differ in scale and granularity. Some encompass broad, enabling technologies with applications across various fields, such as AI, while others focus on more specific technological capabilities like sensing, or economic domains, e.g. energy or space (see Annex 2 for non-exhaustive examples).

As mentioned in Section 3, for this categorisation the authors considered one main area for each signal and, when applicable, a secondary area. To ensure diversity and adequate amount of strategic intelligence for each portfolio area of the EIC, the editorial criteria for this review required the final selection to include at least one signal for each area. Nevertheless, the process of evaluating and ranking signals according to their impact and novelty resulted in an uneven distribution across the 10 critical technology areas (see Figure 4), with certain areas exhibiting a more substantial number of innovation signals. Leading this chart are Advanced Materials, Manufacturing and Recycling Technologies, and Biotechnologies, Advanced Semiconductor Technologies, Energy Technologies, and Space & Propulsion Technologies.

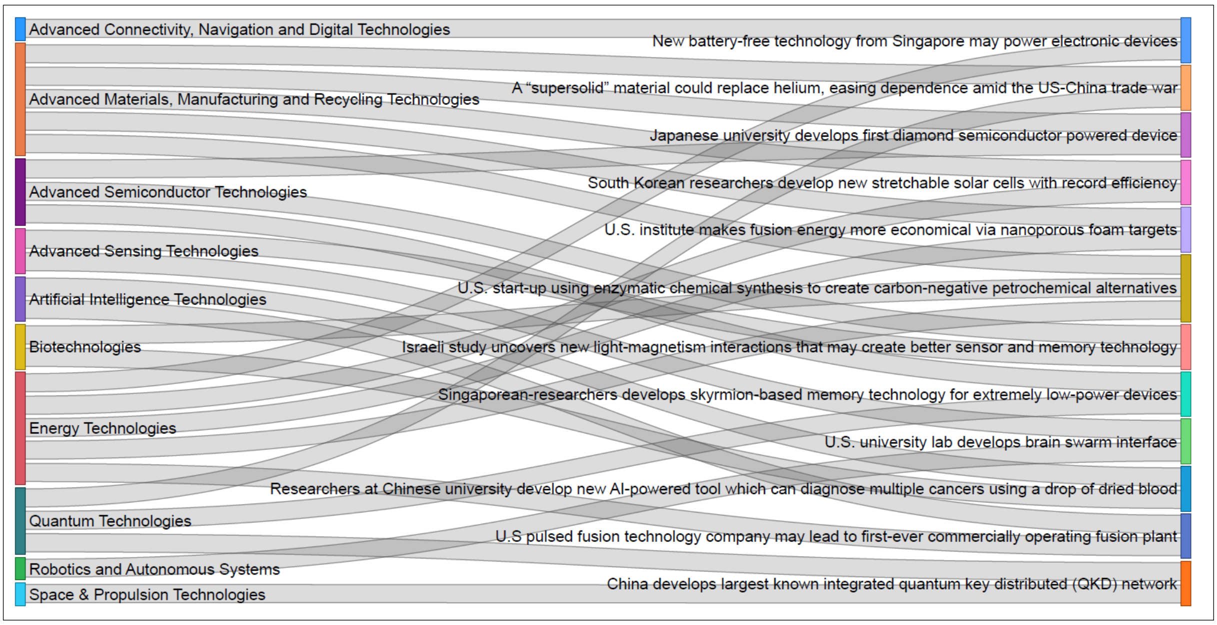
Figure 4. Distribution of the 30 selected signals across the 10 critical technology areas.



Source: Authors.

Additional insights can be extracted by analysing signals that relate to more than one critical technology area (14 out of 30), as this uncovers synergies worth exploring. Figure 5 shows that for these signals, the fields of Energy Technologies, Advanced Materials, Manufacturing and Recycling, Artificial Intelligence Technologies, Biotechnologies, and Advanced Semiconductor Technologies appear as the most horizontal and cross-cutting.

Figure 5. Signals (titles on the right) that connect with more than one Critical Technology Area (on the left).



Source: Authors.

