



Innovation Outlook

Version 1.0 Expanded Edition

Executive Summary

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New Energy and Industrial Technology Development Organization (NEDO)
Technology and Innovation Strategy Center (TSC)

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Introduction

Innovation Outlook identifies frontier areas and other areas that Japan should address to solve social challenges, based on an overview survey of the entire technology field. NEDO's Technology and Innovation Strategy Center (TSC) began formulating *Innovation Outlook* in FY2024, and *Innovation Outlook Ver. 1.0* was published in July 2025.

This *Expanded Edition* adds to and updates Chapter 3, “social challenges and frontier areas.” Specifically, based on the positioning of *Innovation Outlook*, the “vision of the future to be pursued” set forth in *Ver. 1.0*, and continuous overview survey, this edition identifies and proposes new frontier areas beyond what was covered in Chapter 3 of *Ver. 1.0*.

In the *Expanded Edition*, the beginning of Chapter 3 presents an overview of the frontier areas under TSC's jurisdiction that includes those proposed in *Ver. 1.0* and ones that were newly added. Sections 3-1 through 3-6 identify new frontier areas that have been extracted for each of TSC's six technology fields through continuous overview survey of the topics in *Ver. 1.0*. Section 3-7 designates new frontier areas and other areas identified through survey results and analysis that employed a broader perspective of the fields under TSC's jurisdiction as the newly defined fields. In each section, after presenting an overview of the field, social challenges (M) are described along with global trends in related markets, technologies, and policies. Frontier areas (F) to be addressed for solving the social challenges are then presented. Examples of specific steps to take (T) are also illustrated.

Chapter 3. Social Challenges and Frontier Areas

In *Innovation Outlook Ver. 1.0 Expanded Edition*, we started from TSC's report "*The Prosperous Future*" to be Pursued Beyond Innovation¹ (the *Prosperous Future Report*) and extracted social challenges (M) to be solved to realize the society it envisions. Based on the criteria of value provided and function, we proposed solutions in the form of areas to be addressed for innovation, and we identified those considered important as frontier areas (F).

Figure 3 shows an overview of the social challenges (M) and the areas to be addressed for innovation (F) as solutions. Among these are ones proposed as frontier areas and other areas in bright or pale yellow. The pale yellow boxes indicate those proposed in *Innovation Outlook Ver. 1.0*, while the bright yellow represents ones new to the *Expanded Edition*. In addition, the border color of each box indicates its field classification.

Examples of specific steps to take (T) to realize these areas are described for each field in the following sections.

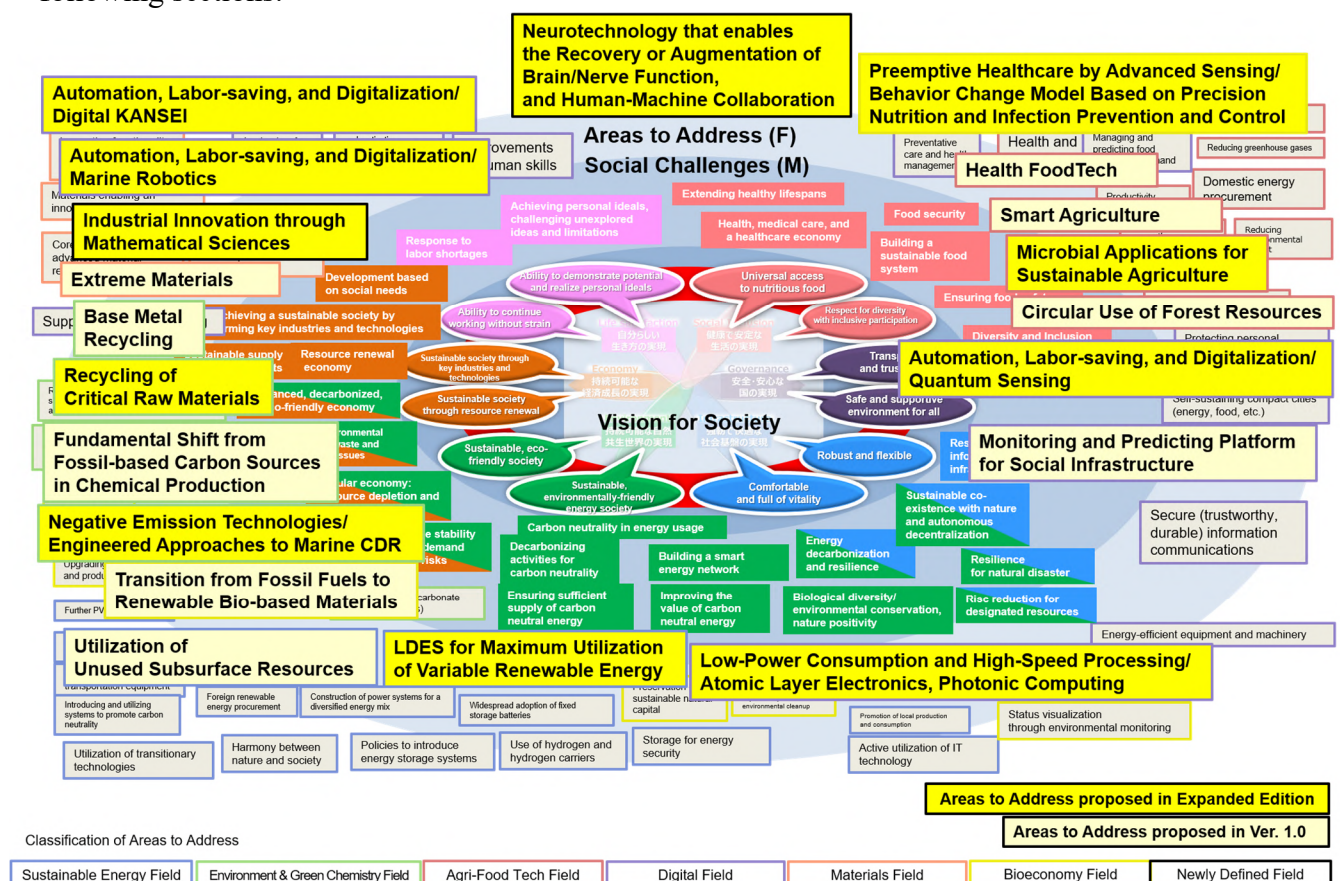


Figure 3: MF overview diagram
(envisioned society M → frontier area to be addressed for innovation F)

¹ The Prosperous Future to be Pursued Beyond Innovation (NEDO TSC, 2021) <https://www.nedo.go.jp/content/100964350.pdf> (accessed March 2026)

3-1 Sustainable Energy Field

3-1-1 Field Overview

Energy exists in a variety of forms in nature and in our environment. To make the best use of this primary energy, it is necessary to convert it into secondary energy—electricity, fuel, or heat—according to purpose. There is generally a supply-demand gap between the conversion (production) and utilization processes. Energy storage must fill this gap, and coordination must occur to balance supply and demand. In *Innovation Outlook Ver. 1.0*, the discussion focused on production and storage among the four processes shown below. In this expanded edition, storage is re-examined and specific steps to take are clarified.

Figure 3-1-1 shows an overview of the sustainable energy field.

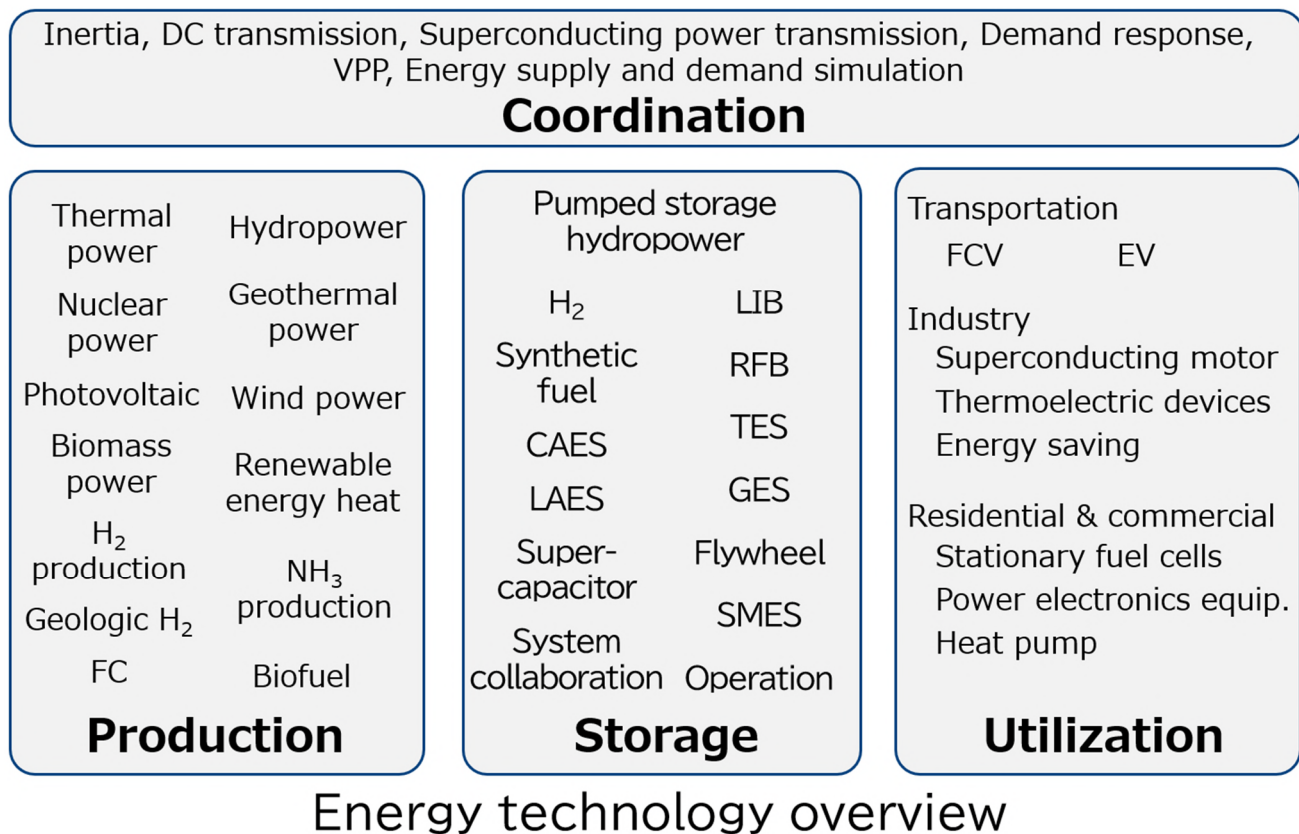


Figure 3-1-1: Sustainable energy field and technology examples

3-1-2 Social Challenges and Frontier Areas: LDES for Maximum Utilization of Variable Renewable Energy

In order to realize a sustainable society, Japan must secure and expand the use of carbon-neutral (CN) energy. This includes renewable energy and fossil-fuel based energy decarbonized through methods such as CCS (carbon capture and storage). However, the rise in photovoltaic power generation in recent years has led to a surplus of electricity during the daytime, particularly in spring and autumn, and corresponding wholesale electricity price drop. Conversely, electricity has been in short supply in the morning and evening, so wholesale electricity prices can soar depending on demand, especially during summer and winter. To be able to store variable renewable energy when supply is excessive and extract it when supply is insufficient, it is necessary to improve storage mechanisms and put them into use to promote the expansion of renewable energy and enhance its value.

In addition, improving resilience against disasters and reducing specific resource risks is becoming an important social issue. Figure 3-1-2 shows an overview of the main areas that should be addressed to solve these issues.

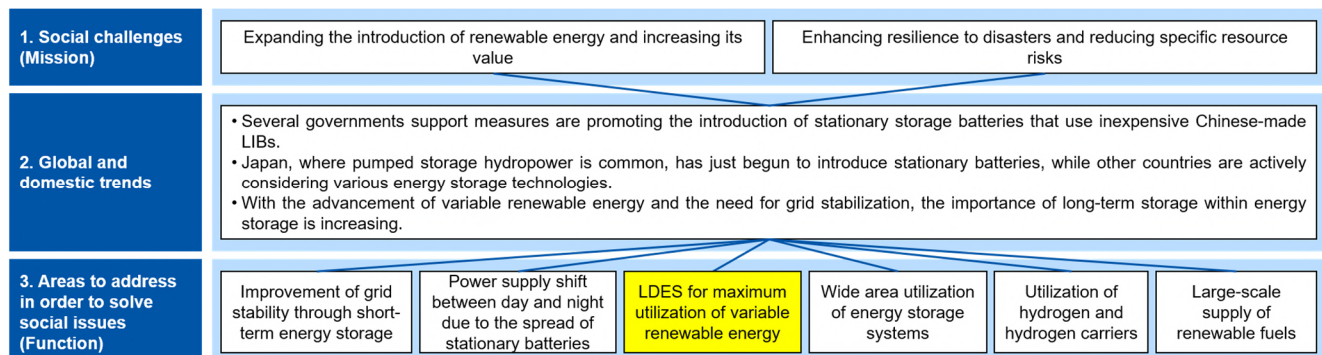


Figure 3-1-2: MF logic model of energy storage area related to the expansion of renewable energy and improved resilience

In considering frontier areas, we can use Figure 3-1-3, which organizes energy storage needs by the output obtained and the time during which that output can be sustained (output duration). In addition to small-scale emergency power supplies to protect and maintain operations, emergency power for hospitals and similar facilities, and stockpiling, the introduction of variable renewable energy is creating new needs: for daily output adjustment, as a hedge against prolonged unfavorable weather for renewables such as cloudy or windless conditions, and for disaster preparedness. To meet these needs without using fossil fuels, secondary batteries, hydrogen, and renewable fuels are expected to play a role. However, many issues remain, including cost and coverage when the output duration exceeds several hours. Therefore, this area is proposed as a frontier area, namely “LDES for maximum utilization of variable renewable energy.”

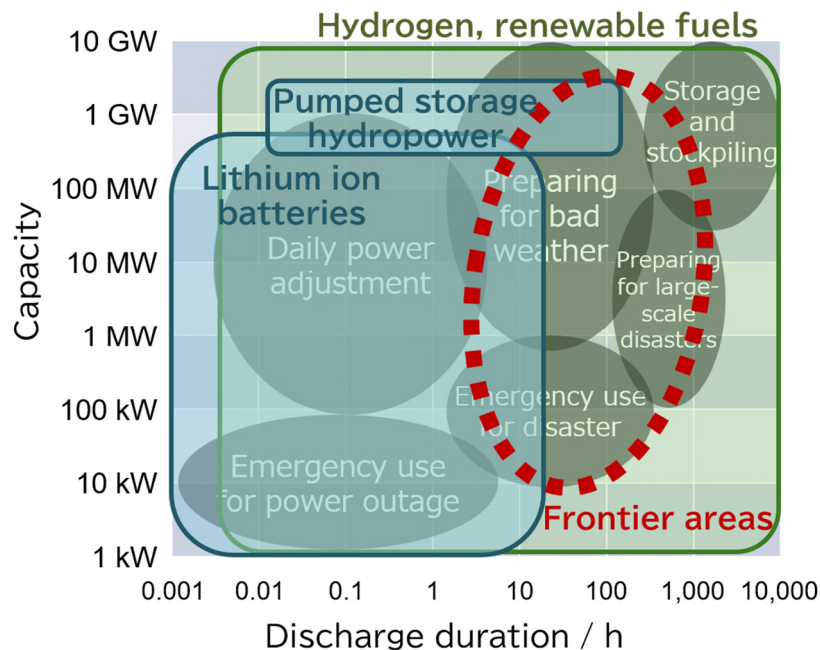


Figure 3-1-3: Frontier areas in energy storage technology

The energy storage market outside of pumped storage, hydrogen, and renewable fuels is forecast to grow from \$58.9 billion in 2024 to \$204.8 billion by 2033. Aside from lithium-ion batteries (LIBs), increasing attention has been focused on LDES (Long-Duration Energy Storage) as an innovative technology, and government agencies and venture companies in the United States, Europe, and China have been accelerating their R&D activities. The compound annual growth rate of LDES is 28.0% on a capacity (GWh) basis, and the share of LDES in total energy storage is expected to expand from 4.0% in 2025 to 11.4% in 2035.

Japan, for its part, possesses various energy-saving technologies in the form of high-efficiency heat pumps and technologies related to gas turbines and bearings. Since these can serve as foundational technologies constituting LDES, they can potentially be leveraged as Japan's strengths.

Furthermore, LDES will serve as a foundational technology for building a resilient energy system that is less susceptible to external risks like natural disasters or international disruptions. If progress is made in the development of domestic technologies that reduce dependence on scarce resources, vulnerability to geopolitical risks and market fluctuations can be mitigated, which is extremely significant from the standpoint of economic security.

3-1-3 Examples of Specific Steps to Take

In this *Expanded Edition*, in order to clarify the specific steps to take, further in-depth study was conducted on energy storage. The technologies required are mapped alongside various energy storage methods on the horizontal axis. The vertical axis starts from the upstream of the supply chain and shows materials and components, constituent equipment, and products and facilities, ending with downstream operations close to the user (Figure 3-1-4). Technologies in which Japan has strengths are underlined.

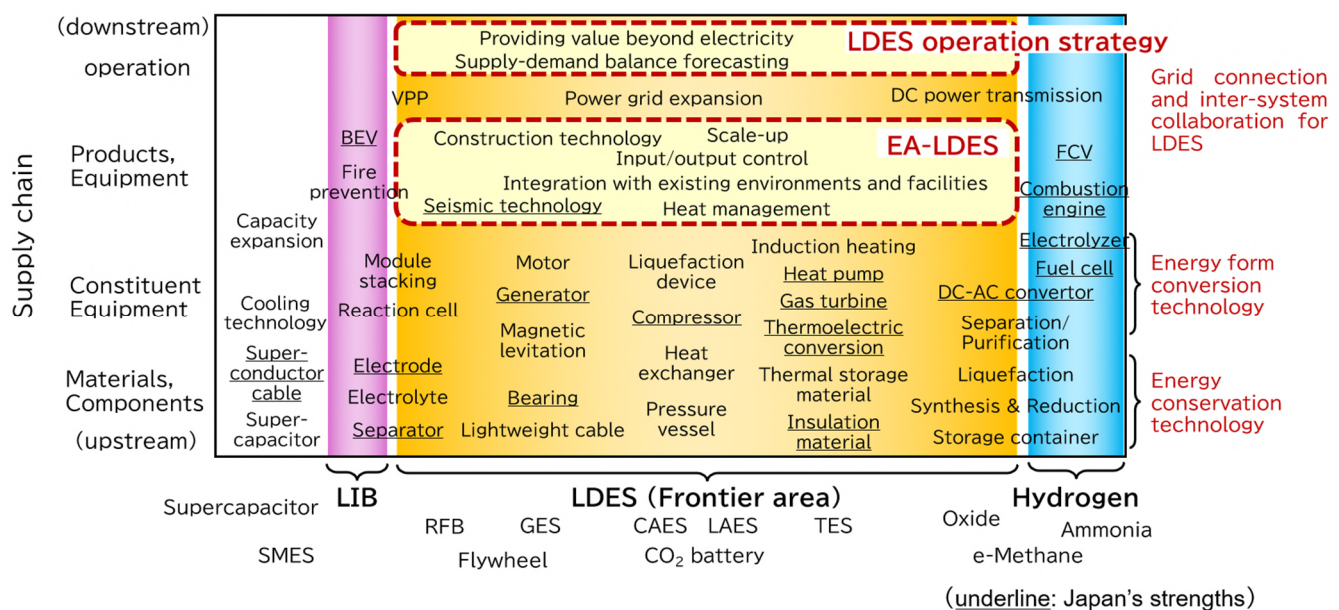


Figure 3-1-4: Mapping of technologies required for energy storage

The dark yellow range in the center corresponds to LDES. Among the elemental technologies required for LDES, there are many in which Japanese companies excel. On the other hand, efforts toward cost reduction at the system level are limited. Since 2020 in Europe and the United States, the number of startups in the LDES field incorporating innovative ideas that go beyond the framework of conventional batteries has been rapidly increasing, and large-scale demonstrations are being carried out in quick succession. Novel mechanisms that could not have been imagined within existing power generation and storage frameworks are being adopted and their effectiveness verified. These include gravity energy storage that uses a giant crane or abandoned mines and oil wells converted into energy storage infrastructure, a CO₂ battery that liquefies and stores CO₂, carbon blocks that store heat at an ultra-high temperature of 2,400°C, and underground storage that pressurized water is kept underground and utilized in place of conventional pumped storage.

