Innovation Outlook Version 1.0

Executive Summary

July 2025

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

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Section 1. Introducing *Innovation Outlook*

1.1 Background and Significance

Social challenges such as climate change, demographic crises, and security threats are becoming more serious and complex in Japan and globally. While addressing these challenges and pursuing economic growth, it is also necessary to create value; advances in carbon neutrality, sustainability, resilience, and well-being will allow us to realize a better and more prosperous vision of the future. To this end, two things are indispensable: the development of innovative technologies that have never been seen before, and the building of a system for real-world social implementation of them. This in turn requires the development of new business models, rules and standards, and ways to foster social acceptance. In other words, in order to realize the vision of the future, innovation that leads to the transformation of the social system and the creation of new industries is imperative. What is called “transformative innovation.”

Transformative innovation can only come about by identifying the new values and functions needed to change social systems. We start with discussions of social challenges, and create new industries based on innovative technologies that can realize them.

Japan has many technologies and industries with strengths other countries do not, such as high-performance materials and components. By leveraging these strengths, we have the potential to create new industries and contribute to solving social challenges. NEDO has always promoted projects to solve social challenges, but up to now the focus has been on individual technologies and industries that built on the past.

However, non-adjacent issues that transcend conventional technologies and industrial fields require consideration that pushes the boundaries of existing operations, systems, human resources, organizations, industries, and cultures. The concept of ambidextrous management has already been adopted by advanced companies and public institutions in Japan and overseas in response to such concerns.

On the other hand, innovation is progressing rapidly, and in the United States, China, and other countries, technological development from the foundational research stage is being accelerated by injecting large amounts of risk money. International discussions are underway on managing innovation in response. Management of the Defense Advanced Research Projects Agency (DARPA, formerly ARPA) in the United States can be seen as a successful model. ARPA’s organizational structures follow the DARPA model of a program director (PD) with discretionary authority to consistently promote challenging issues, from idea exploration to commercialization support, with a high degree of agility. This method of management is gaining popularity.

Against this backdrop, NEDO's Technology and Innovation Strategy Center (TSC) began creating this *Innovation Outlook* in FY2024. We take a bird's-eye view of trends in each field, identify areas that Japan should focus on ("frontier areas," defined in section 1.2), and lay the groundwork for an innovation strategy that charts the path from research and development to real-world social implementation in each area. The management flow shown in Figure 1-1 is the foundation for a system that promotes comprehensive, flexible idea development and commercialization in the frontier areas.