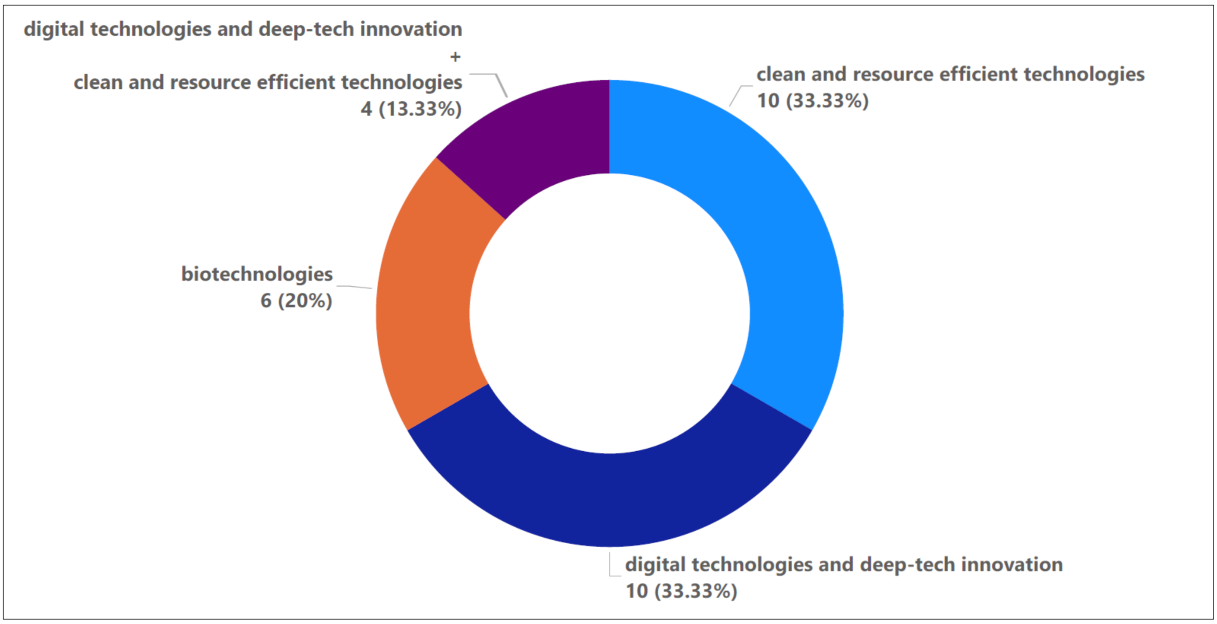
4.1.3 Strategic Technologies for Europe Platform

The Strategic Technologies for Europe Platform (STEP) (European Parliament and European Council, 2024) (see Annex 3) was established by the EU with the objective of bolstering European industry and enhancing investment in critical technologies across the continent. To achieve this, STEP is designed to mobilise and direct funding from 11 different EU programmes toward three target investment areas: Digital Technologies and Deep-Tech Innovation; Clean and Resource-Efficient Technologies; and Biotechnologies.

While STEP's focus on just three domains provides clear direction for the EU's investment, it also creates some limitations for a quantitative assessment of signals in the context of this report. Similar to what was observed with the 10 critical technology areas, the STEP framework reveals some granularity imbalances. For instance, Biotechnologies is a very specific field while potentially covering a wide range of application areas, from health and pollution control to agriculture and food production. In contrast, the other two domains are broader, encompassing a multitude of technology groups and application areas (see Annex 3 for non-exhaustive examples). Moreover, many technology signals could be associated with more than one STEP area such as both Clean and Resource Efficient and Digital and Deep Innovation technologies.

Despite these limitations, the signal distribution under this framework offers some insights (see Figure 6). There is a pronounced emphasis on Clean and Resource Efficient and Digital and Deep Innovation Technologies, reflecting their potential role in driving Europe's (technological) sovereignty.

Figure 6. Distribution of the 30 selected signals across the 3 target investment areas of the STEP, including the situations where more than 1 area is associated.