If Japan's efforts in this area are delayed, most LDES will have to be imported, which could undermine energy security in the long term. It is also necessary to examine operation strategies suited to Japan's climate, power grid, and other environmental conditions in order to ease domestic deployment.

Based on these factors, economical advanced LDES and LDES operation strategy, indicated by the red dashed box in Figure 3-1-4, were judged to be specific steps to take (Figure 3-1-5).

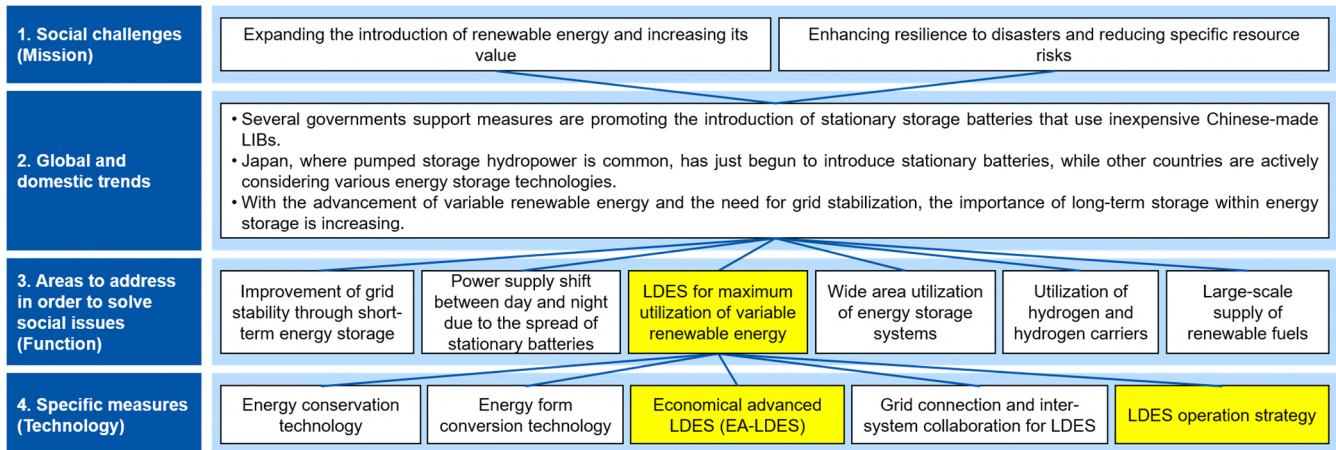


Figure 3-1-5: MF logic model related to LDES

(1) Economical, advanced LDES

Superior economic performance is key to the real-world social implementation of LDES. Unlike with LIBs, there are no restrictions imposed by a need for portability or equipment size, so development should lead to cost reduction. Many solutions can be considered, including technologies for which economies of scale can be expected; the use of existing facilities and the reuse of waste; safer designs, which reduce costs other than those directly related to equipment; added value beyond electricity such as utilization of heat and inertia; the effective use and combination of mature, inexpensive technologies (thereby improving durability and reducing maintenance costs); and freedom from constraints that are not directly required, such as energy density per unit weight, vibration resistance, and high-speed responsiveness. While making the most of the technologies Japan has accumulated to date, it is necessary to develop an economical, advanced LDES system that has a high potential to achieve cost targets, for example, 10 yen/kWh-cycle in terms of levelized cost of storage (LCOS), through demonstration of the feasibility and effectiveness of new ideas and technologies.

(2) Considering the operation strategy of LDES

As renewable energy increasingly becomes the main source of power, addressing supply-demand gaps on a scale ranging from several days to entire seasons and coping with the shortage of grid inertia and short-circuit current caused by the reduction of thermal power generation will emerge as issues. Hybrid operation with LDES equipped with turbine generators and synchronous condensers is required to support stable supplies while securing grid strength, and the effectiveness of this needs to be evaluated and verified. In addition, in order to recoup the investment in LDES—which has a low operating frequency and limited efficiency—optimized operation based on power supply and demand forecasting with AI, the construction of new business models, and market design that supports revenue (such as cap and floor schemes) will be important. Providing technical evidence to support these efforts should also be considered.

3-2 Environment and Green Chemistry Field

3-2-1 Field Overview

The technology fields of environment and green chemistry are shown in Figure 3-2-1. The realization of a circular economy and the removal of CO₂ from the atmosphere and other sources are important for realizing a sustainable society. The *Expanded Edition* focuses its examination on [1] recycling technologies for the realization of a circular economy and [2] negative emission technologies for the removal of CO₂ from the atmosphere and other sources.

Achieving a Circular Economy	Industrial Fossil Fuel Reduction	Managing Environmentally Harmful Substances
Recycling •Base metals (Fe, Al, Cu) •Plastics (mechanical & chemical recycling) •Critical raw materials (rare metals, rare earth elements, etc.) •Collection, dismantling, and sorting •Designing for easy disassembly •Data integration Carbon Recycling •CO₂ capture and separation •Cement and carbonation •Functional chemicals •Fuel and chemicals (synthetic fuels, methanol, methanation, etc.) Unused Resource Utilization •Biomass utilization •Resource recovery from wastewater, exhaust, saltwater, etc. •Water resources Business Model Innovation (e.g., the Sharing Economy)	Feedstock Conversion •Biomass fuels and SAF •Bio-based chemicals •Hydrogen-based ironmaking Fuel Conversion •Use of hydrogen and ammonia in industrial furnaces •Electrification of industrial heating Advanced Heat Utilization •Industrial heat pumps •Thermal energy storage •Waste heat recovery Energy-Efficient Manufacturing Processes •Innovative chemical process	PFAS Countermeasures •Substitution •Separation, recovery, detoxification, and recycling •Analysis Others •Low-GWP refrigerants •SLCFs *1 •Nitrogen cycle management
		Atmospheric CO ₂ Removal
		Negative Emission Technologies •DACCS*2, BECCS*3 •Enhanced weathering •DOC*4, ocean alkalization CO₂ Storage •(CO₂-) EOR*5, deep saline aquifers •CO₂ hydrates

*1 SLCFs: Short-lived climate forcers, *2 DACCS: Direct air carbon capture with storage, *3 BECCS: Bioenergy with carbon capture and storage,

*4 DOC: Direct ocean capture, *5 EOR: Enhanced oil recovery

Figure 3-2-1: Overview of activity in the fields of environment and green chemistry

[Part 1] Recycling Technologies for the Realization of a Circular Economy

3-2-2 [1] Social Challenges and Frontier Areas:

Recycling of Critical Raw Materials, Including Rare Metals and Rare Earth Elements

Critical raw materials like rare metals and rare earth elements are indispensable resources used in everything from the devices we use every day to industrial applications, and are also essential for advancing green transformation (GX) and digital transformation (DX). However, procurement risks for minerals containing these critical raw materials have been increasing, due to the uneven geographic distribution of reserves and the concentration of refined-material production in a small number of countries that arises from economic viability, environmental regulations, and labor conditions. Therefore, from the perspective of economic security, the sustainable supply of these materials is an urgent social issue for Japan.

The frontier areas (F) that should be addressed toward the sustainable supply of critical raw materials (M) are shown in Figure 3-2-2. The areas include diversification of procurement sources for refined products, development of natural resources, strengthening of smelting and processing technologies, recycling, stockpiling, reduction of usage volumes, and development of alternative materials. Among these, recycling stands out as a resource-procurement means that is relatively unaffected by geopolitical influences, since it can maximize the use of domestic resources in the form of end-of-life products and waste. In addition, it is expected to contribute to reduced GHG emissions and environmental impact compared with production from natural resources.

Based on the above, recycling of critical raw materials such as rare metals and rare earth elements is proposed as a frontier area that Japan should address.

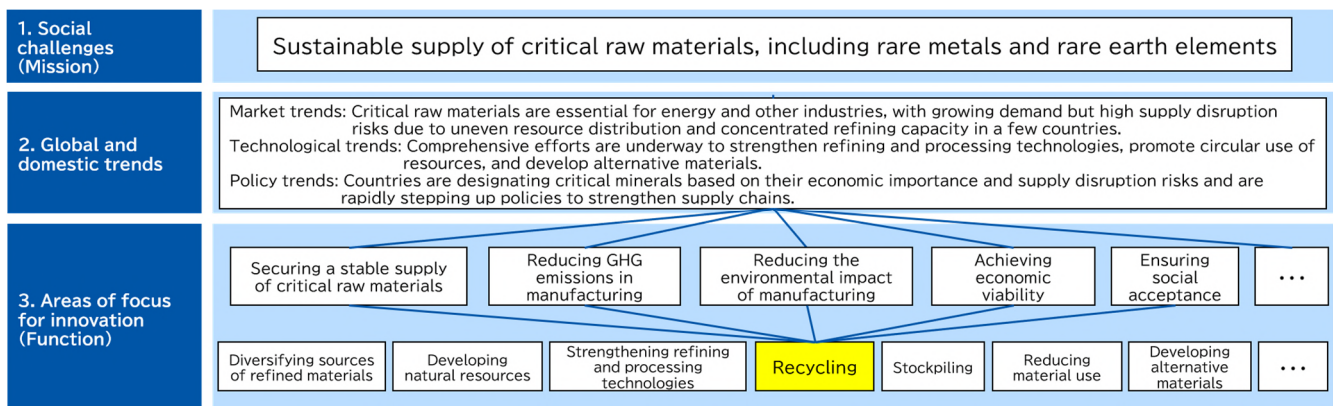


Figure 3-2-2: MF logic model for the recycling of critical raw materials including rare metals and rare earth elements

The secondary materials market for critical raw materials is expected to expand substantially in the future. According to the IEA, it is forecast to reach approximately five times its current level, or \$200 billion, by 2050.² However, while limited attempts at recycling have begun for lithium-ion batteries, rare earth magnets, and similar products, recycling rates remain low at only a few percentage points. For many critical raw materials, including those with semiconductor applications, recycling is uncommon at present due to reasons such as high cost (Figure 3-2-3). Therefore, economically viable recycling technologies would be highly innovative.

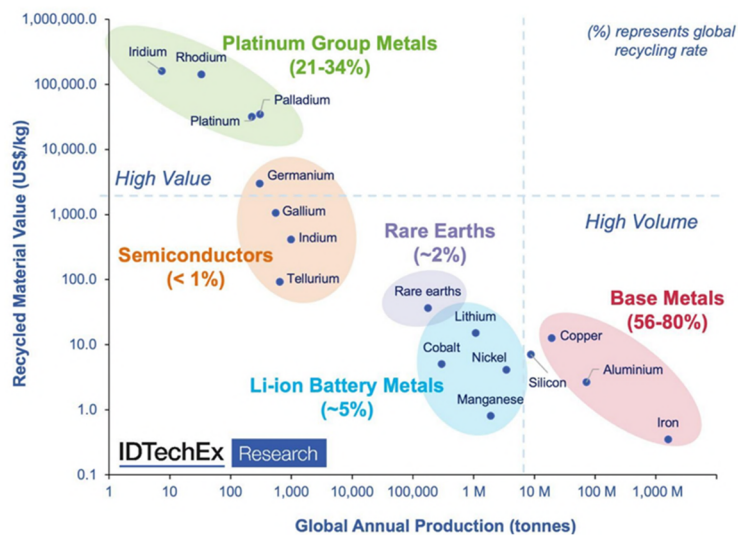


Figure 3-2-3: Overview of critical material supply, value, and recycling rates of individual elements
Source: Critical Material Recovery 2026-2046:Technologies, Markets, Players (IDTechEx)

Japan possesses technologies to recover a wide variety of critical raw materials in the forms of its non-ferrous smelting network centered on copper smelting and established, society-wide resource-recovery systems, and further development of recycling technologies that leverage these Japanese strengths is expected. Critical raw materials are subject to substantial price fluctuations due to the concentration of supply in a small number of countries, export restrictions, and other factors. This has meant that the profitability of recycling tends to be unstable, and is a major factor impeding its progress. Accordingly, economically sustainable recycling technologies and initiatives that are relatively insulated from fluctuations in mineral prices are essential. Furthermore, securing domestic supply sources that do not depend on other countries through the expansion of recycling is important for strengthening Japan's economic security.

² Recycling of Critical Minerals (IEA, 2024)

3-2-3 [1] Examples of Specific Steps to Take

Because critical raw materials are dispersed in trace amounts and in complex forms within diverse products, the recycling process is complex and contributes to high costs. In addition, in some processes, large amounts of acid and liquid wastes are generated, causing increased environmental burdens and treatment costs.

To expand and promote the recycling of critical raw materials, innovative technological development is required in each process from product design through pre-treatment to concentrate target elements (crushing, separation, and extraction) and on to refining and purification. Specific examples are shown in Table 3-2-1.

Table 3-2-1: Examples of specific steps to take in the recycling of critical raw materials

Specific steps to take	Examples of technologies
Design for Recyclability	• Modularization and detachable design of permanent magnets • Use of adhesives that enable selective disassembly • Product designs that allow access to information on elements used in waste products
Pre-Treatment Technologies for Recovering and Upgrading Critical Raw Materials from Waste Streams Prior to Refining	• Selective separation at material interfaces using high-voltage pulse fragmentation and ultrasonic cavitation fragmentation • Efficient metal recovery using supercritical water and supercritical CO₂ • AI-based and analytical techniques for rapid characterization of elemental composition in waste products
Refining and High-Purity Processing Technologies for Reducing Environmental Impact and Achieving Cost-Effectiveness	• Highly selective extraction solvents, such as deep eutectic solvents and ionic liquids • Extraction technologies with reduced use of solvents and acids, using adsorbents, ion-exchange resins, and membrane separation • Metal recovery based on biotechnology • Energy-efficient dry(pyrometallurgical) processes, such as microwave heating and plasma treatment
Resilient Recycling Technologies Robust Against Demand Fluctuations and Supply Shocks	• Recycling technologies that enable the use of shared refining processes, allowing the treatment of diverse feedstocks through adjustments in operating conditions and the flexible recovery of multiple elements
Technologies for recovering critical raw materials from underutilized resources	• Recovery of raw materials from wastewater, sewage, slag, and seawater

To efficiently recover critical raw materials that are dispersed in trace amounts and complex forms within end-of-life products, low-energy, low-cost pre-treatment technologies that concentrate the target elements prior to refining and purification are extremely important. In addition, recycling technologies that employ a common purification process and can handle diverse recycling feedstocks through changes in operating conditions, while enabling the flexible recovery of multiple elements, are promising as resilient recycling systems. Such systems could achieve both economic viability and a stable supply of resources while remaining resilient to supply-demand fluctuations and supply shocks.

To promote the recycling of critical raw materials, institutional support must accompany technological development. Multifaceted measures such as developing recovery infrastructure, introducing incentives for the use of recycled materials, and establishing public shared-use pilot facilities would help promote the recycling of critical raw materials.

[Part 2] Negative Emission Technologies for the Removal of CO₂ From the Atmosphere and Other Places

3-2-2 [2] Social Challenges and Frontier Areas:

Negative Emission Technologies/Engineered Approaches to Marine CDR

Realizing sustainable economic growth and reducing emissions of greenhouse gases like CO₂ is an urgent issue. Key initiatives toward solving this include decarbonizing and reducing energy consumption, adopting negative emission technologies, and reducing non-energy-derived GHGs through means such as feedstock conversion. But in order to decarbonize industries in which CO₂ emissions are unavoidable—for example, steel, chemicals, and cement—in addition to advancing the decarbonization of the materials and manufacturing processes, it is important that the adoption of negative emission technologies be made economically viable.

Carbon dioxide removal, or CDR, can be broadly classified into two categories based on the approach to absorbing CO₂ from the atmosphere and other places: nature-based approaches and engineered approaches. When they are evaluated in anticipation of future technological progress (Figure 3-2-4), engineered approaches have great potential for CO₂ removal, the advantage of more permanent CO₂ fixation, and accurate measurement, reporting, and verification (MRV).

CDR Technologies		CO ₂ Removal Potential	Permanence	MRV	Cost	Environmental Risk	Availability of Recovered CO ₂	Notes
Nature-Based Approaches	Afforestation and Reforestation	△	△	△	○	△	×	Rapid uptake during growth, but vulnerable to harvesting, fire, and other permanence risks.
	Soil Carbon Sequestration	△	△	△	○	○	×	Low cost, but highly variable under environmental conditions and prone to reversal.
	Biochar	△	○	○	○	○	×	High permanence, but constrained by feedstock availability and logistics.
	BECCS	△	◎	◎	△	△	×	High permanence, but challenged by biomass supply and competition for land and water resources.
	Ocean Fertilization	△	△	△	△	△	×	Difficult to quantify CO ₂ uptake, with concerns over ecosystem impacts and international regulations.
Engineered Approaches	Direct Air Capture (DAC)	○	◎	◎	△	○	○	High MRV accuracy and removal potential with renewable energy, but cost reduction remains a challenge.
	Enhanced Weathering	○	○	△	△	△	×	Concerns over heavy metals in rocks, while energy-intensive grinding and MRV remain challenges.
	Direct Ocean Capture (DOC)	○	◎	○	△	○	○	High permanence and removal potential, but ecosystem impacts and pH management remain challenges.
	Ocean Alkalinity Enhancement	○	◎	△	△	△	×	High permanence and potential; electricity demand and by-product management remain challenges.

Source: Prepared by NEDO TSC based on IPCC AR6 (2022), NOAA CDR Strategy (2023), and CICE/North X (2024). Classification into engineered and nature-based approaches is based on atmospheric CO₂ removal pathways.

•MRV : Measurement, Reporting, Verification

Figure 3-2-4: Negative emission technologies, showing the potential of engineered CDR

In particular, direct ocean capture (DOC) is considered an area where Japan's strengths in materials and membrane technologies can be leveraged, and ocean alkalinity enhancement (OAE) is gaining international popularity thanks to the possibility of removing large amounts of CO₂. Engineered approaches to marine CDR, such as DOC and OAE, have high potential for advancement through R&D and for CO₂ removal, and since seawater contains approximately 100 times more CO₂ than the atmosphere, oceanic CO₂ removal is expected to be more cost-efficient than atmospheric recovery. However, domestic development has not been sufficiently pursued (Figure 3-2-5).