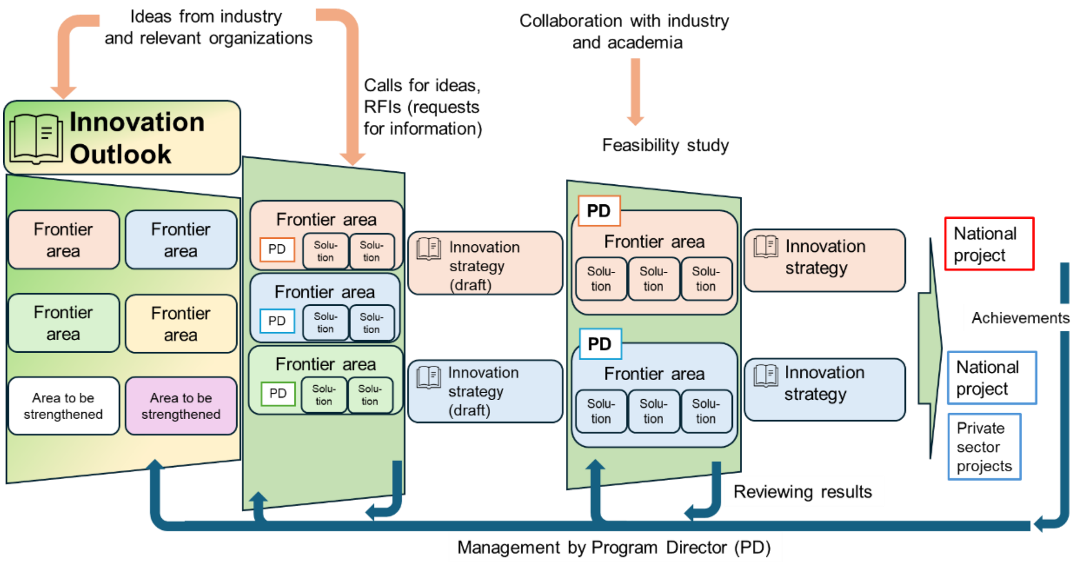

Fig. 1-1: NEDO's frontier area management flow

Innovation Outlook will contribute to policy and project planning by providing information to the Ministry of Economy, Trade and Industry (METI) and other government agencies. We also envision its use by industry leaders, small and medium-sized enterprises, startups, academic organizations, financial institutions, venture capitalists, and the media. We intend to actively disseminate information to public institutions and organizations outside Japan, which will lead to R&D and investment in innovation. In addition, based on feedback from stakeholders and trends in economics, society, and technology, we plan yearly updates to add and expand on frontier areas.

1.2 What Is *Innovation Outlook*?

In order to solve social challenges, *Innovation Outlook* provides a bird's-eye view of market, technology, and policy trends in the fields under the responsibility of TSC and identifies frontier areas based on these trends. We then propose new measures Japan should take, existing areas in which efforts should be focused or accelerated, and cross-disciplinary areas in which integration between domains should be sought.

Section 2 presents the positive, prosperous vision of the future envisioned by TSC. Section 3 analyzes the social challenges that must be overcome if we are to realize this vision of the future, and looks at the market, technology, and policy trends surrounding them. Section 3 also lists frontier areas that Japan should focus on.

(1) Formulation approach and framework

In *Innovation Outlook*, we use a backcasting approach starting from the vision of the society we are aiming for and social challenges we face. We then extract the "functions" and "value provided" required to solve these challenges. We identify frontier areas that should be focused on and analyze multiple technologies with similar functions and values. Finally, we analyze and compile ideas for real-world social implementation of those technologies. Our logic model was built with reference to the MFT® (Mission/Market, Function, Technology) framework one of the frameworks for technology management developed by Arthur D. Little, and is explained on the following page.

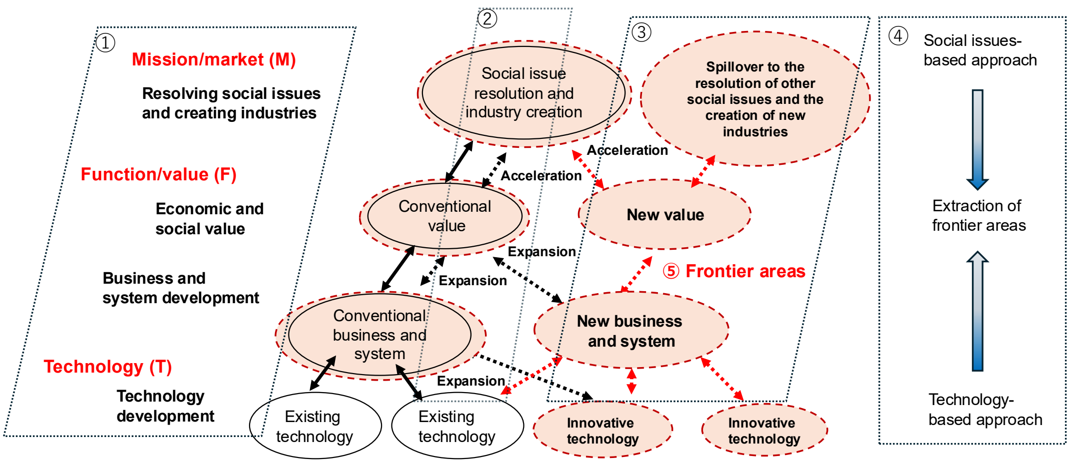

Fig. 1-2: *Innovation Outlook* logic model

Using this logic model, it is possible to study frontier areas, including cross-disciplinary areas, based on the following concepts in Figure 1-2:

1. The resolution of social challenges and the creation of new industries (M) are achieved by continuously expressing the functions (F) that create economic and social value. Functions are assembled as systems that combine multiple technologies (T).
2. When innovative technologies (T) are developed, existing business systems and values (F) are expanded, and social challenges and industry creation (M) are accelerated.
3. When innovative technologies (T) are combined with other technologies (T), new business systems and values (F) are created. In addition to solving social challenges and accelerating the creation of industries (M), new values (F) have the potential to impact other social challenges (M).
4. There are two approaches to connecting technology (T) and social challenges (M). One starts from the technology (T) and considers what kind of values (F) and social challenges (M) it will lead to solving. It is also possible to start from the social challenge (M), then identify the value (F) and technology (T) that it requires.
5. By identifying frontier areas based on values (F), it is possible to discuss what kind of social challenges and industries (M) they will lead to, what technologies (T) should be developed to create value (F), and what kind of business systems should be built to implement them.

(2) Details on frontier areas

At a January 2025 meeting of the Innovation Subcommittee under METI's Industrial Structure Council, the Innovation and Environment Policy Bureau indicated that they would identify frontier areas by evaluating them from five perspectives:

1. Future potential (growth potential and social challenges)
2. Innovativeness of technologies and ideas
3. Japan’s advantages
4. Difficulty in tackling them by relying only on the private sector
5. Technologies important for economic security

TSC added its unique views and approach to these five perspectives, and using the logic model described above, chose its own frontier areas for *Innovation Outlook*.

Based on the idea of ambidextrous management, *Innovation Outlook* makes a point to cover areas that have been underserved by conventional policies due to reasons such as technological and demand uncertainty. As a result, the frontier areas proposed in *Innovation Outlook* may not necessarily be consistent with existing policies and plans in each field. In addition, varied opinions and views of a hypothetical ideal society in 2040 affect backcasting. We intend to disseminate information on the frontier areas proposed in *Innovation Outlook* to related domestic and international organizations in industry, academia, and government, so discussions may be held which lead to effective efforts toward the realization of transformative innovation.

Section 2. TSC's Vision of the Future

To date, TSC has presented multiple visions of the future based on research and analysis of international frameworks and trends. "*The Prosperous Future" to be Pursued Beyond Innovation*[1] [TSC, 2021] (hereinafter referred to as the *Prosperous Future Report*) was an expansive look at a wide range of fields, analyzing a total of 75 reports on prosperity in Japan and overseas from a broad perspective. It identified a "core value compass" with six directions and 12 "visions of society to achieve" when promoting innovation activities. TSC's *Comprehensive R&D Principle for Sustainable Society 2020*[2] report [TSC, 2020] shows the importance of promoting the three social systems of the circular economy, bioeconomy, and sustainable energy in an integrated manner to realize a sustainable society that solves energy and environmental problems. The revised edition[3] published in 2023 [TSC, 2023] highlights digital transformation (DX) as the foundation of the three social systems.

Innovation Outlook continues the work of these publications in examining social challenges that need to be overcome and frontier areas that can help solve them. The *Prosperous Future Report's* Core Value Compass With Six Directions and 12 Visions of Society to Achieve shown in Figure 2-1 form the basis of our analysis.

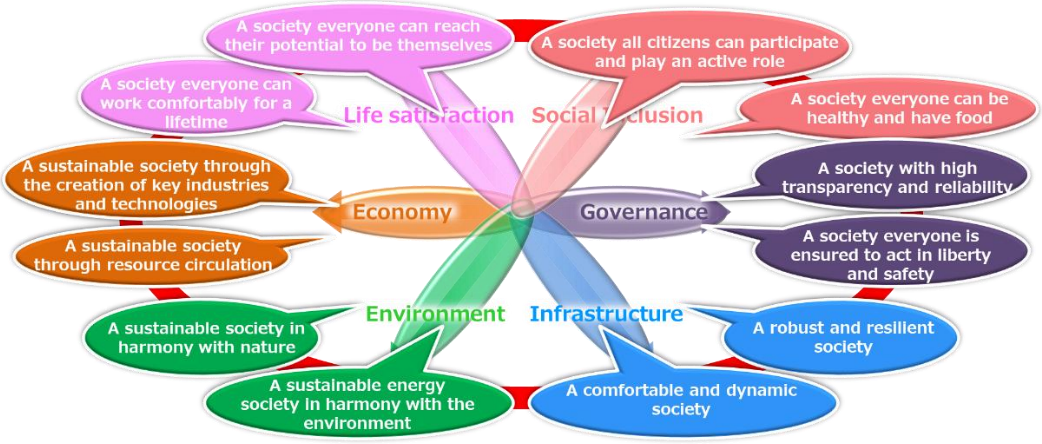

Fig. 2-1: Core Value Compass With Six Directions and 12 Visions of Society to Achieve