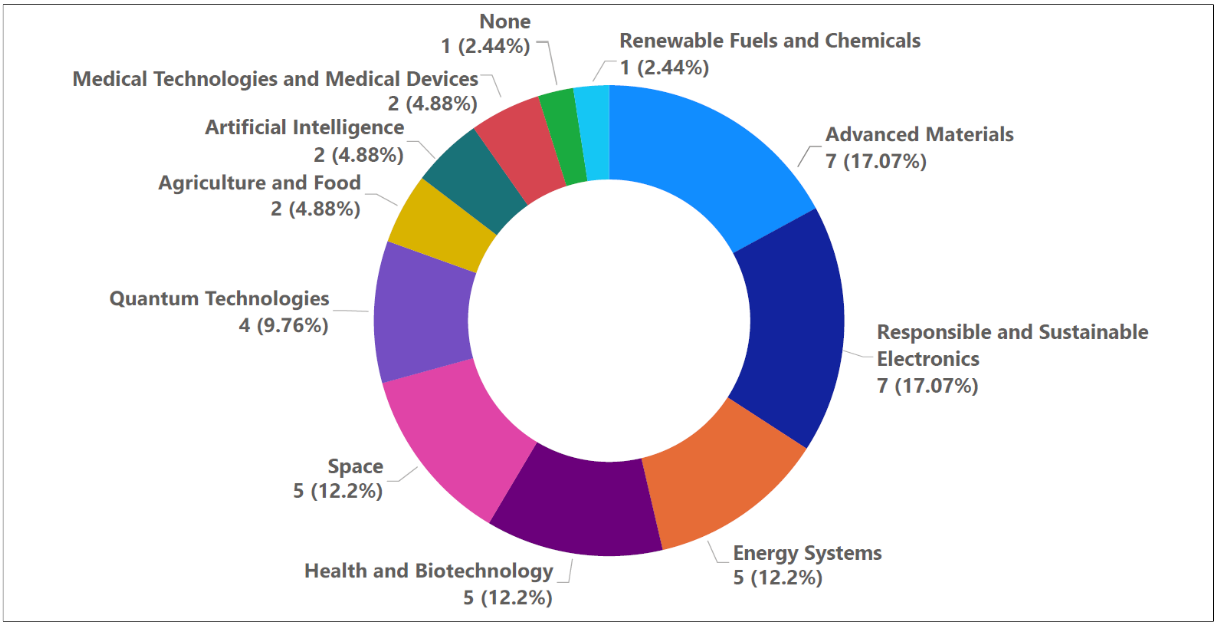


Source: Authors.

4.1.4 EIC Portfolios

When analysing the current selection of signals regarding their distribution across the EIC Portfolios (see Figure 7), the results highlight the importance of the Advanced Materials portfolio and its potential geopolitical significance. Additionally, Responsible and Sustainable Electronics, Energy Systems, as well as the EIC portfolios on Space, and Health and Biotechnology are among the most recurrent connections between the signals and the current EIC portfolio structure. Considering that this literature review incorporates a competitiveness angle, and many signals could be considered as regional strategic innovations, it might be interesting for EIC to monitor the signals in these portfolio areas more closely.

Figure 7. Distribution of the 30 selected signals across the EIC Portfolios.



Source: Authors.

Another noteworthy point relates to the selected signal (and the sectors, subsectors, and technologies associated with it) that does not connect with any EIC portfolio (see Table 2). This signal refers to innovations related to Climate and Environmental Tech.

Table 2. Signal not associated with at least one EIC Portfolio.

Signal number and title		Critical Tech Areas	Sector (primary)	Subsector (secondary)
27	**U.A.E researchers exploring use of lasers to 'shock' clouds into rainfall**	Advanced Sensing Technologies/ Artificial Intelligence Technologies	Climate & Environmental Tech	Water Management & Resilience

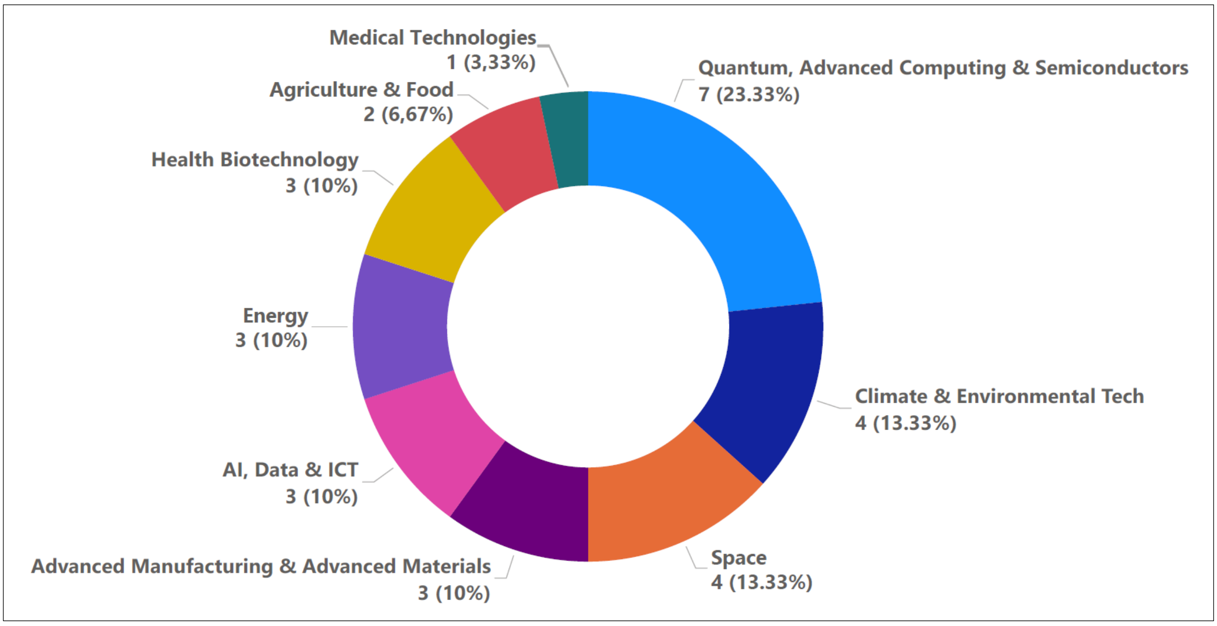
Source: Authors.