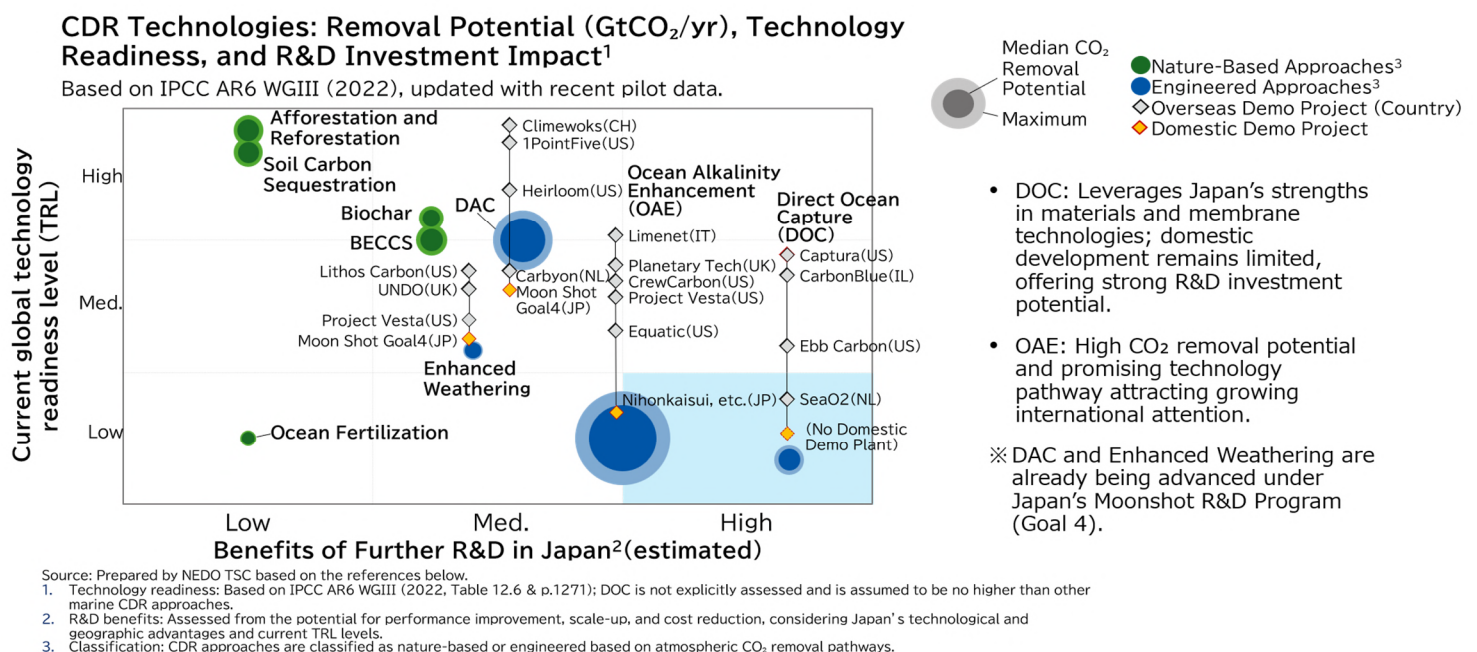


Figure 3-2-5: Removal potential and technology maturity of CO₂ recovery and storage technologies and benefits of further domestic R&D

This *Expanded Edition* proposes “negative emission technologies/engineered approaches to marine CDR” as a frontier area to be addressed for innovation (Figure 3-2-6).

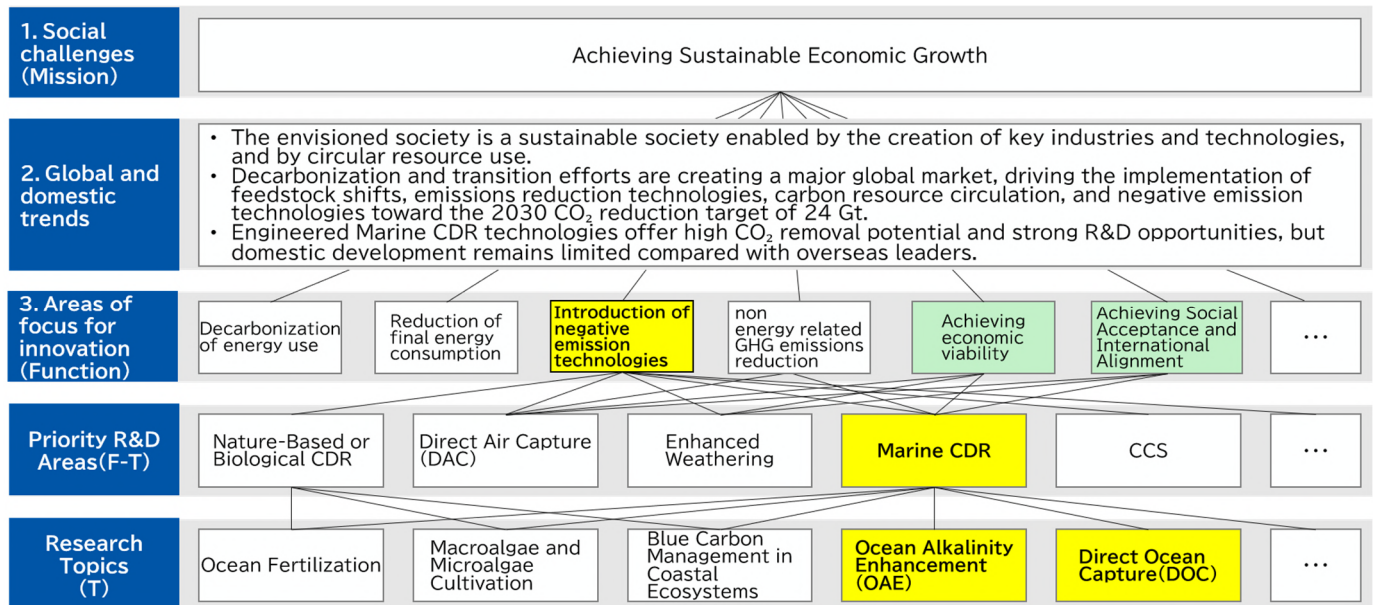


Figure 3-2-6: MF logic model for engineered marine CDR technologies

3-2-3 [2] Examples of Specific Steps to Take

R&D elements of engineered approaches to marine CDR are shown in Figure 3-2-7. It will be important to reduce input energy, equipment, and consumables costs and improve durability in order to make them economically viable. We anticipate system improvements that reduce the cost of technologies using acids generated by electrodialysis or electrolysis to release CO₂ from seawater, as well as the development of materials and membranes that directly recover CO₂ from seawater without these electrochemical methods.

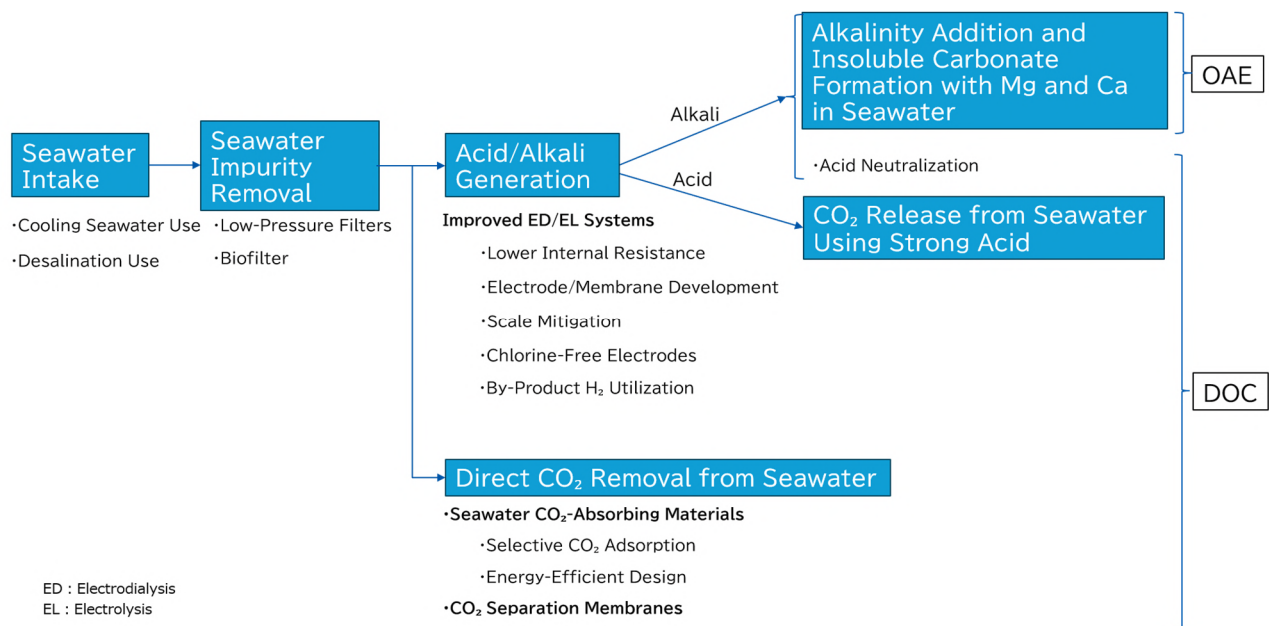


Figure 3-2-7: Examples of R&D elements of engineered marine CDR technologies

3-3 Agri-Food Tech Field

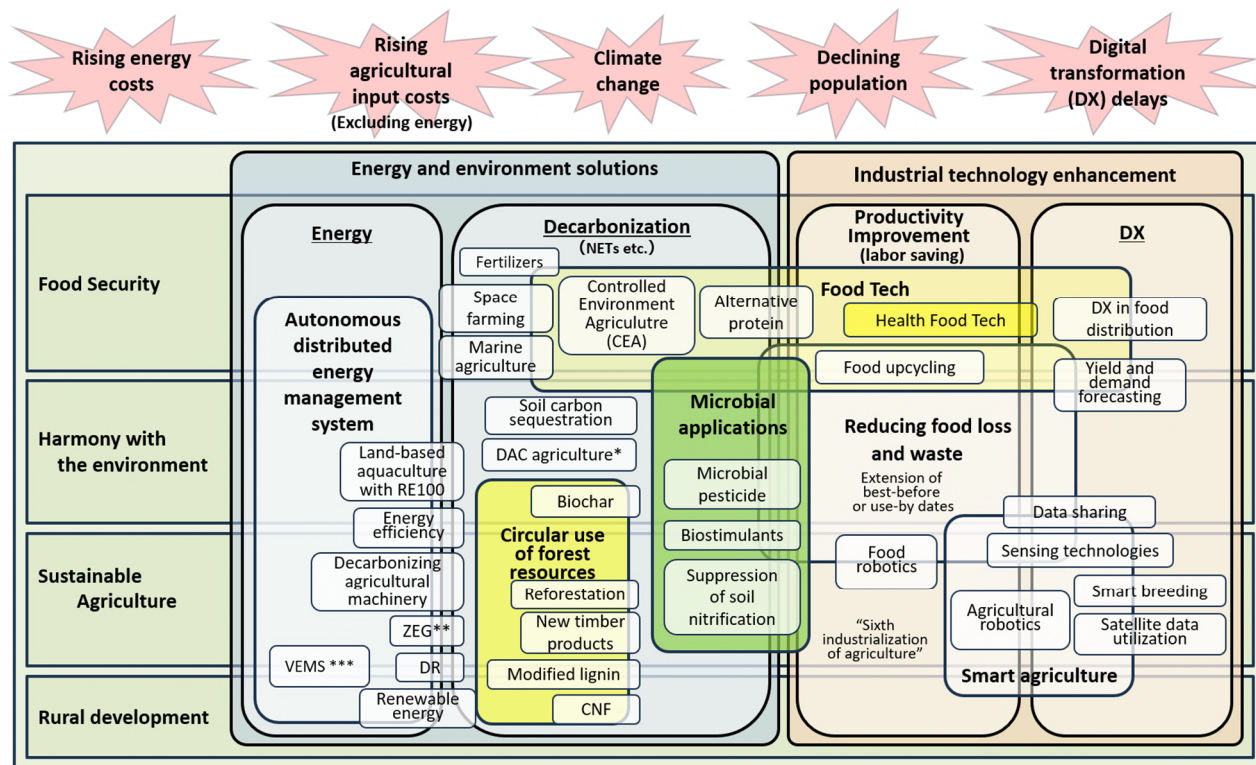
3-3-1 Field Overview

Global food demand is projected to increase substantially as the population continues to grow, raising concerns about famines and protein shortages. Combined with external factors such as climate change and international conflicts, food security issues are a concern worldwide.

In Japan, it is estimated that the number of core agricultural workers supporting production will decline to one-fourth of the current level over the next 20 years. Delays in adopting digital technology and a high level of dependence on imported fertilizers and energy make the foundation of agricultural production fragile. Agriculture, forestry, and fisheries are sources of greenhouse gas emissions due to, among other factors, substantial consumption of heavy oil in horticultural facilities and fishing boats. These sectors also place a substantial burden on the environment through excessive use of chemical pesticides and chemical fertilizers.

In order to strengthen the foundation of agricultural production and enhance the sustainability of domestic agriculture, a multifaceted approach that includes the reduction of environmental burdens is required.

Innovation Outlook Ver. 1.0 Expanded Edition organizes recent trends related to the reduction of environmental burdens and examines new frontier areas, beginning with an overview of the agri-food tech field shown in Figure 3-3-1.



* DAC agriculture is a Moonshot Research and Development Program aiming to develop crops with dramatically improved carbon-fixation capacity.

** ZEGs, or Net Zero Energy Greenhouses, are greenhouses with considerably reduced annual energy consumption through improved heat insulation, use of natural energy, and high-efficiency equipment. They also produce energy (e.g., through photovoltaic power generation) while maintaining high horticultural productivity and comfortable environments.

*** VEMS, or a Village Energy Management System, is a community EMS targeting rural areas.

Figure 3-3-1: Overview of the agri-food tech field

Elemental technologies, technology areas, and systems are organized on vertical and horizontal axes that reflect NEDO's mission and the fundamental principles of the "Basic Act on Food, Agriculture, and Rural Areas"

3-3-2 Social Challenges and Frontier Areas:

Utilization of Microorganisms Toward Sustainable Agriculture

Innovation Outlook Ver. 1.0 set “building sustainable food systems” and “strengthening food security” as social issues to be solved (M) and classified the areas to be addressed (F) into three groups: environmental improvement, securing quantity, and ensuring quality. The *Expanded Edition* explores recent trends in markets, technology, and policy and focuses on reducing environmental burdens within the theme of environmental improvement.

Initiatives around the world are expanding in regenerative agriculture, organic agriculture, and other forms of sustainable agriculture that work in harmony with the environment, and the global market for organic foods is estimated to reach approximately \$670 billion by 2034.³ Soil management and the functions of microorganisms are key in sustainable agriculture. Microbial inoculants are being looked to as substitutes for chemical fertilizers and chemical pesticides and come with the added benefits of reduced environmental burdens, plant growth promotion, plant disease and pest control, and improved environmental resistance. The global market for agricultural biologicals, including microbial inoculants, is estimated to reach approximately \$35 billion by 2030.⁴

Microorganisms are incredibly diverse, with the number of species of bacteria and fungi estimated to exceed 10 million; however, only about 1% have been isolated.⁵ Because microorganisms are difficult to isolate and cultivate and because multiple microorganisms mutually influence one another through symbiosis, competition, suppression, and other interactions, elucidating their functions had made little progress until recently. Now, owing to advances in microbial screening technologies, multiomics big data analysis of the metagenome (genetic information) and metabolome (metabolites) combined with the use of AI, and elucidation of elemental dynamics in the rhizosphere, progress has been made in exploring and clarifying the functions of microorganisms as well as elucidating interactions between microorganisms and plants. Research is being done in Japan on microorganism screening and technologies that enclose them in microdroplets, and this area is expected to be one of the country’s strengths. Japan also has well-developed fermentation technology, such as microbial utilization technologies, rooted in a food culture nurtured over many years.⁶

³ Organic Food Market (FORTUNE BUSINESS INSIGHTS) (Japanese; accessed March 2026)

⁴ Agricultural Biological Market (MarketsandMarkets, 2025) <https://www.marketsandmarkets.com/Market-Reports/agricultural-biological-market-100393324.html> (accessed February 2026)

⁵ Development of Isolation Methods for Novel Microorganisms (Bio-Manufacturing Research Center, AIST) <https://bprc.aist.go.jp/s-katou/research/theme08> (Japanese; accessed February 2026)

⁶ Explanatory Materials of the Secretariat for the First Food-Tech Working Group (MAFF, December 2025, Japanese) <https://www.maff.go.jp/j/kanbo/attach/pdf/foodtech-13.pdf> (accessed February 2026)

The MIDORI Strategy for Sustainable Food Systems mentions the reduction of the use of chemical fertilizers and chemical pesticides and the development of technologies for using biostimulants (including microbial inoculants) that contribute to their reduction,⁷ and in 2025, guidelines on the labeling of biostimulants and related requirements were established.⁸ In the EU, biostimulants are covered by 2022’s “Fertilizing Products Regulation,” and the “Soil Monitoring Law,” which came into effect in December 2025, requires the monitoring of organic matter, biodiversity, and other factors while promoting soil recovery and enhancement of carbon storage as measures to strengthen food security. Even from the perspective of biodiversity, microorganisms are of great interest.

Another noteworthy trend is that fertilizer has been designated as one of the specified critical products under the “Act on the Promotion of Ensuring National Security Through Integrated Implementation of Economic Measures.” By developing microorganism technology, we anticipate a reduction in fertilizer use and the discovery of alternative technologies.

While focusing on enhanced agricultural sustainability and the utilization of microorganisms, the *Expanded Edition* proposes the utilization of microorganisms toward sustainable agriculture as a frontier area (F) within the environmental improvement group.

An overview of this field as seen through the logic model is shown in Figure 3-3-2.

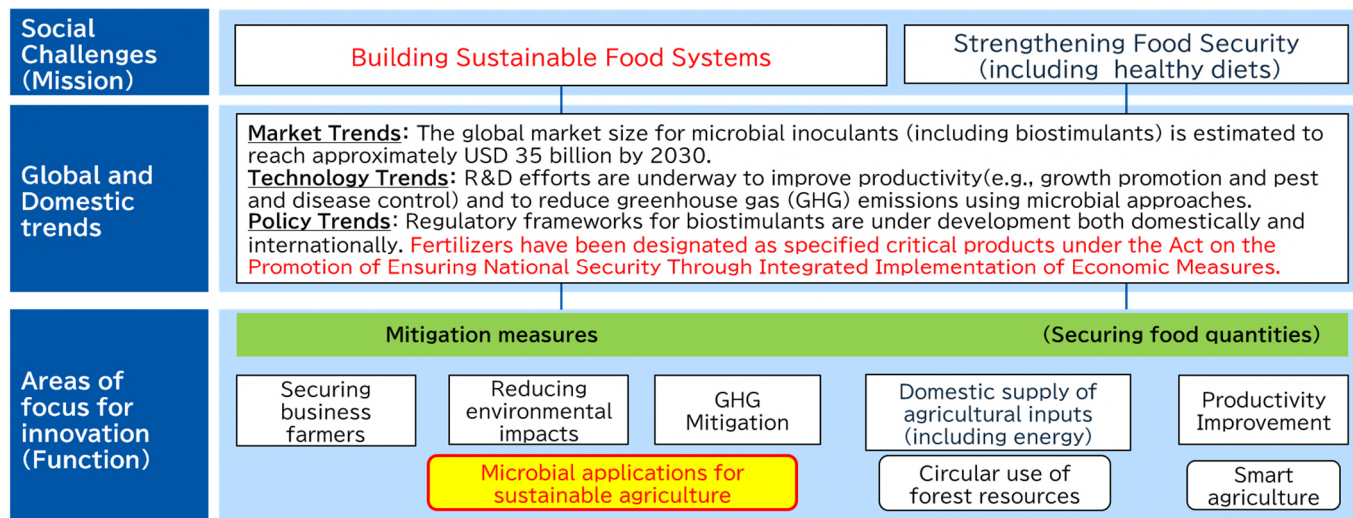


Figure 3-3-2: Social challenges and frontier areas as seen through the MF logic model

⁷ MIDORI Strategy for Sustainable Food Systems (MAFF, 2021, Japanese)

<https://www.maff.go.jp/j/kanbo/kankyo/seisaku/midori/attach/pdf/index-10.pdf> (accessed February 2026)

⁸ Guidelines on Labeling and Related Requirements for Biostimulants (MAFF, Japanese)

<https://www.maff.go.jp/j/syouan/attach/pdf/biostimulant-28.pdf> (accessed March 2026)

3-3-3 Examples of Specific Steps to Take

To realize the “utilization of microorganisms toward sustainable agriculture” proposed in 3-3-2, we anticipate the elucidation of the functions of microorganisms, the microbiome, and the interactions between microorganisms and plants. We also foresee the development of microbial inoculants that contribute to reduced environmental burden, plant growth promotion, plant disease and pest control, improved environmental resistance, and other benefits. Examples of specific steps are introduced below.