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[1] https://www.nedo.go.jp/content/100964350.pdf (NEDO TSC, 2021)
[2] https://www.nedo.go.jp/content/100968255.pdf (NEDO TSC, 2020)
[3] https://www.nedo.go.jp/content/100964787.pdf (NEDO TSC, 2023) Japanese only

Section 3. Social Challenges and Frontier Areas

As mentioned in Section 2, *Innovation Outlook Ver. 1.0* will examine social challenges to overcome (M) and areas to focus on to solve them (F) in order to realize a certain vision of the future. TSC proposes frontier areas to consider based on five specific perspectives: future potential (growth potential and social challenges), innovativeness of technologies and ideas, whether they align with Japan's strengths, the difficulties of relying only on the private sector, and importance for economic security.

Figure 3-1 shows an overview of social challenges (M), areas to focus on (F), and those proposed as frontier areas (F, in yellow).

The following sections will look in detail at the social challenges and frontier areas, and define specific measures that can be taken in each technology field related to the themes under TSC's jurisdiction (sustainable energy, environment and green chemistry, agri-food tech, digital field, materials, and bioeconomy).

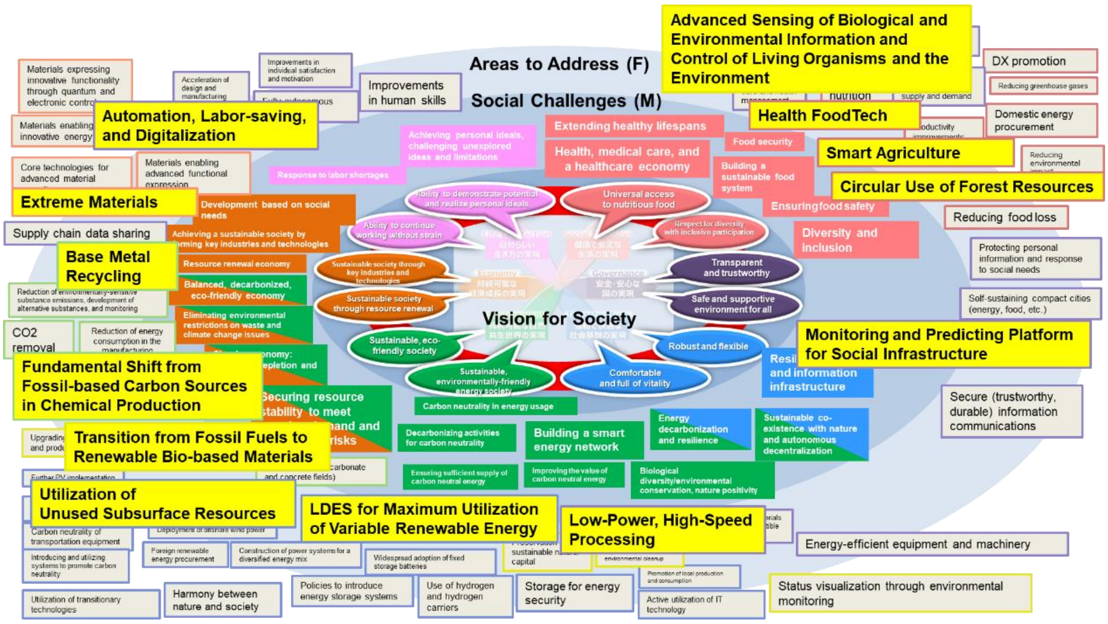


Fig. 3-1: Social challenges and frontier areas examined in *Innovation Outlook Ver. 1.0*

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 the purpose. There is generally a supply-demand gap between the conversion (production) and usage steps. Energy storage must fill this gap, and adjustment must occur to balance supply and demand. In this publication, we focus on two steps in this process: production and storage.