4.1.5 EIC Taxonomy

The EIC taxonomy, used in this report, facilitates a more granular signal analysis, as it consists of two levels and vertical categories (see Annex 3 for more details). Compared to other EIC taxonomies, this one, developed independently of the EIC Portfolios, provides for a more balanced distribution of sectors and additional granularity, through a detailed and diversified list of subsectors.

The use of this EIC taxonomy shows an apparent concentration of signals in certain primary sector areas, such as Quantum, Advanced Computing & Semiconductors, Climate & Environmental Tech, and Space (see Figure 8).

Figure 8. Distribution of the 30 selected signals across the sectors (primary level) of the EIC Taxonomy.

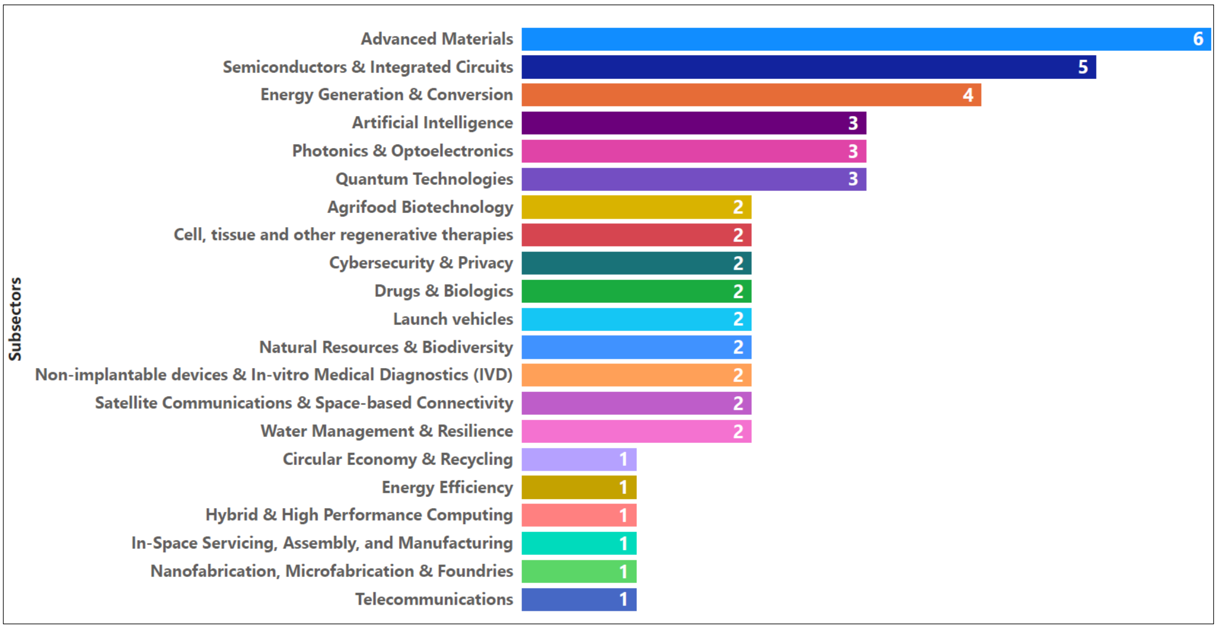


Source: Authors.

None of the selected signals could be attributed to the sectors Built Environment or Mobility. This does not necessarily indicate that those areas are less innovative or less strategically important, as the sample of signals is not large enough for such conclusions.

When an analysis is done following the secondary level, i.e. the list of subsectors, one can observe a notable recurrence of the fields of Advanced Materials, Energy Generation & Conversion, and Semiconductors & Integrated Circuits (see Figure 9).

Figure 9. Distribution of the 30 selected signals across the subsectors (secondary level) of the EIC Taxonomy.



Source: Authors.

4.1.6 Impact & Novelty

As stipulated in Section 2, for the selection of the final list, each signal was scored in two dimensions - impact and novelty – on a scale from 1 (lowest) to 5 (highest). In terms of impact, the highest grade represented a potential significant geopolitical effect. For the authors, this is closely linked to competitiveness and the need for technological sovereignty and strategic autonomy. Regarding novelty, and as noted in subsection 4.1.1, the reviewers considered all maturity levels and types of innovation (e.g. incremental or disruptive).

Although this final list includes signals that scored quite high on both dimensions, the assessment process identified four signals, among the final 30, that stand out slightly:

- Researchers in U.S and China focus on elastocalorics materials for higher efficiency cooling without greenhouse causing hydrofluorocarbons HFCs (Signal 26),
- A “supersolid” material could replace helium, easing dependence amid the US-China tech war (Signal 30),
- Developing industrial-scale microbiome mining for drug and material discovery in U.S. (Signal 10),
- Researchers in China develop 12-inch one-atom thick (2D) wafers for more efficient, higher performance chips (Signal 01).