One challenge for real-world social implementation in this area is that results obtained at the laboratory level are difficult to rapidly deploy to actual farmland. Analysis and demonstration must take environmental factors into account, and it is necessary to collaborate and complement existing initiatives.

(1) Elucidation of the functions of microorganisms and the microbiome

To utilize microorganisms and the microbiome which they make up, it is necessary to elucidate their functions, mechanisms of action, interactions with plants, and related aspects.

Efforts are under way at Waseda University to characterize the interactions between plants and microorganisms, acquire useful microorganisms, build a database called the AgriSoil Microbiome Atlas, and comprehensively archive the biological, chemical, and physical factors of soil.⁹ Based on this multilayered collection of big data, the university will conduct modeling and simulations and work on the construction of a platform for sustainable farming through environmental control (Figure 3-3-3). While the current focus is on soybeans and rhizobium, it will be necessary to expand the platform to perform data collection of other major crops such as rice and its microorganisms.

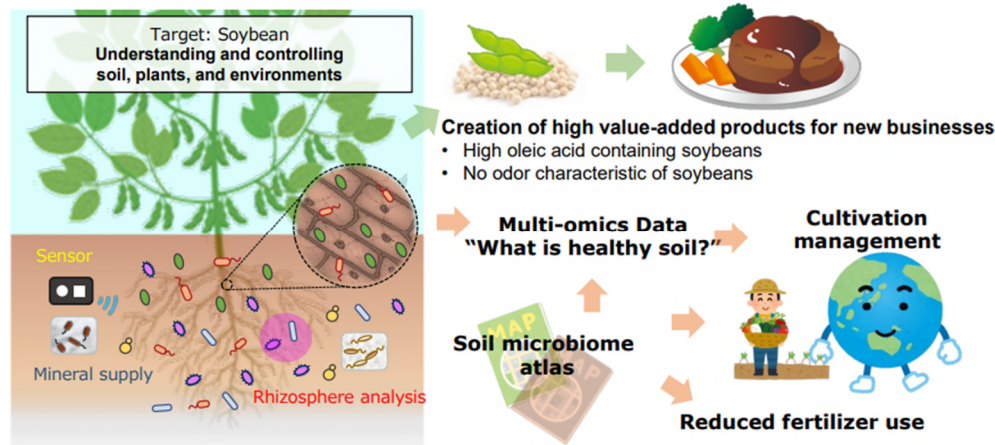


Figure 3-3-3: Examples of initiatives that elucidate the functions of microorganisms and the microbiome

Source: Moonshot Research and Development Program, Goal 5 (BRAIN)

⁹ Moonshot Agriculture, Forestry and Fisheries R&D Program (Moonshot Goal 5): Construction of a Platform for Sustainable Farming Through Environmental Control Based on the AgriSoil Microbiome Atlas (BRAIN, Japanese)
https://www.naro.go.jp/laboratory/brain/moon_shot/theme/files/MSPJ%202.pdf (accessed February 2026)

(2) Microbial nitrification suppression

As a measure to reduce GHGs, we must reduce the nitrous oxide (N_2O) emitted from farmland as a result of fertilizer use. If nitrification can be suppressed along the pathway from ammonia nitrogen through nitrate nitrogen to N_2O , we can also expect the erosion of fertilizer components to be prevented.

Technology to suppress N_2O generation from soil with microorganisms is being developed at Tohoku University. Plant symbiotic microorganisms such as rhizobium are capable of reducing N_2O , and nitrogen-fixing bacteria that live on rice plant roots can perform oxidation of CH_4 (methane). Efforts are under way to elucidate these GHG reduction mechanisms at the molecular level (Figure 3-3-4).¹⁰ To reach the target of an 80% reduction in GHG emissions from farmland, the establishment and dissemination of such technology in actual cultivated fields need to be pursued.

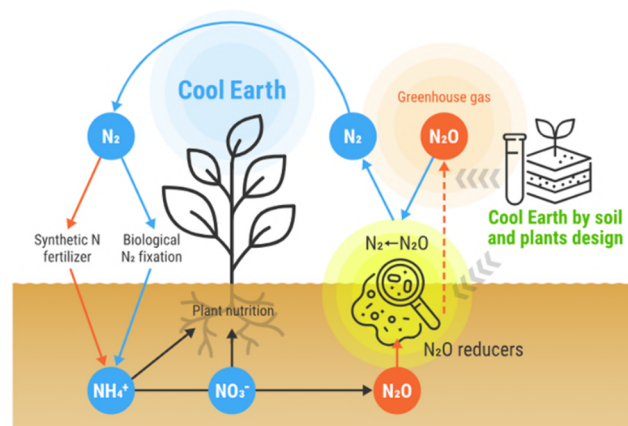


Figure 3-3-4: Examples of initiatives for the mitigation of N_2O emissions using microorganisms

Source: Moonshot Research and Development Program, Goal 4 (dSOIL)

¹⁰ Cooling the Earth With Microorganisms (dSOIL Project Secretariat) <https://dsoil.jp/en/> (accessed February 2026)

(3) Microbial pesticides

To reduce the use of chemical pesticides, the development of novel control agents with low environmental risk is required. Microbial pesticides are agents that leverage biological actions among microorganisms, such as competition, suppression, and parasitism, and are expected to reduce the risk of the emergence of chemical resistance and pesticide-resistant pests.

At Pennsylvania State University in the United States, tomatoes in an experimental facility were subjected to spray treatment with microorganisms extracted from field tomatoes. After inoculation with a bacterial speck disease pathogen, a reduction in pathogen amount was confirmed, indicating microorganisms may provide a disease control effect.

At the National Institute of Advanced Industrial Science and Technology (AIST), research is under way to elucidate the mechanisms of predatory bacteria with the aim of building a foundation for integrated pest management to treat against soil-borne disease.

(4) Biofertilizers and agricultural biologicals

The development of biofertilizers and agricultural biologicals such as biostimulants can reduce the use of chemical fertilizers. However, biofertilizers and agricultural biologicals may not have consistent results depending on environmental factors such as crop type and soil makeup.

In the United States, a company called Pivot Bio is focused on the fact that ordinary nitrogen-fixing bacteria have reduced nitrogen fixation activity under high-nitrogen conditions due to the *nifL* gene. They hope to use genome editing technology to disable it and promote nitrogen fixation even under high-nitrogen conditions. Their efforts are drawing attention as a way to commercialize biological nitrogen fixation (BNF) for corn.

3-4-1 Field Overview

As shown in Figure 3-4-1, the digital field comprises the field of IT, including AI and other technologies that generate and process data; application fields such as automotive and robotics that leverage IT; and foundational fields such as electronics and semiconductors that support IT.

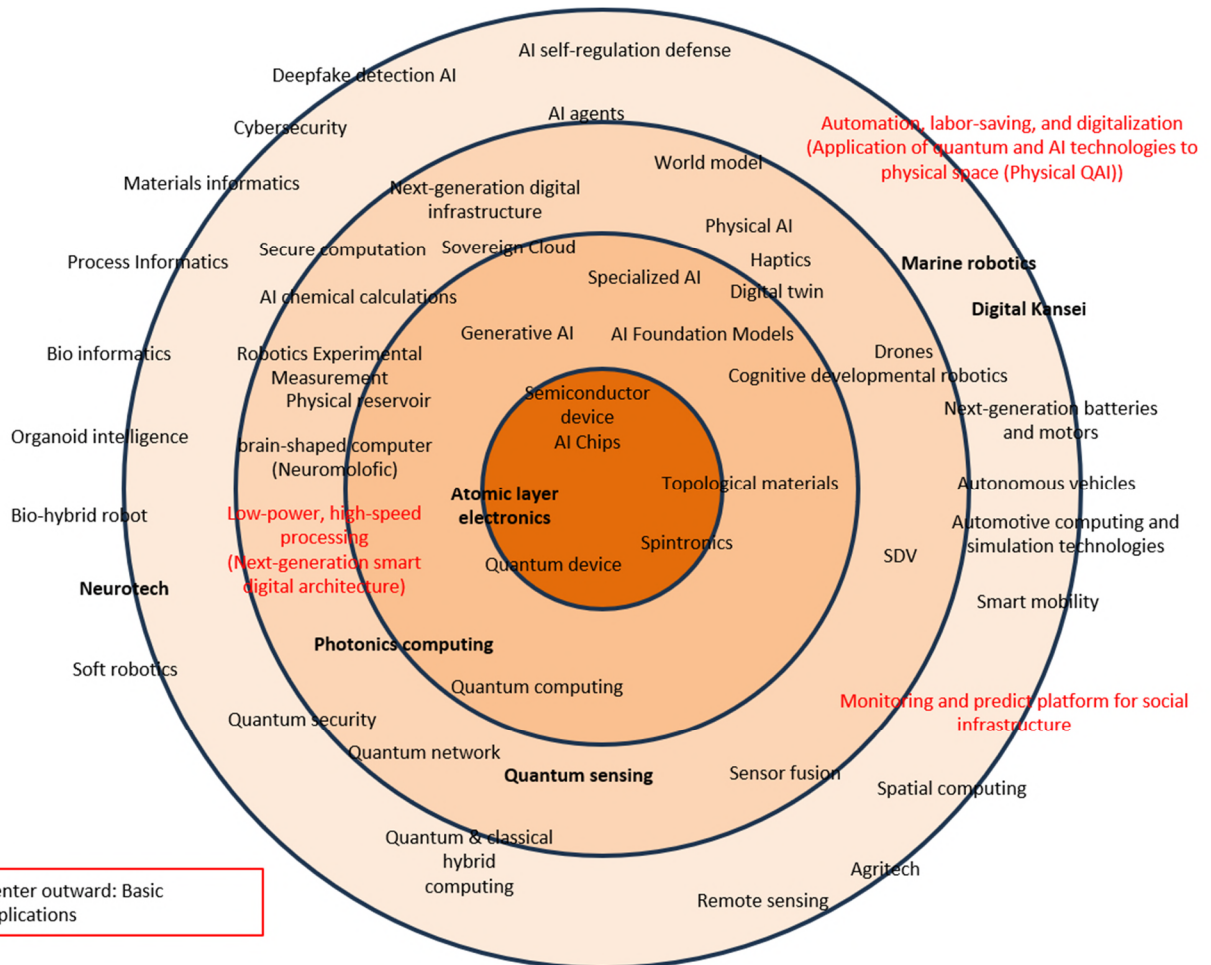


Figure 3-4-1: Overview of the digital field

3-4-2 Social Challenges and Frontier Areas:

Low Power Consumption and High-Speed Processing (Atomic Layer Electronics and Photonic Computing)

Automation, Labor-Saving and Digitalization (Quantum Sensing, Marine Robotics, and Digital KANSEI)

The digital field plays a role in solutions to almost all social issues including those addressed by other fields. Among the achievements which must occur in order to solve social issues, those functions that could potentially be realized using technologies related to the digital field are organized here.

We evaluated the magnitude of social impact for the six value axes considered in the *Prosperous Future Report*. When each function will be implemented in society was estimated as the “realization timing,” referring to the concept of TRL (Technology Readiness Level). Figure 3-4-2 plots the functions according to their realization timing and magnitude of social impact.

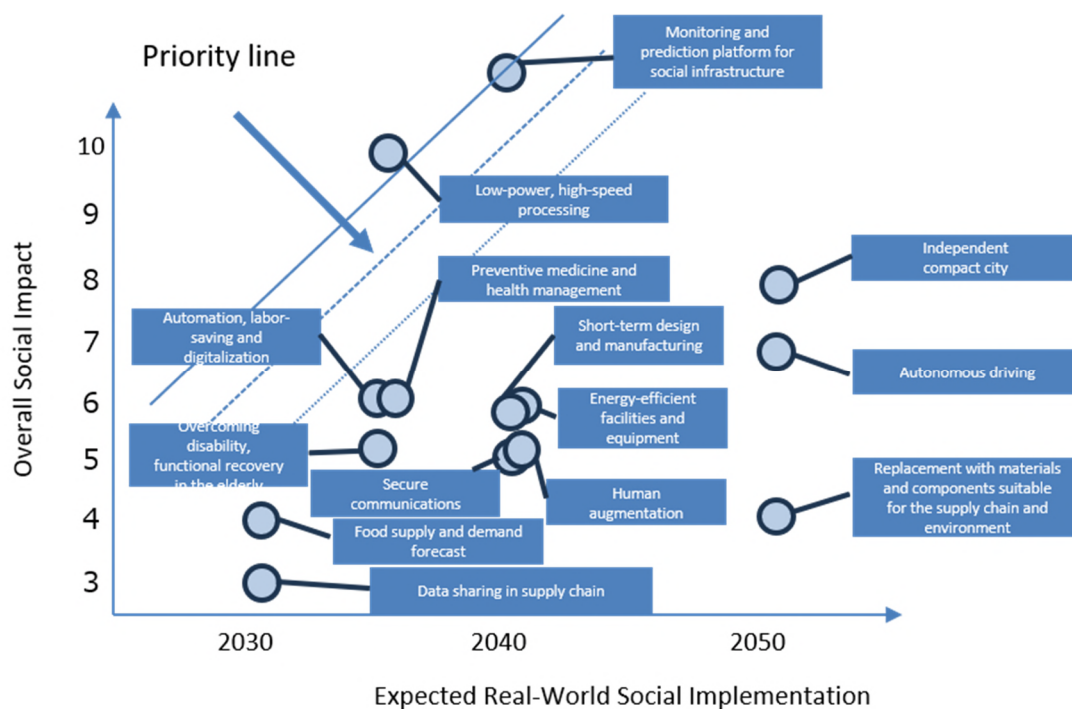


Figure 3-4-2: Social impact and realization timing of the functions

Based on these results, *Innovation Outlook Ver. 1.0* proposed low power consumption and high-speed processing, a monitoring and predicting platform for social infrastructure, and automation, labor-saving and digitalization as frontier areas to be prioritized, because these have a large impact on society and can be achieved in the near term. After further examination, the *Expanded Edition* proposes more specific areas. Within low power consumption and high-speed processing, atomic layer electronics and photonic computing are proposed as frontier areas. Under automation, labor-saving and digitalization, quantum sensing, marine robotics, and digital KANSEI are proposed as frontier areas.

(1) Low power consumption and high-speed processing (next-generation smart digital architecture)

Generative AI has developed remarkably quickly, and is expected to increasingly be used to boost economic growth and strengthen the industrial base overall. It can also contribute significantly to solutions for social issues such as work-style reform and the declining working-age population. On the other hand, in order to achieve carbon neutrality by 2050, it will be necessary to substantially reduce the enormous amount of electricity consumed by the development and use of generative AI (Figure 3-4-3). Specifically, in addition to reducing power consumption at data centers, it will be important to develop innovative AI chips and systems that enable generative AI to operate with low power consumption at the edge, where use is expected to increase. Atomic layer electronics and photonic computing, which are hardware approaches to reducing electricity consumption during information processing, are proposed as areas to be addressed.

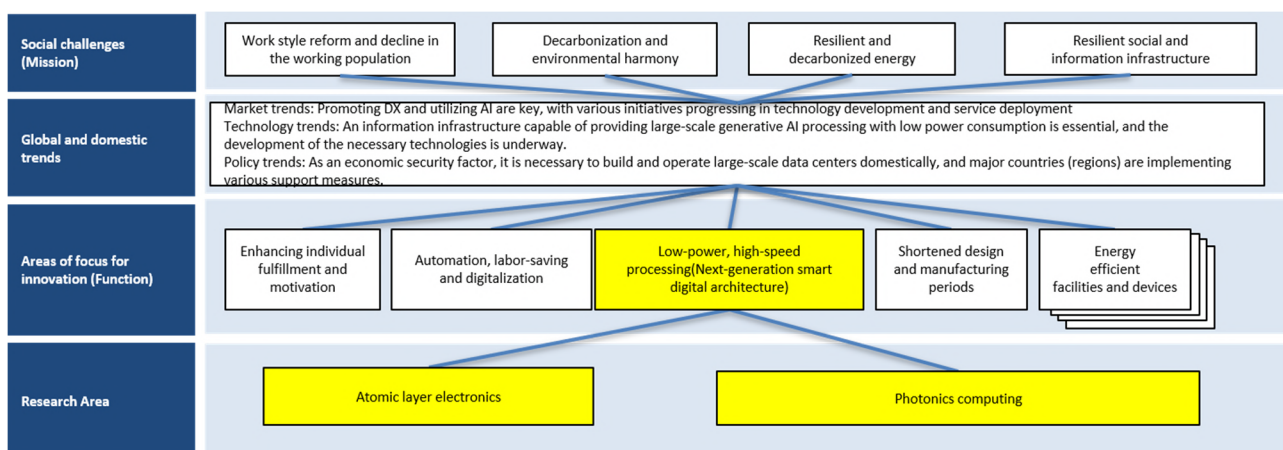


Figure 3-4-3: MF logic model for atomic layer electronics and photonic computing: low power consumption and high-speed processing (next-generation smart digital architecture)

(2) Monitoring and predicting platform for social infrastructure

As described in *Innovation Outlook Ver. 1.0*, a monitoring and predicting platform for social infrastructure is important to enhance the resilience of social infrastructure and respond to natural disasters and pandemics. Furthermore, by incorporating related technologies into the circular economy during non-emergency situations, they can contribute toward maximizing production and service activities—for example, through greater efficiency in agriculture—and this area has the

potential to develop into a solution for a broader range of social issues, thus delivering a substantial impact.

Therefore, the future vision of a digital society will be considered from a broader perspective targeting social infrastructure, and the specific areas to be addressed to achieve it will be continuously reexamined and presented in *Ver. 2.0*.

(3) Automation, labor-saving and digitalization (physical Q & AI; the application of quantum and AI technologies to physical space)

As the working-age population declines and society ages, it is becoming more and more difficult to pass down the knowledge and skills of proficient workers and secure human resources for manufacturing, logistics, construction, long-term care, and the maritime sector. Technological development must achieve automation and labor-saving, including through the use of physical AI.

If we can measure and digitize objects that have been difficult to measure with conventional sensing technologies, or measure them with even higher precision, the creation of new industries can be expected. One can anticipate the application of quantum technology for this purpose, and in particular, quantum sensing. This enables the precision measurement of objects that could not be measured conventionally by leveraging quantum phenomena, and is a key area for launching new quantum industries in fields such as semiconductors, aerospace, national resilience, and healthcare.