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

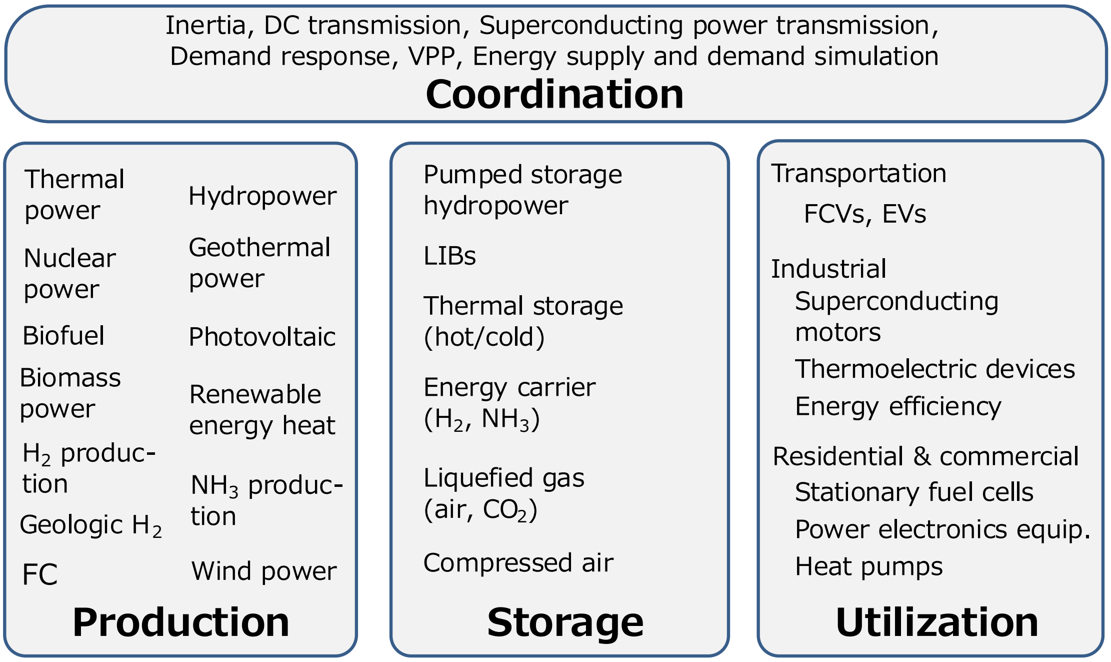


Fig. 3-1-1: Sustainable energy field and technology examples

3.1.2 Social Challenges and Frontier Areas: Utilization of Unused Subsurface Resources; 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 that offsets carbon through methods such as CCS (carbon capture and storage.) However, Japan has limited space; notably, the amount of suitable flat land is small compared to the size of its economy. Therefore, in order to promote the adoption of carbon neutral energy, we must not only provide economic support but also support technological development.

Due to a rise in solar power generation in recent years, the amount of electricity generated during midday has increased. This daytime surplus leads to lower wholesale electricity prices, especially in spring and autumn. But there is a shortage of power every morning and evening, and wholesale prices soar depending on demand, in particular during summer and winter. The social challenge here is to expand the adoption of renewable energy and improve on its merits. This requires implementing advanced storage systems so variable renewable energy can be stored when there is excess supply and drawn on when there is a shortage.

(1) Utilization of unused subsurface resources

Figure 3-1-2 looks at the main areas to be addressed in securing a sufficient amount of CN energy.