4.2 Cross-cutting analysis and conclusions

Across the 30 selected signals, there are thematic areas potentially highly relevant to the EU context and which may warrant further investigation into R&D&I opportunities. Therefore, the authors would like to stress the following final notes.

4.2.1 Cross-cutting analysis

Many signals presented in this report refer not to significantly novel technologies, but to later-development stages or scaling-up of already existing technologies. They also point to concrete applications of technologies, namely in enhancing capabilities that bear potential for technology leadership. This is exemplified in the below signals:

- U.S. pulsed fusion technology company may lead to first-ever commercially operating fusion plant (Signal 26),
- Israel-based researchers achieve more drought-resistant tomatoes using CRISPR (Signal 12),
- U.S. based company aims to boost speeds of existing CPU and GPU through industry’s first in-package silicon photonics chiplets (Signal 02),
- China-based firm launches first batch of 15,000 satellites to compete with SpaceX’s Starlink with aims for global coverage by 2027 (Signal 18),
- India’s domestic electric propulsion system for satellites (Signal 20)

This report contains an analysis of only 30 signals, therefore statistically significant observations cannot be concluded. The authors wish to highlight that exploring incremental innovation opportunities may be valuable in the context of building and developing critical technologies and staying competitive. The hurdles to breakthrough technologies can be costly and time-consuming, requiring significant investment in development and supply chain rebuilding, when oftentimes there is an established technology available which just needs tweaking. Sometimes focusing on brand new tech breakthroughs can be distracting rather than helping critical tech industries move forward. The key consideration is that while developing numerous breakthrough technologies significantly advances research and innovation—and thereby enhances competitiveness—it does not necessarily translate into substantial progress along the learning curve or lead to meaningful reductions in cost.

The EIC supports both open and challenge-based endeavours, covering all technology maturity levels. It has been recognized that disruptive and incremental innovation may require different policy and regulatory approaches and funding structures if we are to optimally reap their benefits (Sachs, 2020). In terms of competitiveness, and achieving economies of scale through incrementalism, there seems to be some merit in having a healthy balance of incremental innovation projects in the portfolios managed by EIC.

4.2.2 Gaps identified and points for reflection

The signals surfaced in this report offer insights which have the potential to inform EIC Strategic Intelligence, either through the scope of its current portfolios or via a cross-thematic challenges'[10] approach. By completing this analysis, the authors observed gaps in the current EIC portfolio offerings compared to the technologies identified in the signals.

4.2.2.1 Climate-adaptation tech

In the context of accelerating climate change, with a potentially higher frequency of extreme weather phenomena such as droughts, the development of climate-adaptation technologies presents significant opportunities. The selected signals, namely Signal 12 (drought-resistant tomatoes) and Signal 16 (lasers to 'shock' clouds into rainfall), advance these in two key areas.

Firstly, advancements in agricultural biotechnology, such as the use of CRISPR to create drought-resistant crops, offer promising solutions to food security challenges. Further research and development of these technologies could enable their application in drought-prone regions, such as those in some member states. Secondly, innovative approaches to weather modification show potential for enhancing precipitation in these same water-scarce areas. Further testing and refining these technologies, as well as exploring their feasibility and scalability could be considered.

4.2.2.2 Neurotech

The neurotechnology field is experiencing rapid growth, with numerous promising developments emerging. Signal 25 showcases a brain-swarm interface, demonstrating the innovative combination of swarm robotics and brain-computer interface technology, enabling users to control robots with their thoughts. Signal 09 related to organoid intelligence does not refer to neurotechnology per se but is a multidisciplinary field which has to do with relying on the 3D cultures of brain cells to develop biological computing. Moreover, organoid intelligence research could also improve our understanding of brain development, learning, and memory, potentially helping to find treatments for neurological diseases. Furthermore, synergies could be developed between neurotechnology and other enabling

[10] The EIC challenges are the thematic funding calls.

technologies, such as robotics, or artificial intelligence.

4.2.2.3 Digital and network security

The digital and network security landscape is poised for significant advancements. Firstly, the development of federated approaches to AI, such as Federated Learning and Federated Operation of LLM (signal 05), offers improved privacy and energy efficiency. Secondly, the creation of integrated quantum key distribution (QKD) networks (signal 06) promises unhackable encrypted communications.

Both areas already align with existing EIC portfolios, namely Quantum Systems and Technologies and AI, demonstrating the EU's current investment in these fields. However, maintaining this forward-looking approach with a renewed focus on cybersecurity could be crucial to ensure more innovative solutions contribute to the EU's autonomy, sovereignty, and resilience in the face of evolving cyber threats.