Japan is a maritime nation with the sixth-largest maritime zones under national jurisdiction in the world. The anticipated development and utilization of these vast waters is hampered by the fact that human resources (crews and divers) are in short supply. Marine robotics such as AUVs (autonomous underwater vehicles) and USVs (unmanned surface vehicles) are needed to address labor shortages, improve productivity and working environments, and enhance safety in the maritime industry.

On the other hand, relying on generative AI for automation and workforce reduction risks harming diversity, individuality, and workplace culture, since it averages information based on large amounts of data. The Japanese concept of *kansei*¹¹, which takes into account individual sensibilities while helping to enhance them, when applied in the form of digital KANSEI, can contribute not only to automation and labor-saving but also increase each individual's sense of purpose and motivation, improve human abilities and individual well-being, and realize an inclusive society.

¹¹ Kansei is a uniquely Japanese concept describing the integrated human capacity for sensation, perception, emotion, intuition, aesthetic appreciation, and value judgment.

Accordingly, quantum sensing, marine robotics, and digital KANSEI, which promote automation, labor-saving and digitalization, are proposed as areas to be addressed (Figure 3-4-4).

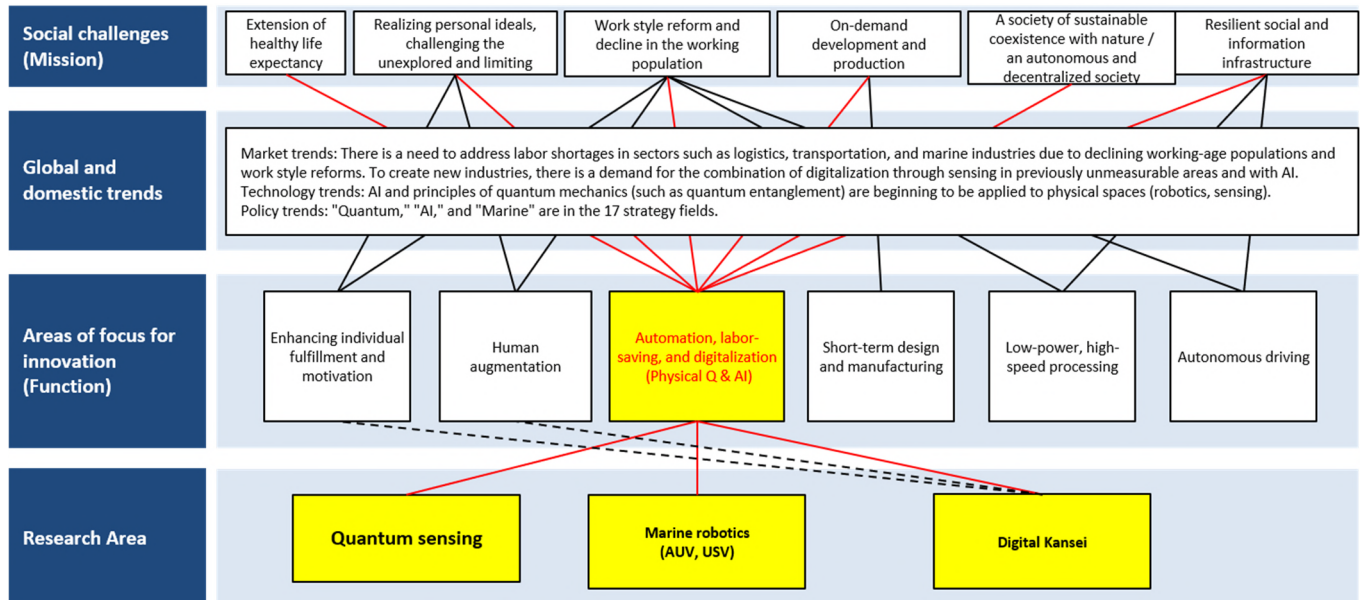


Figure 3-4-4: M-F logic model for quantum sensing, marine robotics, and digital KANSEI: automation, labor-saving and digitalization (physical Q & AI; the application of quantum and AI technologies to physical space)

3-4-3 Examples of Specific Steps to Take

(1) Low power consumption and high-speed processing (next-generation smart digital architecture)

Atomic layer material is being pursued as a new class of channel material that can reduce the electric power consumed even in general-purpose processing platforms. This hardware approach works with the conventional scaling law (More Moore) or adds multifunctionality (More Than Moore). Beyond CMOS approaches are also useful; these implement a general-purpose computer based on the four arithmetic operations using spin or photons instead of electrons. Other ideas that have been explored in recent years include physical reservoir computing, brain-inspired (neuromorphic) computing, organoid intelligence using biomaterials, and spin arithmetic elements and quantum devices based on atomic layer material or topological materials.

(i) Atomic layer electronics

Atomic layer electronics are regarded as a promising way to extend the conventional scaling law, and their introduction to the market is expected around 2037 (Figure 3-4-5). At present, film formation technology at the 300-mm wafer level has largely been established, and the focus is shifting to the establishment of other processes required for device fabrication and integration as well as to the development of technologies to integrate these processes. Although there is a large body of laboratory research, the key to real-world social implementation is the effort to connect this research to integrated processes that can be mass produced.

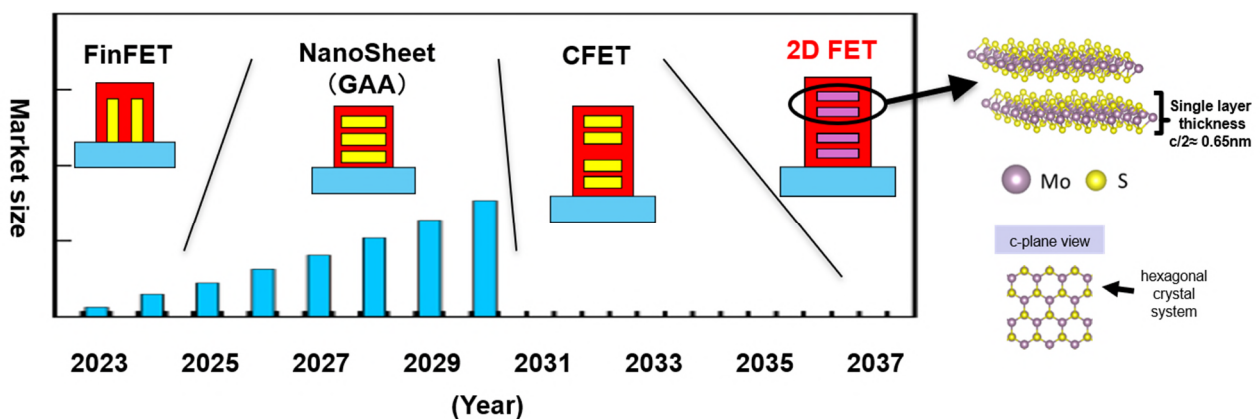


Figure 3-4-5: Positioning of atomic layer electronics (2D FET) on the technology roadmap

(ii) Photonic computing

There are two conceivable approaches to realize photonic computing: one that implements neural networks with photonics, and one that uses the four arithmetic operations with photonics to build a conventional general-purpose computer (Figure 3-4-6).

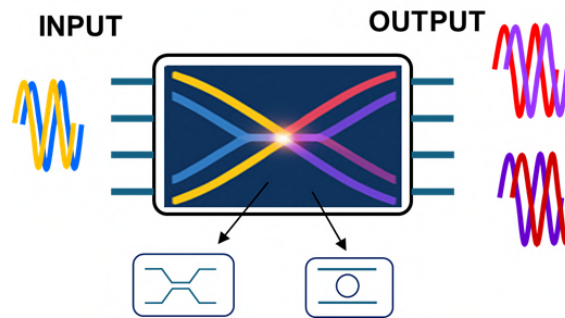


Figure 3-4-6: Diagram of an optical computing element

The implementation of simple neural networks such as those used in machine learning is at the research and development stage. FS is attempting to verify whether the transformer model that underpins generative AI can be implemented on a photonic neural network and if it is useful or not. In December 2025, a solid-state device that processes the operations specific to generative AI using photonics directly on a chip was announced, and the technology is rapidly progressing.

When it comes to computers that use photonics, the implementation of the computing machine itself is currently the major challenge. However, the possibility of implementing the sum-accumulate operation with photonics may be within reach. Initial-stage activities include the design and construction of a system capable of executing in parallel the sum-accumulate operation required to run a small-scale LLM, as well as the execution of a small-scale LLM and evaluation of its accuracy and performance.

(2) Monitoring and predicting platform for social infrastructure

For this item, refer to the *Innovation Outlook Ver. 1.0 Executive Summary*.

(3) Automation, labor-saving and digitalization (physical Q & AI; the application of quantum and AI technologies to physical space)

Advanced technologies support the creation of new industries. Digitalization through quantum sensing allows measurements in previously inaccessible domains and at levels of precision unattainable with conventional technologies. The advancement of marine robotics leverages Japan's strength as a maritime nation with the sixth-largest maritime zones under national jurisdiction in the world. AI is being trained to understand *kansei* information, such as nonverbal and nonlogical human preferences and emotional changes. New physical systems like soft robotics and bio-hybrid robots are emerging, while cognitive development robotics and real haptics are being looked at as methods to create AI models for robots.

(i) Quantum sensing

Quantum sensing enables the detection of minute physical quantities that cannot be captured by conventional sensing such as gravity and magnetic fields. This “power to visualize the invisible” is expected to contribute to solving social issues by allowing labor-saving automation, preventive maintenance of infrastructure, and early pathological diagnosis. It is also expected to play the role of a core technology for data generation in a data-driven society—that is, as a “future sensory organ.”

Japan is a leader in foundational research into the optical lattice clock and the atomic clock, which offer not only unprecedented high-precision time standards but can function as gravity sensors. They are expected to serve as tools for disaster prevention (e.g., crustal deformation monitoring), environmental preservation, and resource exploration, but the development of optical devices that enable miniaturization, weight reduction, and cost reduction while maintaining high precision is required.

Diamond NV centers (nitrogen-vacancy centers) are another development that Japan excels at. The material and device are key to widespread use, and by achieving unparalleled high-sensitivity measurement of current, magnetism, and temperature, wide-ranging utilization in industrial fields such as non-destructive defect analysis of semiconductors is also foreseeable (Figure 3-4-7). Manufacturing and processing technology must be developed to contribute to further improvements in precision and cost reduction.

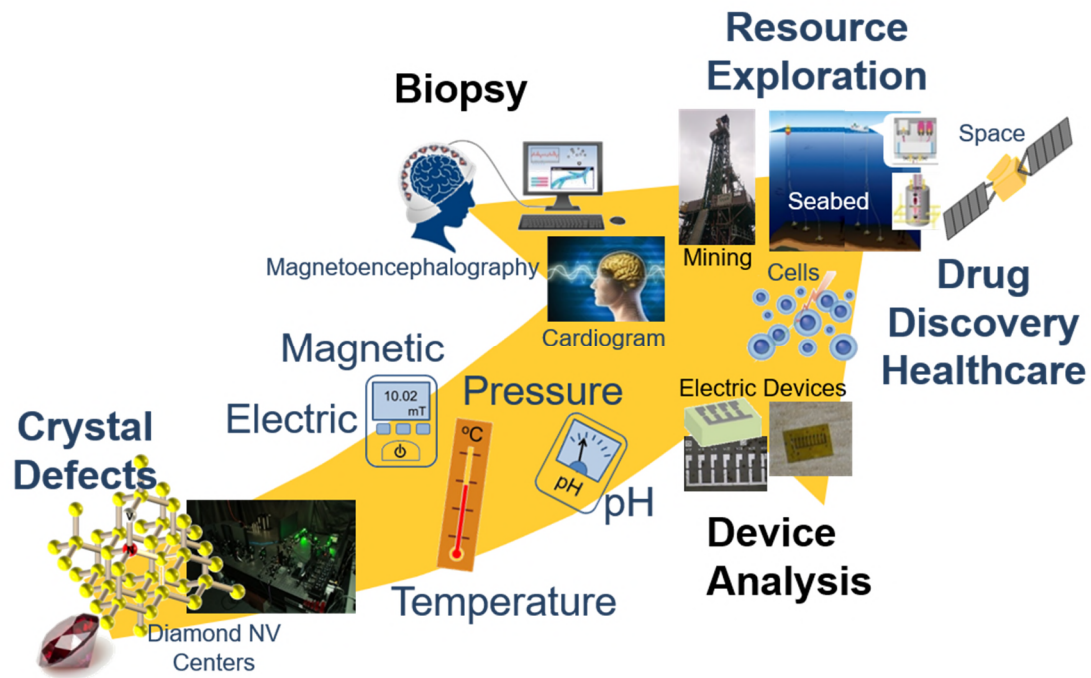


Figure 3-4-7: Measurement targets and application fields of diamond and other NVCs

(ii) Marine robotics

Cooperative control of underwater and surface vehicles is allowing marine data to be collected across vast ocean expanses, and initiatives that utilize it, like ocean visualization and the ocean digital twin, are progressing¹² (Figure 3-4-8). This data can contribute to the exploration of seabed and fisheries resources, more accurate weather forecasting, and CO₂ emissions reductions through route optimization for cargo vessels.

Current AUV operation typically uses a support vessel (a manned ship) to deploy, launch, and recover the AUV, and observation data is checked after recovery. This comes with challenges such as adverse weather, operating time constraints, personnel costs, and vessel charter fees. If an AUV can autonomously depart from and return to port or dock with a zero-emission USV to travel between the port and the target waters, it is possible to reduce the costs associated with personnel and the support vessel and lower CO₂ emissions from the consumption of marine fuel.

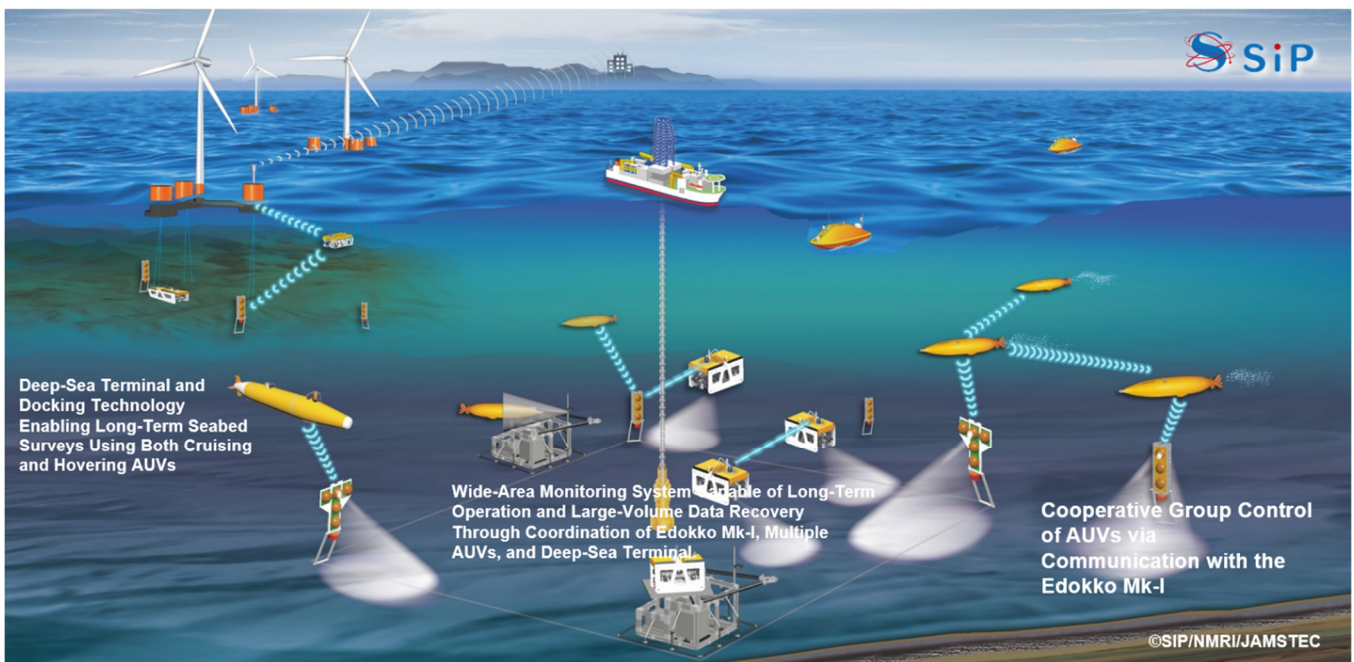


Figure 3-4-8: Examples of marine robotics technology development

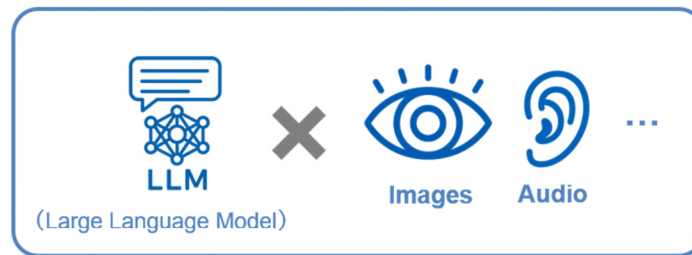
Provided by JAMSTEC

¹² SIP Phase 3, “National Platform for Innovative Ocean Developments” (Cabinet Office Strategic Innovation Creation Program) <https://www.jamstec.go.jp/sip3/e/> (accessed March 2026)

(iii) Digital KANSEI

Digital KANSEI is a concept and technological foundation for using digital technology to capture, understand, support, and augment the sensibilities (*kansei*) humans need to comprehend the external world, find value, and build relationships with others and society. With the recent progress of generative AI, understanding abstract representations such as images and speech as well as language has improved dramatically. However, in order to better understand *kansei* information, it is essential to build models that measure and estimate multisensory information experienced through the body, such as touch, smell, and taste, and nonverbal reactions such as a heartbeat, brainwaves, and facial expressions. Digital KANSEI is positioned as a foundational technology through which AI and digital systems coexist and coevolve with humans while respecting differences in individual values, cultural backgrounds, and ways of feeling (Figure 3-4-9). In terms of market trends, it is expected to advance fields such as medical care, the automotive industry, customer service, and marketing across the globe. Digital KANSEI technology is expected to boost Japanese manufacturing strength by interpreting the intuition and tacit knowledge of skilled workers, enabling skill transfer. It can also enhance individual abilities and well-being through teacher agents that elicit emotional responses and encourage growth.

Current Generative AI (e.g., VLMs)



Acquisition of Abstract Representations Through Learning



AI That Understands Affective Information (Digital Kansei)



Learning-Based Acquisition of Abstract Representations = Realization of “Digital Kansei”

Figure 3-4-9: Comparison of current generative AI and AI that understands affective information (digital KANSEI)

3-6 Bioeconomy Field

3-6-1 Field Overview

The bioeconomy spans an extremely wide range of industrial fields, including medical and healthcare, food, materials, energy, and the environment. It is built on renewable resources. Its market and products are also highly diverse, and closely tied to a wide range of societal challenges including climate change, resource depletion, biodiversity loss and aging societies (Figure 3-6-1). Biotechnology forms the core, but integration with adjacent technological fields such as digital tech, AI, materials, electronics, and electrical engineering is indispensable, and interdisciplinary integration of knowledge is the source of competitiveness. In recent years, as exemplified by structural analysis AI, mRNA technology, and genome editing, there has been an increasing number of cases in which foundational research outcomes have been translated into real-world social implementation and industrialization within a short period (Figure 3-6-1).