4.2.2.4 Critical raw materials

Using the selected signals as a reference, the critical raw materials sector offers promising research and development opportunities, not only in sourcing but also in recycling and finding alternatives for those materials that are already in short supply.

Firstly, new technologies like muon scanning (signal 27), provide a fresh approach to finding new mines, making mineral exploration more efficient and accurate. This technology can help meet the growing demand for critical metals and support the shift to clean energy.

Secondly, advances in electrochemical separation techniques (signal 29) enable the efficient recovery of precious metals like gold and platinum from complex mixtures, including electronic waste. Lastly, the development of alternative materials like "supersolids" can reduce our reliance on critical raw materials like helium (signal 30).

Development in these areas can help create practical and scalable solutions, reducing our dependence on certain non-EU suppliers and traditional methods, and promoting a more sustainable and secure supply of critical raw materials.

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List of abbreviations and definitions

The following list contains the most recurring abbreviations used throughout this report. For all others, please consult the body text or footnotes.

Abbreviations	Definitions
°C	Degrees Celsius
3D	Three Dimensional
4D	Four Dimensional
6G	Sixth-generation wireless
AI	Artificial Intelligence
AVs	Autonomous Vehicles
BMIs	Brain-Machine Interfaces
CO^2	Carbon dioxide
CPU	Central Processing Unit
CRM	Critical Raw Materials
DNA	Deoxyribonucleic Acid
EC	European Commission
EIC	European Innovation Council
EISMEA	European Innovation Council and SMEs Executive Agency
ELM	Engineered Living Materials
EM	Electromagnetic
ESG	Environmental, Social and Governance
EU	European Union
FUTURINNOV	FUTURe-oriented detection and assessment of emerging technologies and breakthrough INNOVation
GNSS	Global Navigation Satellite Systems (inc. Galileo, GPS, GLONASS, Baidu, etc)
GPS	Global Positioning System
GPT	Generative Pre-training Transformer
GPU	Graphics Processing Unit
I/O	Input / Output
IC	Integrated Circuit
IoT	Internet of Things
ISO	International Organization for Standardization
JRC	Joint Research Centre
KWs	Kilowatts
Li-ion	Lithium ion
LLM	Large Language Model
MEMS	Micro-Electromechanical Systems
MGA	Miscibility Gap Alloys
ML	Machine Learning

Abbreviations	Definitions
MWs	Megawatts
NLP	Natural Language Processing
nm	Nanometre
PNT	Positioning, Navigation, and Timing
R&D	Research and Development
R&D&I	Research, Development and Innovation
RF	Radiofrequency
RFID	Radio-Frequency Identification
RNA	Ribonucleic Acid
SNN	Spiking Neural Networks
SoC	System-on-Chip
STEP	Strategic Technologies for Europe Platform
TES	Thermal Energy Storage
TOPS/W	Tera Operations Per Second per Watt
TRL	Technology Readiness Level
UK	United Kingdom
US/USA	United States of America
VUCA	Volatility, Uncertainty, Complexity and Ambiguity
WLANs	Wireless Local-Area Networks

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Annexes

Annex 1. EIC taxonomy

The EIC taxonomy used in this report represents an evolution of the versions presented in Volumes 1 and 2. It is also adaptation, for the purpose of this project, of the final version developed by the EIC in collaboration with the European Investment Bank (EIB).

This taxonomy was originally developed for internal feedback for policy and external reporting on funding allocations and impact assessments. Its simultaneous multilevel and non-hierarchical structure makes it a good framework for future-oriented technology analysis, allowing the association of signals and trends with multiple fields and domains and highlighting novel aspects and spill-over effects.

The authors disclose below only the full list of primary levels, the rules used to apply it, and the classifications used in the final selected signals (Sections 3 and Subsection 4.1.5). For more information and for the most recent version please refer to: https://eic.ec.europa.eu/horizon-europe-eic-taxonomy_en

1) List of sectors (primary level)

— Agriculture & Food

— Energy

— Climate & Environmental Tech

— Built Environment

— Mobility

— Health Biotechnology

— Medical Technologies

— Space

— Advanced Manufacturing & Advanced Materials

— AI, Data & ICT

— Quantum, Advanced Computing & Semiconductors

2) Rules for use of the EIC taxonomy, adopted through this report

— **Sector** (primary level):

- 1 mandatory selection.

— **Sub-sector** (secondary level):

- Main: 1 mandatory selection from the sector chosen before.
- Additional: 1 optional selection from any sectors.

Note 1 – some exceptions can be made to add a second additional sub-sector, namely when a signal contains very strong connections with multiple sectors (e.g. Semiconductors developed for energy-efficient AI).

— **Technologies/applications** (tertiary level):

- Main: 1 mandatory selection from the sector chosen before.
- Additional: 3 optional selections from any sector.

Note 2 – technologies/applications are not necessarily connected with a specific sub-sector.

Note 3 – for the "Social Innovation, Culture & Creative Industries" sector, the technologies/ applications should be chosen from other sectors.

— **Verticals** (only applicable if one or more of the following sectors are chosen: "Health Biotechnology"; "Medical Diagnostics"; and "Energy" and/or the subsector "Advanced Materials":

- 1 mandatory selection from the respective sector or subsector

Note 4 - Verticals are not necessarily connected with a specific sub-sector (except for "Advanced Materials") or a specific technology/application.

Note 5 – The verticals for the 2 sectors related with health are the same.

Annex 2. List of 10 critical technology areas

This list includes non-exhaustive examples of each area, following annex 1 to the Commission Recommendation (EU) 2023/2113 of 3 October 2023 on critical technology areas for the EU's economic security for further risk assessment with Member States. For more information please visit: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202302113

— **Advanced semiconductors technologies**

- Microelectronics, including processors
- Photonics (including high energy laser) technologies
- High frequency chips
- Semiconductor manufacturing equipment at very advanced node sizes

— **Artificial intelligence technologies**

- High Performance Computing
- Cloud and edge computing
- Data analytics technologies
- Computer vision, language processing, object recognition

— **Quantum technologies**

- Quantum computing
- Quantum cryptography
- Quantum communications
- Quantum sensing and radar

— **Biotechnologies**

- Techniques of genetic modification
- New genomic techniques
- Gene-drive
- Synthetic biology

— **Advanced connectivity, navigation and digital technologies**

- Secure digital communications and connectivity, such as RAN & Open RAN (Radio Access Network) and 6G
- Cyber security technologies incl. cyber-surveillance, security and intrusion systems, digital forensics
- Internet of Things and Virtual Reality
- Distributed ledger and digital identity technologies

- Guidance, navigation and control technologies, including avionics and marine positioning

— **Advanced sensing technologies**

- Electro-optical, radar, chemical, biological, radiation and distributed sensing
- Magnetometers, magnetic gradiometers
- Underwater electric field sensors
- Gravity meters and gradiometers

— **Space & propulsion technologies**

- Dedicated space-focused technologies, ranging from component to system level
- Space surveillance and Earth observation technologies
- Space positioning, navigation and timing (PNT)
- Secure communications including Low Earth Orbit (LEO) connectivity
- Propulsion technologies, including hypersonics and components for military use

— **Energy technologies**

- Nuclear fusion technologies, reactors and power generation, radiological conversion/enrichment/recycling technologies
- Hydrogen and new fuels
- Net-zero technologies, including photovoltaics
- Smart grids and energy storage, batteries

— **Robotics and autonomous systems**

- Drones and vehicles (air, land, surface and underwater)
- Robots and robot-controlled precision systems
- Exoskeletons
- AI-enabled systems

— **Advanced materials, manufacturing and recycling technologies**

- Technologies for nanomaterials, smart materials, advanced ceramic materials, stealth materials, safe and sustainable by design materials
- Additive manufacturing, including in the field
- Digital controlled micro-precision manufacturing and small-scale laser machining/welding
- Technologies for extraction, processing and recycling of critical raw materials (including hydrometallurgical extraction, bioleaching, nanotechnology-based filtration, electrochemical processing and black mass)

Annex 3. List of the 3 targeted investment areas of the strategic technologies for Europe platform (STEP)

The list includes indicating and non-exhaustive examples[11] of technologies listed in each of the 3 target investment areas - foreseen in the Regulation (EU) 2024/795 of the European Parliament and of the Council of 29 February 2024, establishing the Strategic Technologies for Europe Platform (STEP). For more information and details on each example please visit: https://strategic-technologies.europa.eu/index_en

— **Digital technologies and deep tech innovation**

- Advanced semiconductors technologies
- Artificial intelligence technologies
- Quantum technologies
- Advanced connectivity, navigation, and digital technologies
- Advanced sensing technologies
- Robotics and autonomous systems

— **Clean and resource efficient technologies**

- Solar technologies
- Onshore wind and offshore renewable technologies
- Battery and energy storage technologies
- Heat pumps and geothermal energy technologies
- Hydrogen technologies
- Sustainable biogas and biomethane technologies
- Carbon capture and storage technologies
- Electricity grid technologies
- Nuclear fission technologies
- Sustainable alternative fuels technologies
- Hydropower technologies
- Other renewable energy technologies
- Energy system-related energy efficiency technologies
- Renewable fuels of non-biological origin technologies