The *Innovation Outlook Expanded Edition*, while acknowledging the broad scope of the bioeconomy, focuses on the healthcare economy, particularly disease prevention and health promotion, because of their social relevance and the fact that Japan has competitive advantages in these areas.

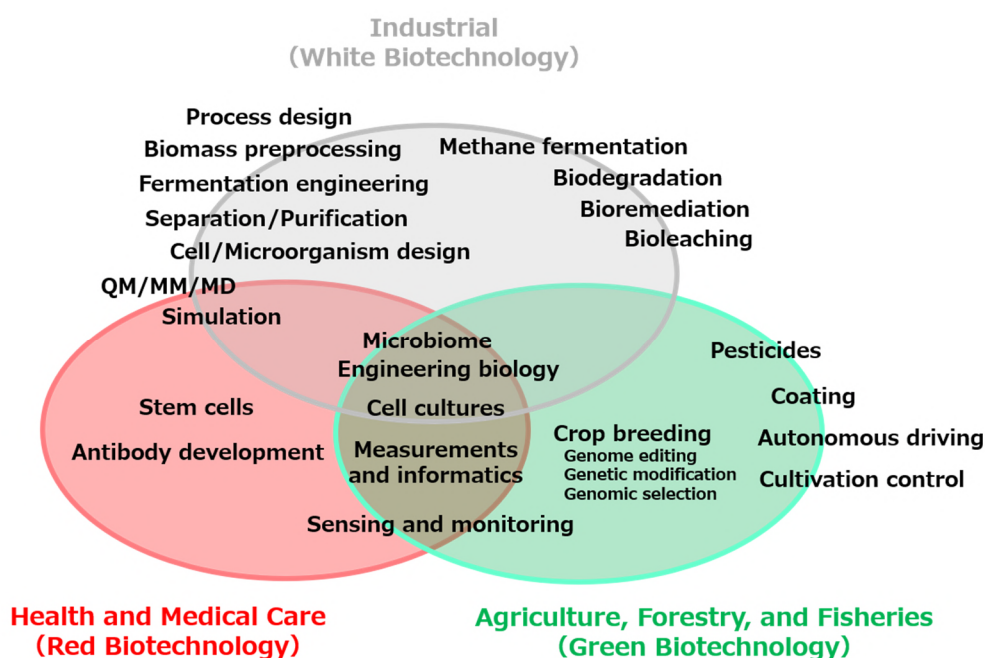


Figure 3-6-1: Technology landscape of the bioeconomy sector

3-6-2 Social Challenges and Frontier Areas:

Preemptive Healthcare Through Advanced Sensing: Building a Behavior Change Model Based on Precision Nutrition and Infection Prevention and Control

Against the backdrop of aging populations around the world and a rise in chronic diseases, the healthcare sector faces a structural challenge: shifting from a treatment-centered model to one based on disease prevention and health promotion. In Japan, the “Bioeconomy Strategy” published in 2024 clearly identified lifestyle improvement healthcare and digital health as priority markets, and “Action Plan 2023: For the Realization of a New Healthy Society” envisions achieving a cumulative domestic market size of 77 trillion yen by 2050 for services related to health promotion and long-term care outside of those covered by public health insurance. Investment in wearable devices and digital health services is accelerating, and the number of new services premised on the continuous acquisition of biometric data in everyday life is increasing, giving this field substantial market potential.

In preventive healthcare, it is difficult to connect daily behavior and health outcomes, making sustainable behavior change a persistent challenge. Conventional evaluation relies on a few examinations per year. However, continuously visualizing biological responses and metabolism in relation to diet, exercise, sleep, and stress every day would allow us to build a feedback loop that constantly monitors interventions and biological responses. At the core of this is behavior change based on advanced biological sensing. To continuously measure biomarkers without placing a burden on subjects, advanced non-invasive or minimally invasive sensing technologies that provide high sensitivity and high specificity are indispensable. A leading example in the medical domain is in the management of type 2 diabetes, where sensing combined with feedback is beginning to yield outcomes that lead to behavior change. For example, by integrating continuous glucose monitoring (CGM) with lifestyle data and providing personalized optimization of dietary and physical activity interventions on a continuous basis, improvements in metabolic indicators such as HbA1c, insulin resistance, and beta cell function have been reported, along with a reduction in the need for pharmacotherapy in some studies. These findings indicate that continuous intervention and feedback loops based on individual sensing data can lead to behavior change that actually improves health outcomes.

Diet is highly controllable and closely tied to everyday life, and precision nutrition that is optimized according to an individual’s needs has attracted growing attention in this field. To translate precision nutrition into effective behavior change, it is essential not only to quantify the impact of nutritional

interventions on biological indicators, but also to understand the functions of the gut microbiota and interindividual variability, and to incorporate these responses into the evaluation framework. A mechanism that provides timely feedback on the longitudinal changes in such personal data promotes sustained behavior change. Furthermore, since there is significant individual variation among older adults, evaluation based on changes from an individual's baseline and past data, rather than comparison with general reference values, leads to effective interpretation of intervention effects. Real-world social implementation of precision nutrition requires large-scale data infrastructure of diet and the gut microbiota and advanced sensing technologies that enable its measurement and integration into daily life.

Japan has already built a large-scale public database of gut microbiota linked to dietary information. It also has strong technological capabilities in the development of sensors, materials, and precision instruments, and a proven track record in the real-world social implementation of functional foods. These assets would enable Japan to demonstrate international competitiveness in deploying preemptive healthcare that combines precision nutrition and advanced sensing.

The MF logic model for the healthcare sector is summarized in Figure 3-6-2. To realize preventive healthcare, we propose the following as a frontier area to be addressed: preemptive healthcare through advanced sensing (building a behavior change model based on precision nutrition and infection prevention and control).

This area requires long-term, large-scale investment to build the scientific evidence base, and involves significant institutional and regulatory uncertainty, making it difficult for the private sector to make progress on its own. From an economic security standpoint, maintaining human capital through disease prevention, biometric data, and sensing technologies is strategically important and of substantial national significance. Accordingly, it has been selected as a frontier area.

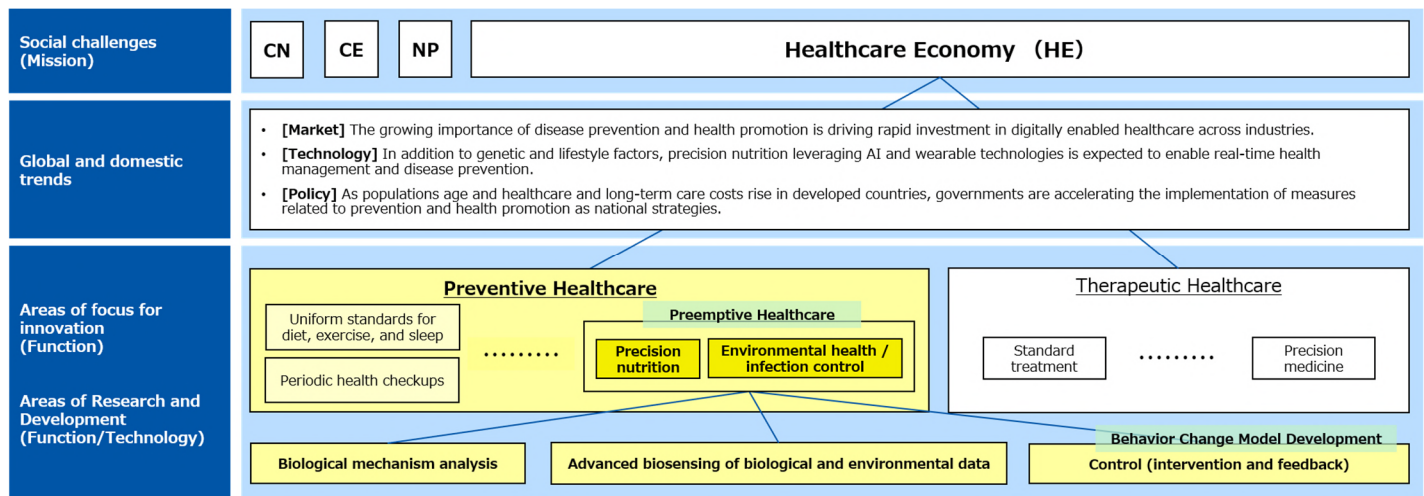


Figure 3-6-2: MF logic model in the healthcare sector

Figure 3-6-3 illustrates a framework for realizing behavior change based on advanced sensing related to precision nutrition and infection prevention and control.

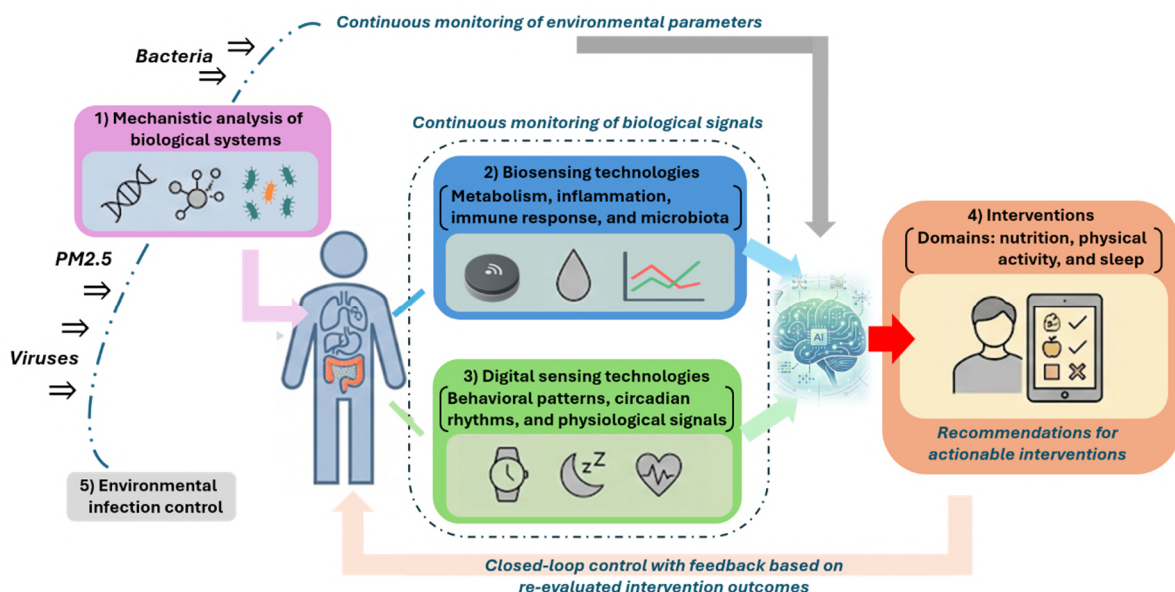


Figure 3-6-3: Personalized preemptive healthcare enabled by continuous bio-environmental sensing

The precision nutrition process begins by identifying the biological information, or biomarkers, to be monitored during intervention (1) based on an understanding of biological mechanisms. Next, to grasp how these biomarkers fluctuate in daily life, continuous measurements are conducted using non-invasive or minimally invasive technologies (2, 3). The collected multidimensional data are then analyzed, and an intervention strategy optimized for each individual's physiology is designed and

presented (4). The responses to the intervention are again evaluated by the measurement systems in (2) and (3) and reflected in the next intervention as a data-driven feedback loop. In addition, infection prevention and control and environmental sensing that targets pathogens and hazardous substances in the environment will continuously visualize exposure risk, enabling society-level preemptive healthcare linked to the optimization of individual behavior (5).

3-6-3 Examples of Specific Steps to Take

Preemptive healthcare should be founded on advanced sensing at two distinct levels: individual and societal. This way intervention can be delivered before diseases or health risks become apparent.

At the individual level (steps 1-4), one way biological sensing can be used is for precision nutrition that captures individual variations in metabolism and responses to diet to enable personalized preventive intervention. At the societal level shown in step 5, real-time sensing of viruses in the environment can assess the risk of outbreaks at the population level, aiding infection prevention and supporting preemptive healthcare as a social system.

(1) Analysis of biological mechanisms

(i) Multi-omics analysis

Understanding highly variable, individual metabolic responses and the effects of nutritional interventions requires multi-omics analysis that integrates the genome, transcriptome, proteome, metabolome, and more. This clarifies causal structures and networks of biological responses that cannot be captured by a single indicator and allows researchers to look for reliable molecular biomarkers that contribute to precision nutrition.

In particular, the ability to efficiently separate indicators rooted in biological mechanisms from incidental correlations by extracting molecules that vary consistently across multiple omics layers is a great strength.

(ii) Functional analysis of the gut microbiota (microbiome)

The gut microbiota is deeply involved in health through the metabolism of food, immune regulation, and inflammation control, and individual variations are a major determinant of the effectiveness of precision nutrition. What is important is not merely the presence of bacteria, but their functional aspect; which metabolites they produce and what effects these have on the body.

Multi-omics analysis makes it possible to simultaneously capture the DNA information of gut bacteria and their corresponding metabolites, accelerating our understanding of the mechanisms linking the gut microbiota/metabolism/health indicators. This will enable the development of new intervention strategies, including diets designed based on gut microbiota characteristics and the use of postbiotics.

(2) Biosensing

Sensing devices for biomolecules are composed of a molecular recognition element, an electrode (transducer), a substrate, a signal processing circuit, and a power supply (Figure 3-6-4). The molecular recognition element, which specifically captures the target molecule, is the core component that defines the selectivity, sensitivity, and measurement response speed.

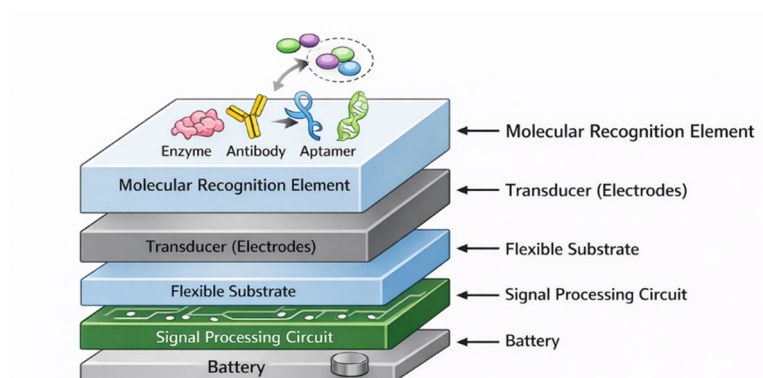


Figure 3-6-4: Conceptual diagram of the general components of a biomolecular sensing device

(i) Direct electron transfer enzymes (DET-type enzymes)

Enzymes are mature recognition elements in biomolecular sensing and are increasingly being redefined as device components that can be designed at the molecular level. In particular, direct electron transfer enzymes (DET-type enzymes), which directly exchange electrons with the electrode, can achieve high selectivity and high sensitivity without a mediator, and are considered next-generation elements that might be well suited to multi-sensing. Advances in cryo-electron microscopy and computational science have shed light on the molecular mechanisms of DET's capabilities, such as electron transfer pathways and orientation, putting AI-driven de novo design and the creation of semi-artificial enzymes increasingly within reach.

(ii) Nucleic acid aptamers

Nucleic acid aptamers are molecular recognition elements that offer specificity comparable to antibodies with the advantages of being chemically synthesizable, more stable, and cost-effective. They can target a wide range of molecules from small compounds to proteins and can help detect molecules that are difficult to find with enzymes. On the other hand, constraints in binding and dissociation kinetics pose challenges for continuous measurement, and improvements through advanced structural design and signal transduction mechanisms will be key in the future.

(3) Digital sensing

Smartphones, smart rings, and similar devices now make it possible to continuously measure digital biomarkers (DBMs) such as activity level, sleep, and heart rate changes during daily activities. Sensing of behaviors like walking speed or keystroke characteristics is a promising way DBM can capture early signs of cognitive decline or disease. A major advantage of DBMs is that they can capture changes in behavior and physiological status in a non-invasive, large-scale, and continuous manner. In high-precision analyses using millimeter-wave sensors and motion capture, reductions in the range of motion of the ankle joint during walking have been reported as beneficial in the early detection of sarcopenia, and in the future, home-based diagnosis using video from a smartphone is also anticipated.

Integrating and visualizing the biological information obtained through biosensing (2) and digital sensing (3) above, a healthcare-oriented digital twin that reproduces and predicts an individual's physiological state and behavioral characteristics in virtual space is on the horizon. However, its use requires rigorous governance of data and protection of personal information.

(4) Intervention through precision nutrition

Precision nutrition is an intervention technology that integrates the search for molecular biomarkers with biological and digital sensing to support concrete behavior change. Its distinctive feature is the dynamic design of dietary intervention, optimized for each individual by integrating multi-layered data including genetic information, metabolic characteristics, gut microbiota, and lifestyle habits.

Large-scale cohort studies have shown that postprandial glucose responses differ substantially among individuals even when consuming the same meal, and that incorporating gut microbiota information enables improved prediction of postprandial responses. These findings demonstrate that

precision nutrition goes beyond mere nutritional guidance and can be a data-driven intervention science. In Japan, proposals for effective precision nutrition that reflect the food culture of a traditional Japanese diet rich in fermented foods and take into account the characteristics of gut microbiota in the Japanese population will be the keys to implementation.

As shown in 1-4 above, visualizing mechanism-based biological responses and building integrated loops of intervention and feedback connects our understanding of molecular-level biological responses, device development, and data analysis with behavior change at the individual level, and forms the core technological foundation that can bring preemptive healthcare into real-world social implementation.

(5) Infection prevention and control and environmental sensing

Realizing preemptive healthcare at the societal level requires more than the optimization of individual behavior. Technologies to visualize pathogens in the environment and improve prevention of infection are also needed. Challenges are the efficient capture of airborne viruses, detection at low concentrations, and the establishment of rapid detection methods that do not rely on PCR tests.

One example of this is the wet electrostatic sampler. This enables highly efficient capture, but requires measures to prevent evaporation of the collection liquid during long-term operation. Technologies such as the CONAN and SHERLOCK methods can achieve highly accurate, rapid, low-cost detection, and can readily accommodate variants.

There is also a need for foundational technologies that shift infection prevention and environmental measures from “suppression after spread” to “containment at an early stage.” These would include rapid, localized, non-persistent control of pathogens detected at an early stage without using chemical agents. Examples include atmospheric pressure, low-temperature plasma and deep ultraviolet (DUV) LEDs.

The integration of these technologies is expected to enable the construction of a system that continuously monitors viruses in public spaces and understands infection risk in advance.

The concrete methods set out in this section constitute a technological foundation that implements preemptive healthcare in a multi-layered manner, from measurement at the molecular level to intervention for behavior change and infection prevention at the environmental and societal levels.

3-7 Newly Defined Fields

In the *Innovation Outlook Ver. 1.0 Expanded Edition*, neurotechnology [1] and industrial innovation through mathematical sciences [2] are newly added fields we investigated and analyzed.

[1] Neurotechnology

3-7-1 [1] Field Overview

Neurotechnology is defined by the OECD as “devices and procedures that are used to access, monitor, investigate, assess, manipulate, and emulate the structure and function of neural systems.”¹³ TSC considers neurotechnology to be a group of technologies that perform measurement and analysis of brain and neural activity and apply the data to applications and products. It includes BMIs (brain-machine interfaces), neuromodulation devices, and neural activity monitoring systems, and has the potential to contribute to the early diagnosis of neurological disorders, alleviate symptoms, and improve the efficiency of rehabilitation. It is also attractive as technology that can help address the shortage of medical and long-term care personnel. Applications are expected to extend well beyond medicine and rehabilitation to a wide range of fields including education and entertainment.