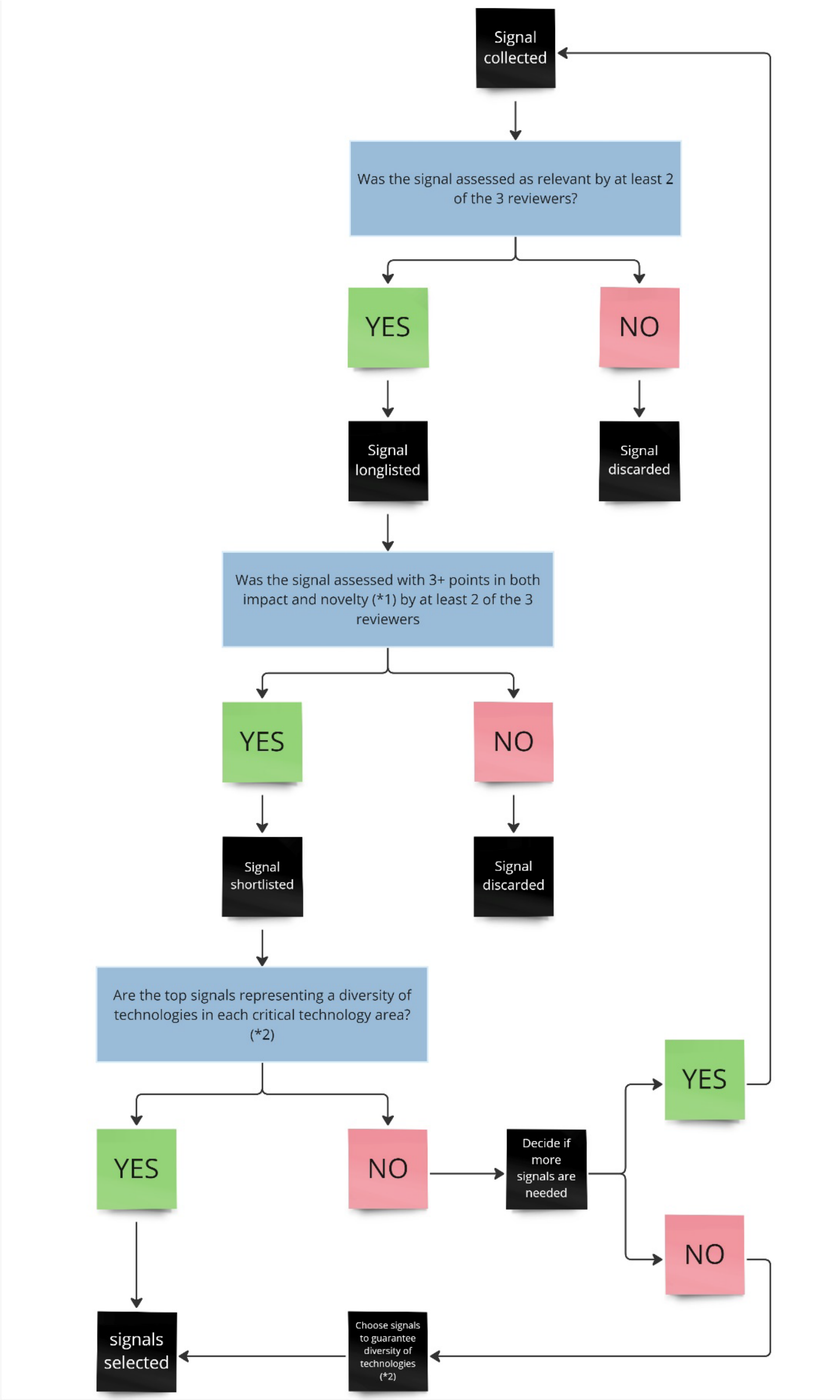
[11] As foreseen in the initiative's website at the time of this report's submission for publication.

- Biotech climate and energy solutions
- Transformative industrial technologies for decarbonisation
- CO[2] transport and utilisation technologies
- Wind and electric propulsion technologies for transportation
- Other nuclear technologies
- Other clean and resource efficient technology areas
- Advanced materials, manufacturing, and recycling technologies
- Technologies vital to sustainability such as water purification and desalination
- Circular economy technologies

— **Biotechnologies**

- DNA/RNA
- Proteins and other molecules
- Cell and tissue culture and engineering
- Process biotechnology techniques
- Gene and RNA Vectors
- Bioinformatics
- Nanobiotechnology

Annex 4. Decision tree and process flow for the assessment and selection of signals.



(*1) - The impact rating refers to the potential contribution of the technologies present in the signal for the EU's technological development and leadership. The novelty dimension refers to the signal's uniqueness, and how it could bear fewer known developments to the wider public, independently of the maturity level of the technologies behind it. (*2) - at least two signals per critical technology area and avoid repeating enabling technologies or combination of enabling technologies.

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