¹³ Responsible innovation in neurotechnology enterprises (OECD, 2019) https://www.oecd.org/en/publications/responsible-innovation-in-neurotechnology-enterprises_9685e4fd-en.html (accessed March 2026)

3-7-2 [1] Social Challenges and Frontier Areas:

Neurotechnology That Enables the Recovery or Augmentation of Brain/Nerve Function and Human-Machine Collaboration

Neurotechnology is expected to contribute to the realization of three of the “12 Visions of Society to Achieve” presented in TSC’s *Prosperous Future Report*: a society where everyone can reach the potential to be themselves, a society where everyone can work comfortably for a lifetime, and a comfortable and dynamic society. In *Innovation Outlook Ver. 1.0*, regarding the digital field, the combination of automation, labor-saving, and digitalization were proposed as solutions toward resolving the social issues of work style reform and the decline in the working population as well as helping society achieve personal ideals and challenge unexplored ideals and limitations. Collaborative multi-purpose autonomous assistive robots were envisioned as understanding human instructions to collaborate with humans, and BCIs (brain-computer interfaces) and BMIs were seen as important elements. Regarding the bioeconomy field, advanced sensing of biological and environmental information, and control of living organisms and the environment were mentioned in regard to resolving the social issue of healthcare economy. By conducting advanced sensing of biological information and performing appropriate responses and controls, a foundation that supports the acquisition of biological data related to neurotechnology can be formed.

After further consideration, we now conclude that by integrating “automation, labor-saving, and digitalization” from the digital field with “advanced sensing of biological and environmental information and control of living organisms and the environment” from the bioeconomy field, we can anticipate the realization of human functional recovery, human augmentation, and human-machine collaboration based on advanced measurement and analysis of brain and neural information.

Therefore, this expanded edition proposes “neurotechnology that enables the recovery or augmentation of brain/nerve function and human-machine collaboration” as a frontier area to be tackled (Figure 3-7-1-1).

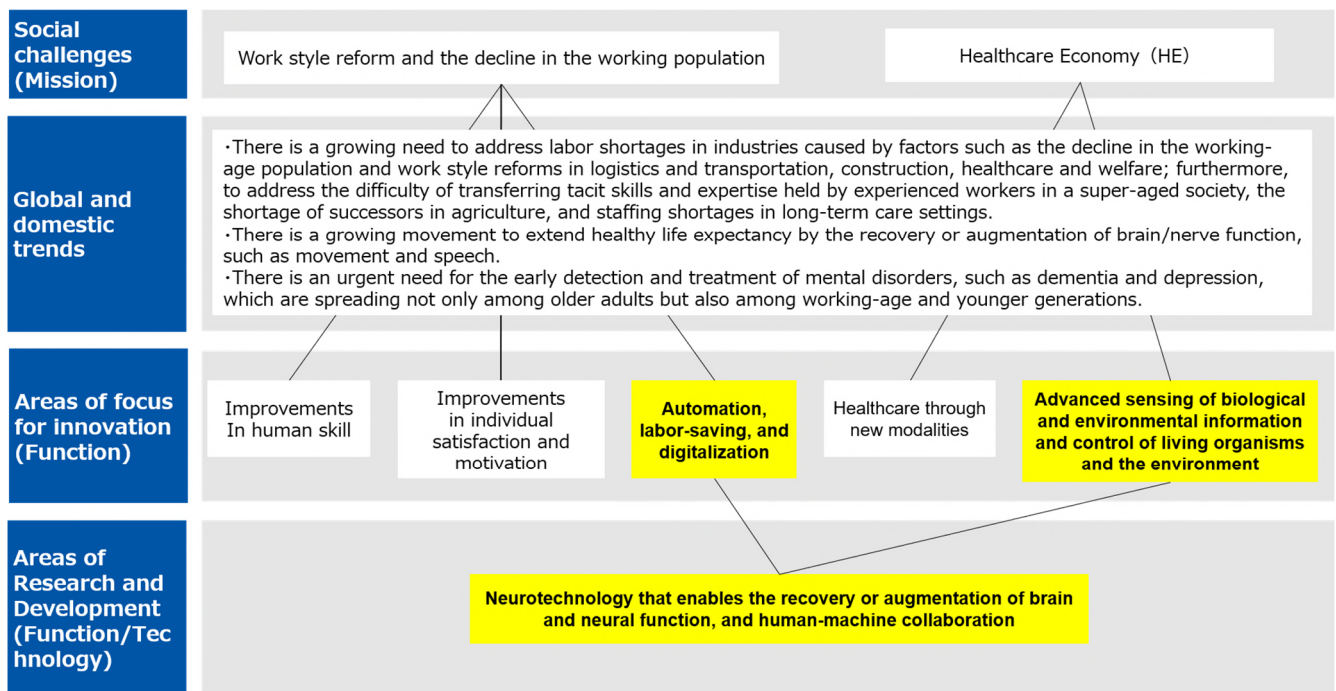


Figure 3-7-1-1: MF logic model of neurotechnology

(1) Market trends

The applications of neurotechnology extend well beyond medicine and a broad range of markets is envisaged. Medical devices such as the electroencephalograph, MRI, and MEG (magnetoencephalograph) have been developed and are being used in clinical settings. There are also initiatives to apply the measurement results of brain and neural activity to business decision-making and marketing. Taken together, the market size of neurotechnology is projected to grow to approximately \$60 billion (about JPY 9 trillion) by 2035.

(2) Technology trends

The number of research papers in this field has been steadily increasing, with the U.S. and China leading. Japan ranks eighth overall, but it is fourth in brain organoid research and fifth in the fields of BCI/BMI and decoding, which shows Japan is nonetheless in the mix. Patent applications related to EEG, MRI, NIR, and MEG have been on the rise. Ricoh and Hamamatsu Photonics each hold a large number of patents related to MEG.

One of the goals of BCI is neuroprosthetics (neural prostheses), wherein a thought in the brain can be inferred (decoded) by measuring brain and neural activity and enable thought-to-speech or the ability to move a robotic arm. Here, the neural activity accompanying the thought must be

decoded and responded to instantaneously, and the tendency is therefore toward invasive measurement. However, in some areas R&D is also being conducted to enable measurement that is minimally invasive, using sheet-shaped electrodes or endovascular electrodes.^{14,15} Japan is a global leader in materials technology and transmission technology for measured signals, and the race to develop low invasive electrodes can be an important research target.

(3) Policy trends

(i) R&D policy

Neurotechnology R&D has been centered in the U.S. and Europe.

In the U.S., foundational technology development began with DARPA projects starting in the late 2000s. In Europe, an infrastructure called EBRAINS¹⁶ was built based on the Human Brain Project (2013–2023).¹⁷ It provides data, tools, and services for brain-related research. China set forth a policy of nurturing industry in nearly all technological areas of BCI and leading the world in the BCI industry, as outlined in its national strategy (an opinion paper by seven ministries),¹⁸ in July 2025. In Japan, the Cabinet Office’s Moonshot Research and Development Program and MEXT’s Strategic Research Program for Brain Sciences (SRPBS) are among the related initiatives being promoted.

(ii) Initiatives related to ethical aspects

With the growing use of non-invasive approaches such as fMRI to measure human brain activity, research on neuroethics is being conducted in parallel with neuroscience. Neuroethics comprehensively addresses how research outcomes in neuroscience and their real-world social implementation affect human understanding, legal systems, and society.¹⁹

In November 2025, UNESCO established new standards on neuroethics to advance brain science research while respecting human rights and dignity, and these were adopted by member

¹⁴ <https://precisionneuro.io/> (accessed March 2026)

¹⁵ <https://www.jimed.jp/en> (accessed March 2026)

¹⁶ Europe’s Digital Infrastructure for Brain Research, <https://ebrains.eu/> (accessed March 2026)

¹⁷ Human Brain Project, <https://www.humanbrainproject.eu/en/> (accessed March 2026)

¹⁸ Implementation Opinions of Seven Ministries on Promoting the Innovative Development of the Brain-Computer Interface Industry, https://www.miiit.gov.cn/zwgk/zcwj/wjfb/yj/art/2025/art_ea3ff408de194612891df352d24dd26a.html (Chinese; accessed March 2026)

¹⁹ Trends in the Ethics of Neurotechnology (Tokyo University of Information Sciences, 2025, Japanese) https://www.mext.go.jp/content/20250627-mex_life-000043435_9.pdf (accessed March 2026)

states.^{20, 21} The recommendation aims to establish safeguards so that innovations in neurotechnology benefit those who need support from it without infringing on mental privacy. Similar initiatives are also under way at the OECD and in the EU.

In Japan, the third Healthcare Policy (a Cabinet decision from February 18, 2025) states that “efforts in ‘social co-creation’ will be strengthened,” and requires that, “based on the concept of Responsible Research and Innovation (RRI), so that R&D in the health and medical field can proceed while gaining society’s understanding and trust,” “Ethical, Legal and Social Issues (ELSI) shall be addressed from the early stages of R&D.”²²

(iii) Initiatives on the concept and regulation of neurodata

With the progress of R&D in neurotechnology, a vast amount of data related to neuroscience has been collected. In the U.S., states like Colorado have begun to regulate neural data and biometric information. However, what is meant by brain/neural data and what is covered under these laws differ from state to state. For this reason, the U.S. Senate is also discussing the regulation of brain/neural data under a unified federal framework.²³

²⁰ Ethics of Neurotechnology: UNESCO Adopts the First Global Standard in the Cutting-Edge Technology (UNESCO) <https://www.unesco.org/en/articles/ethics-neurotechnology-unesco-adopts-first-global-standard-cutting-edge-technology> (accessed March 2026)

²¹ UNESCO Adopts First Global Ethical Framework for Neurotechnology (digwatch, 2025) <https://dig.watch/updates/unesco-adopts-first-global-ethical-framework-for-neurotechnology> (accessed March 2026)

²² Headquarters for Healthcare Policy (Japanese) <https://www.cas.go.jp/jp/seisakukaigi/kenkouiryoku/senryaku/index.html> (accessed March 2026)

²³ The MIND Act: Balancing Innovation and Privacy in Neurotechnology (Cooley, 2025) <https://www.cooley.com/news/insight/2025/2025-09-25-the-mind-act-balancing-innovation-and-privacy-in-neurotechnology> (accessed March 2026)

3-7-3 [1] Examples of Specific Steps to Take

The advancement of non-invasive measurement of brain and neural activity (1), industrial development contributing to the prevention, early detection, and treatment of brain/neurological diseases (2), and the industrial application of brain-inspired systems (3) are presented as key themes (Figure 3-7-1-2).

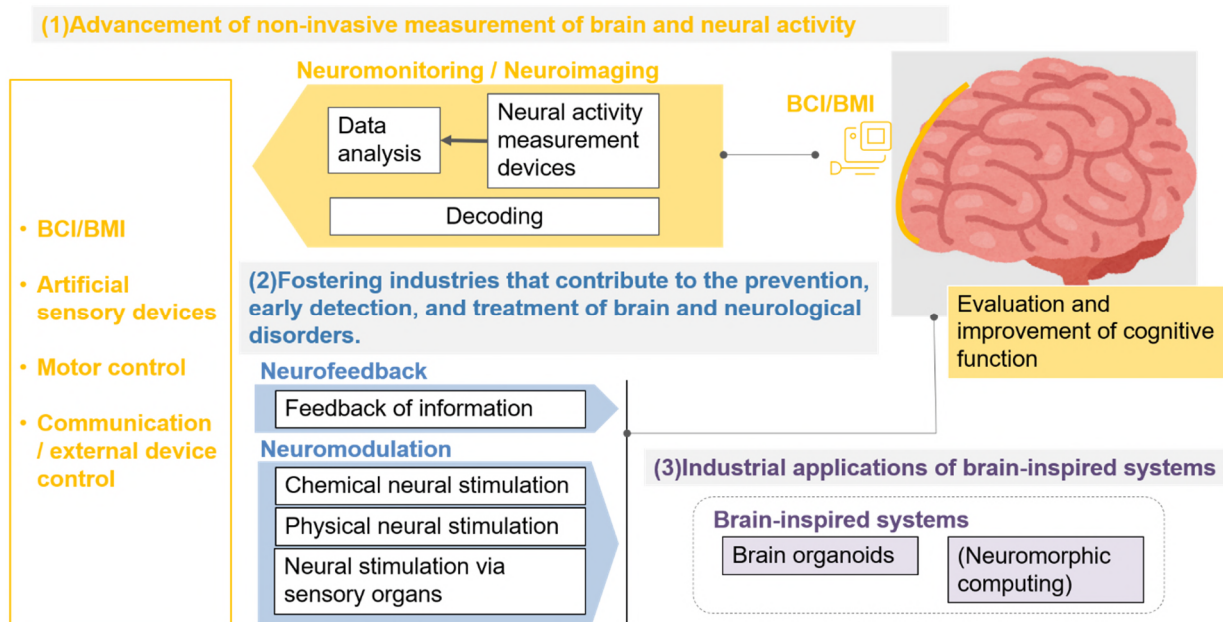


Figure 3-7-1-2: Key themes in neurotechnology

(1) Advancement of non-invasive measurement of brain and neural activity

In neurotechnology, being able to safely acquire large volumes of high-quality data such as EEGs is important, and the development of electrodes and measurement devices as well as next-generation brain activity measurement methods are considered key issues.

Specifically, we foresee non-invasive measurement devices that compensate for the weaknesses of existing methods aimed at improving accuracy, simplifying the measurement environment, and reducing the burden on subjects. We also propose improving the accuracy of non-invasive measurement methods with analyses such as data cross-checking through multiple-method, simultaneous measurement.

(2) Industrial development contributing to the prevention, early detection, and treatment of neurological disorders

Information obtained through the measurement of brain and neural activity is being used to guide therapeutic interventions and for neuromodulation. However, the effects vary greatly among individuals, and research on optimized feedback and stimulation methods or combinations of them is an important challenge. Once methods of health maintenance and prevention tailored to individual traits become clear, the creation of businesses that offer such methods to patients can be expected.

(3) Industrial application of a brain-inspired system

Organoids are cultured cells, such as iPS cells, that have been differentiated into various organs and tissues. Their demonstration for R&D use in drug development is progressing. Brain organoids mimic brain and neural activity, and in addition to being used for research on drug responses, are also being examined for possible use as computers (neuromorphic computing). Although there is much research left to do before realization, expectations are high, because there is a prospect of solving the power-consumption challenges of current von Neumann architecture.

[2] Industrial Innovation Through the Mathematical Sciences

3-7-1 [2] Field Overview

The mathematical sciences take the structures and theories developed within mathematics and use them to reframe complex phenomena in nature, society, and industry from the perspectives of structure and causality, thereby connecting those phenomena to understanding, prediction, and control. They make it possible to abstract essential characteristics such as structures, relationships, and invariants and treat them as a common language. In recent years, methods that combine data science and AI with mathematical models, as well as analyses of high-dimensional and complex structures using topology and geometry, have been increasingly applied to practical problems. With industrial application as the ultimate goal, this section examines how Japan's industrial foundations can be advanced by leveraging the strengths of the mathematical sciences, engineering sciences, AI, and data-driven approaches.

3-7-2 [2] Social Challenges and Frontier Areas: Advancement of Industrial Foundations Based on Geometry- Information

The engineering sciences and their industrial applications have been central to innovation to date. Recently, countries such as the United States and China have been making massive investments in advanced technologies such as digitalization and AI. AI relies heavily on statistical learning and large-scale data; however, in fields where data is scarce or difficult to obtain, significant challenges remain in capturing the essential structures and invariants of data groups, providing theory-based explanations, and ensuring generalization guarantees. Japan is at a particular disadvantage compared with other countries in terms of model development scale and data volume, because foundation models and cloud infrastructure are controlled largely by overseas players. Furthermore, dependence on large-scale data has made constraints related to semiconductors, including GPUs (graphics processing units), and power consumption is increasingly apparent.

Under these constraints, Japan needs to consider a strategy distinct from those pursued by other countries in order to solve industrial challenges and drive innovation. The *Nature Index*,²⁴ an indicator of the strength in academic research, ranks Japan fifth in the world, reflecting its extensive academic base. In industry, Japan has continuously ranked first in the world for approximately 30

²⁴ Nature Index (Springer Nature) <https://www.nature.com/nature-index/country-outputs/Japan> (accessed March 2026)

years in the *Economic Complexity Index*²⁵ published by the Harvard Kennedy School of Harvard University, maintaining competitiveness in both the scale and diversity of export industries centered on manufacturing. Japan's strength therefore lies in the long-standing coexistence of scientific principles cultivated in university disciplines such as physics, measurements and control, and materials sciences, with advanced industrial technologies developed at manufacturing sites, including equipment and quality control. The key to Japan's future innovation lies in effectively incorporating novel or underutilized scientific principles from universities into manufacturing sites.

The origins of the mathematical sciences can be traced back to the construction of mathematical frameworks represented by Euclidean geometry before the Common Era. In ancient Greece, for example, geometric concepts influenced architecture and art, and mathematics developed in close connection with philosophy, art, and architecture. Analytic geometry and calculus, established in the latter half of the 17th century, became linked with mechanics in the 18th century, and were widely used in engineering and industry during the Industrial Revolution. Subsequently, in the 20th century, the development of computers connected mathematical theories based on linear algebra and probability theory with computational science, enabling advanced equation-based model analysis and its application to large-scale, high-dimensional problems. In the latter half of the 20th century, machine learning was established and diverged from the mathematical fields centered on probability theory and statistics, and deep learning developed dramatically in the 2010s. These technologies evolved into what is now known as AI and brought major transformations to industry and society. In this way, scientific principles developed and matured in the mathematical sciences have successively spun out into industrial fields, advancing the engineering sciences and driving industrial innovation.

What is required next is a fourth wave of innovation driven by mathematical sciences. In other words, a new paradigm is needed—one driven by the next generation of mathematical sciences, overcoming the limitations and challenges currently facing AI and enabling dramatic improvements in explainability, reliability, and generalizability (Figure 3-7-2-1).

²⁵ Atlas of Economic Complexity 10.0 Brings New Data and Product Space Design (Growth Lab of Harvard Kennedy School)
<https://growthlab.hks.harvard.edu/news/atlas-economic-complexity-100-brings-new-data-and-product-space-design/> (accessed March 2026)

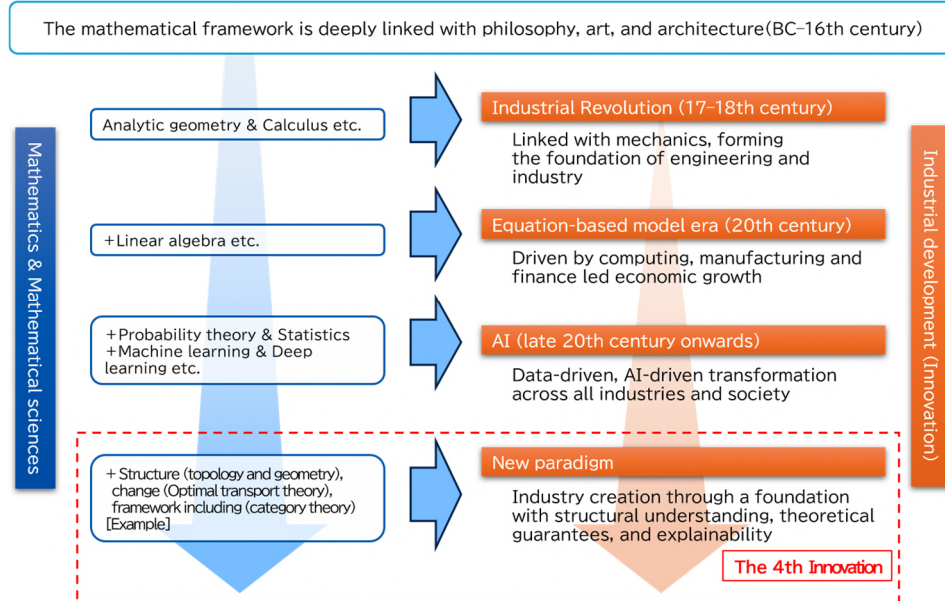


Figure 3-7-2-1: Realization of innovation through mathematics and mathematical sciences

Japan has an environment in which a robust academic foundation, strong even by global standards coexists with diverse and advanced industrial clusters. In addition, the elemental technologies and intellectual bases that support the next generation of mathematical sciences, such as advanced hardware, AI technologies, and experts versed in mathematical theory, are concentrated domestically.

Organically linking these together and proactively realizing the next generation of mathematical sciences will not only add depth to Japan's technological competitiveness and strengthen the structural foundations of industry but will also lead to the creation of sustainable innovation originating from Japan (Figure 3-7-2-2).

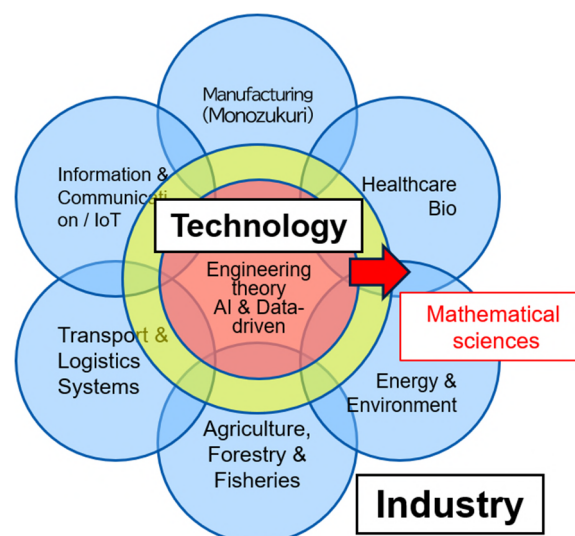


Figure 3-7-2-2: Concept of industrial innovation through mathematical sciences

Taking into account the methods listed in MEXT’s strategic objective, “The science of prediction and control that serves as the foundation of a new society and industry (mathematical foundations for prediction),” and considering their compatibility with Japanese industry, we focused on geometric methods such as geometry and topology as starting points for the next generation of mathematical sciences. These methods make it possible to understand characteristics of data groups, such as shapes, movements, and connections, that are difficult to capture using conventional approaches, and may enable the construction of explainable inference foundations that do not depend on massive amounts of data. When applying these methods to real-world industrial problems, it is important to combine and integrate geometric methods with equation-based models and AI, which are central to the engineering sciences (Figure 3-7-2-3).

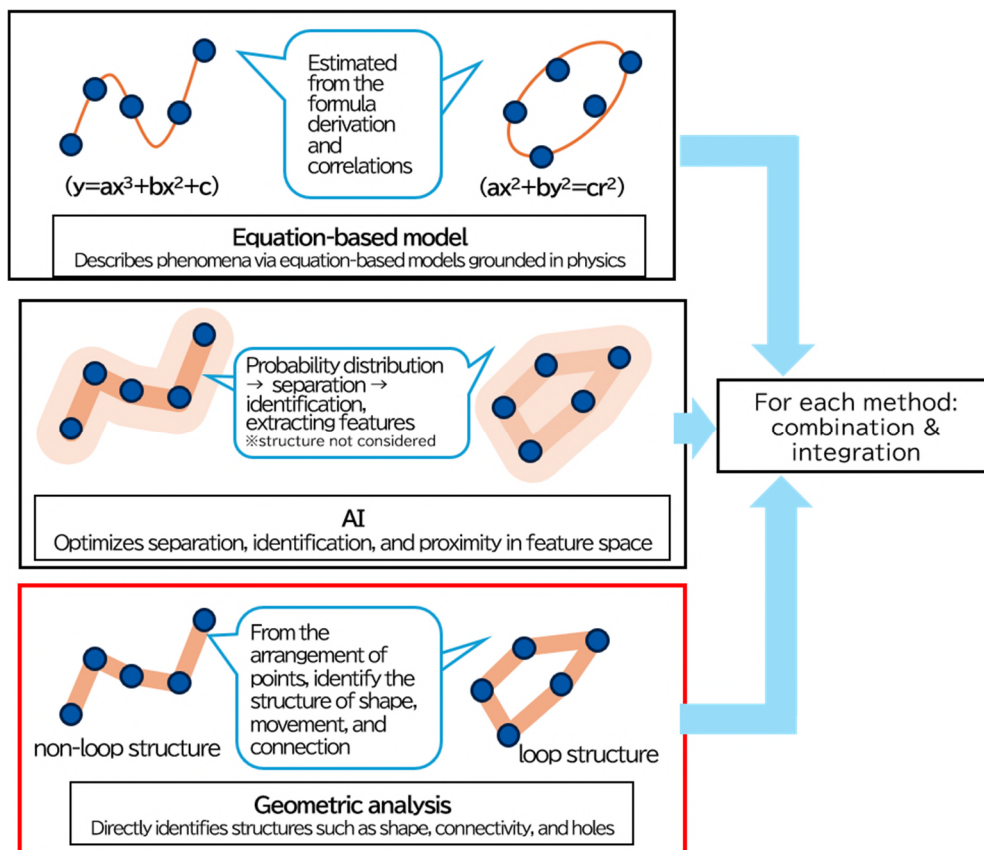


Figure 3-7-2-3: Combination and fusion of equation-based models and AI with geometric methods

Based on the above, we propose “industrial innovation through the mathematical sciences” as a frontier area to be addressed in solving challenges in Japanese industry and driving industrial innovation. Given that geometric methods are beginning to be incorporated into AI development and that research in areas such as topology has been revitalized in recent years, we consider the fusion of methods from geometry and algebraic geometry with information from sources such as the engineering sciences and AI to be an effective first step. Accordingly, to build the next generation of mathematical sciences, we propose “advancement of industrial foundations based on geometry-information” as an R&D area to be addressed (Figure 3-7-2-4).

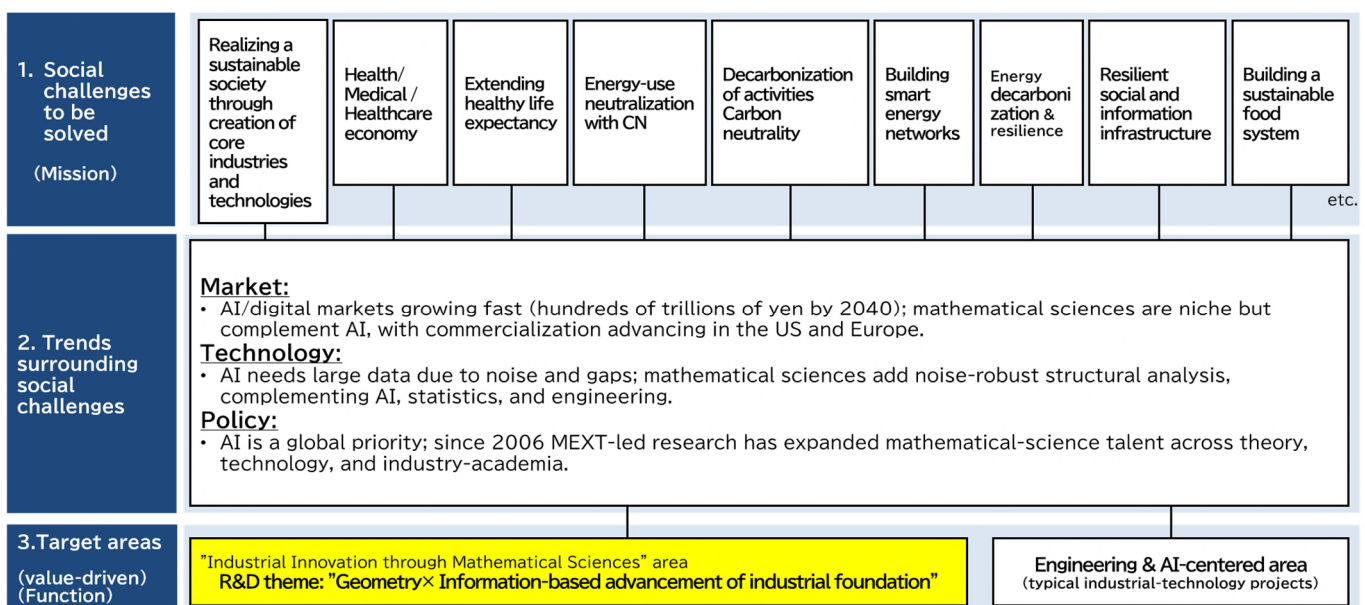


Figure 3-7-2-4: MF logic model of industrial innovation through the mathematical sciences

Market trends in AI and digital technologies indicate growth in fields such as manufacturing, advanced technology, materials, logistics, and semiconductors. McKinsey & Company estimate the potential added value of AI in 2040 to be JPY 390 to 660 trillion,²⁶ with the added value from analytical technologies based on geometry-information estimated at around JPY 40 to 120 trillion. Overseas, organizations such as IBM Research and Ayasdi, now SymphonyAI, in the U.S. and the Fraunhofer-Gesellschaft in Europe are advancing initiatives toward real-world implementation.

As for technology trends, multivariate and complex data from sensors, simulations, designs, and operational logs continue to accumulate, noise and differences in scale make structural understanding

²⁶ The Economic Potential of Generative AI: The Next Productivity Frontier (McKinsey & Company, 2023)
<https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-economic-potential-of-generative-ai-the-next-productivity-frontier#/> (accessed March 2026)

difficult with conventional methods. Under such circumstances, analytical technologies based on geometry-information, which focus on shape, structure, and connectivity, can demonstrate their strengths. One such method is persistent homology, whose effectiveness has been demonstrated in glass structure analysis and time-series AI. Furthermore, through streamline topology analysis and optimal transport theory, progress is being made in expanding from structural understanding to prediction, diagnosis, and control.

Since the publication of the 2006 report *The Forgotten Science: Mathematics* by the National Institute of Science and Technology Policy, Japan has continuously promoted policies that link mathematics and the mathematical sciences with social issues. The Japan Science and Technology Agency places importance on building mathematical foundations that can capture future changes and uncertainties through initiatives such as PRESTO, CREST, and the strategic objective of mathematical foundations for prediction. In the topological data analysis community at Tohoku University and the Math Clinic at Kyoto University, progress is being made in applications of mathematics that start from industrial issues. Initiatives aimed at realizing the next generation of mathematical sciences are also advancing, including the mathematics application and industry-academia collaboration initiative by Keidanren and Tohoku University.

3-7-3 [2] Examples of Specific Steps to Take

The following describes examples of specific steps to advance industrial foundations based on geometry-information.

(1) Topological data analysis

Persistent homology, a method within topological data analysis, is a mathematical sciences approach that extracts features based on the shape and structure of data across multiple scales. By adding mathematical structural information to conventional analysis methods, it can improve analytical accuracy and reliability. Examples of application to point clouds, time series, and images are presented below. Based on these cases, application to a wide range of industrial fields, including manufacturing, is also feasible.

(i) Application to material structure analysis

Glass is an amorphous material and lacks long-range order, making it difficult to describe the structural characteristics of its atomic arrangement. By applying persistent homology to atomic-arrangement data, researchers proposed a method for characterizing the medium-range order inherent in glass across multiple scales. By analyzing atomic arrangements as point cloud data and extracting ring and void structures using persistence diagrams, they showed that the hierarchical structure unique to glass, distinct from crystalline or random arrangements, can be visualized and quantified (Figure 3-7-2-5).²⁷

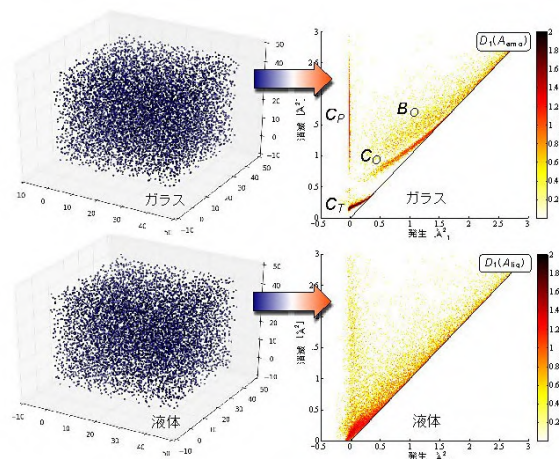


Figure 3-7-2-5: Atomic arrangement of SiO₂ (left) and its persistent homology (right)

(ii) Application to time-series analysis

In time-series analysis, persistent homology enables the extraction of structural feature quantities inherent in time-series data. In a joint study by Fujitsu and Inria, the French National Institute for Research in Digital Science and Technology, this method was applied to real electroencephalogram (EEG) data to detect delirium.²⁸ By analyzing EEG time series as geometric features, the study confirmed that waveform structures corresponding to the slowing phenomenon characteristic of delirium states can be extracted.

(iii) Application to diagnostic imaging

In diagnostic imaging, fusing persistent homology with deep learning can improve analytical accuracy. Yu-Min Chung *et al.* extracted lesion regions from skin images, learned image features

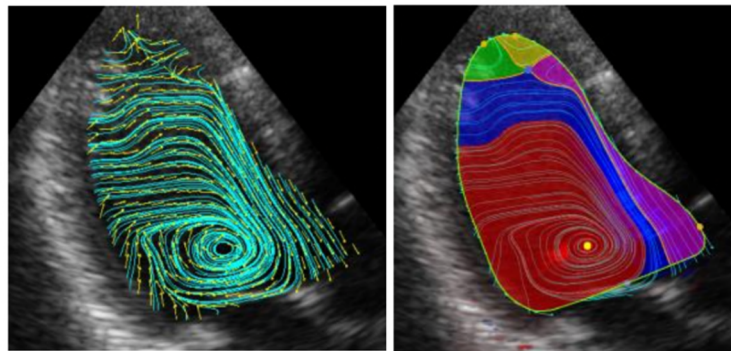
²⁷ Mathematical Elucidation of the ‘Shape’ of Glass: Reading Order Within Disorder Through Topology (Tohoku University, 2016) (Advanced Institute for Materials Research, Tohoku University, 2016)
<https://www.jst.go.jp/pr/announce/20160614/index.html> (Japanese; accessed March 2026)

²⁸ Development of World’s First Time-Series AI Technology for Identifying Anomaly Factors: Supporting the Discovery of Root Causes of Anomalies That Even Experts Find Difficult to Notice (Fujitsu Limited, 2021)
<https://info.archives.global.fujitsu/global/about/resources/news/press-releases/2021/0716-01.html> (accessed March 2026)

using deep learning, and extracted geometric and topological information on lesion shapes based on persistent homology.²⁹ Integrating these features to classify skin tumors into seven categories improved accuracy from 80.6% without geometric information to 85.1% with it.

(2) Streamline topology analysis

Streamline topology analysis is an approach that Japan has been pursuing for real-world implementation for 20 years. By analyzing topological features such as bifurcation and confluence of streamlines and vortex structures appearing in fluids and fields, it aims to capture the essential structure of complex physical phenomena. In the JST Mirai Program³⁰ this method was applied to cardiac blood flow. By analyzing streamlines and vortex structures formed in the intracardiac flow field, researchers extracted and visualized the structure of complex blood-flow patterns associated with heartbeats. In engineering, applying this method to numerical simulation and measurement data based on fluid dynamics, it is possible to structurally extract the characteristics of flows (Figure 3-7-2-6).



$$s_{\emptyset 1} \left\{ \left[\infty_{+}, \lambda_{\sim}, a_{\sim} \left\{ \sigma_{\sim -}, \infty_{\sim} \right\} \right], \lambda_{\sim}, \lambda_{\sim}, \lambda_{\sim} \right\}$$

Figure 3-7-2-6: Characteristic topological structures expressed as strings (bottom) derived from the vector flow diagram of a cardiac ultrasound (top left), and representation of specific vortex regions within cardiac blood flow (top right)

²⁹ Persistence Curves: A Canonical Framework for Summarizing Persistence Diagrams (Yu-Min Chung *et al.*, Cornell University, 2021)

<https://arxiv.org/abs/1904.07768> (accessed March 2026)

³⁰ World's First Construction of a Theory to Identify Vortex Blood Flow Within the Heart (Japan Science and Technology Agency, 2025)

<https://www.jst.go.jp/pr/announce/20230818/index.html> (Japanese; accessed March 2026)

(3) Optimal transport theory

Optimal transport theory is a mathematical sciences approach that quantitatively captures the correspondences and structures of change between different states or distributions based on distances and costs. Its distinctive feature is that it is not merely an optimization method but can also structurally describe how distributions change and correspond to one another.

In the medical and life-science fields, research is progressing in which cell-population data obtained through single-cell RNA sequencing (scRNA-seq) is represented as probability distributions, and changes in cell-state distributions at different time points are continuously captured through optimal transport.³¹

In engineering and industry, this could be used as a mathematical foundation for capturing structures of change in phenomena that are described as distributions, such as statistical distribution changes in material microstructure and state transitions occurring during manufacturing processes.

If structural feature quantities related to shape, structure, transitions, and flows that were difficult to capture with conventional methods can be extracted and fused with machine learning, statistical models, and optimization methods, conceivable use cases include early abnormality detection, state classification, behavior prediction, control, and design optimization. In doing so, emphasis should be placed not only on improving analytical accuracy but also on supporting decision-making by deepening understanding of phenomena and improving explanations.

³¹ Estimation of Cell-Differentiation Dynamics From Time-Series scRNA-seq Data: Development of the Comprehensive Trajectory-Estimation Framework scEGOT (Tohoku University, 2025)
<https://www.sci.tohoku.ac.jp/news/20250206-13593.html> (Japanese; accessed 31 March 2026)

Conclusion

In *Innovation Outlook Ver. 1.0 Expanded Edition*, we were able to propose new frontier areas through continuous overview survey in each technology field. Based on an overview survey from a broader perspective spanning fields under TSC's jurisdiction, we were also able to propose frontier areas as newly defined fields.

To create innovation in the frontier areas proposed in *Innovation Outlook Ver. 1.0* and its *Expanded Edition*, it is important to incorporate a variety of innovative technological ideas. In *Innovation Outlook*, we presented technologies of interest to TSC with examples of specific steps to take (T); however, to increase the likelihood of successful innovation, it is also necessary to gather technological ideas latent outside TSC, including those in academia and industry. Based on the results of feasibility studies conducted through request for information, we will therefore organize and advance large-scale technology development projects.

In addition, to achieve the real-world social implementation of these innovative technologies, it is essential to firm up efforts that drive transformation of the social system by building business models and considering rulemaking. To that end, taking *Innovation Outlook* as a starting point, it is considered effective to conduct integrated, comprehensive discussions that bring together diverse insights in collaboration with relevant ministries and agencies, industry, academia, venture capital and financial institutions, and the media. Based on these discussions, we will formulate the Innovation Strategy, outlining the path to realizing innovation.

We hope that *Innovation Outlook Ver. 1.0* and its *Expanded Edition* serve as references for readers considering their own initiatives. We look forward to feedback on the ideas related to frontier areas proposed here, as well as on the formulation of an innovation strategy.

TSC Foresight

Innovation Outlook Version 1.0 Expanded Edition

Executive Summary

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