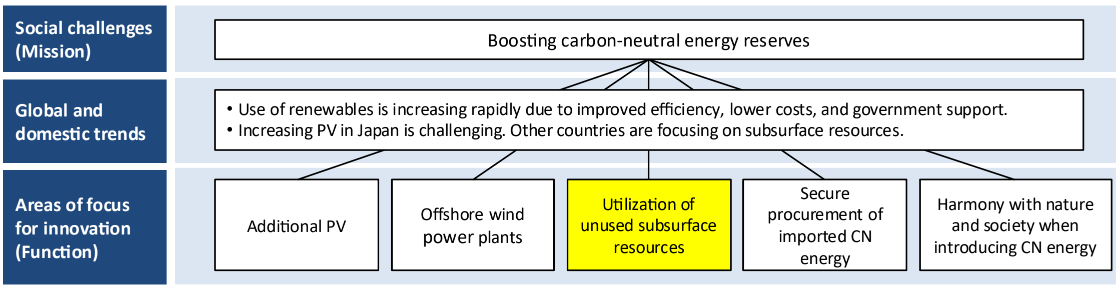


Fig. 3-1-2: MF logic model of CN energy

Figure 3-1-3 on the next page shows various technologies (such as power generation, which is a major area to be tackled) organized by possible location. Based on this, we propose utilization of unused subsurface resources be considered as a frontier area, as abundant resources are expected to exist underground that have not been fully utilized.

Specific measures include next-generation geothermal power such as enhanced geothermal systems (EGS), closed-loop and super-critical geothermal power generation, and geologic hydrogen.

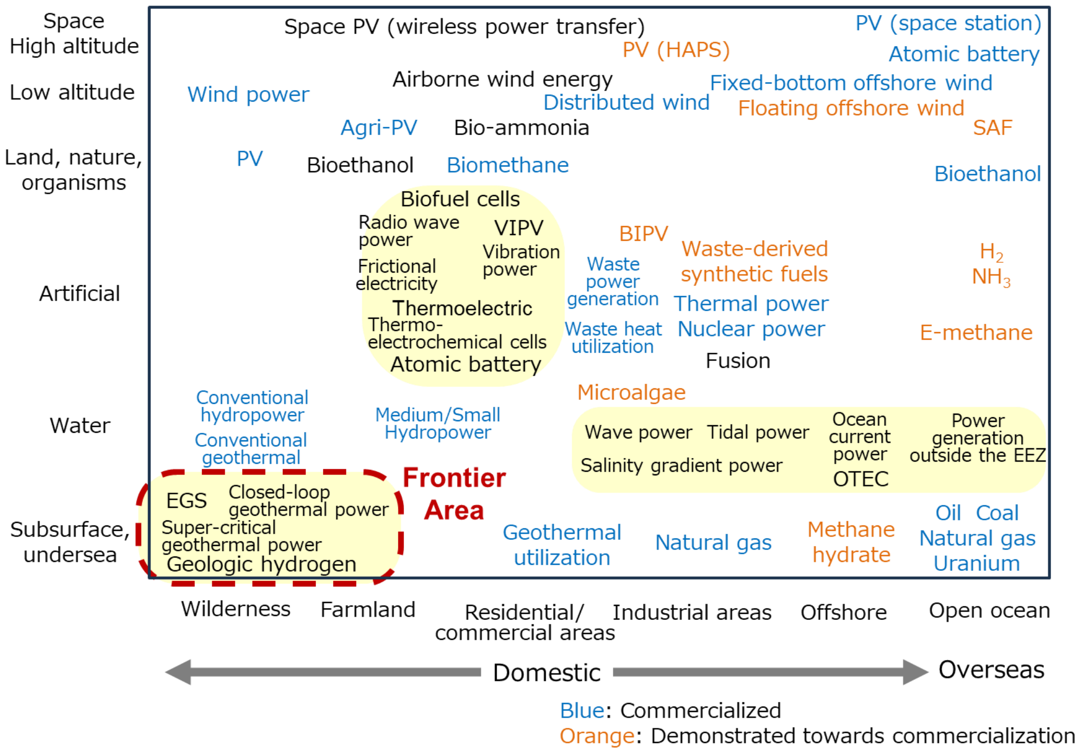


Fig. 3-1-3: Possible locations for energy for power generation in Japan

The use of next-generation geothermal power generation and geologic hydrogen has the potential to meet Japan's energy needs in the future. Research and development in these innovative technologies has been accelerating in the United States and Europe.

Japan's territory is home to volcanic zones and plate boundaries, so geothermal and valuable rocks necessary for geologic hydrogen production can be obtained near the surface. There are many researchers in the field of geology and related domestic industries, so there is a possibility for Japan to take advantage of these strengths. In addition, as a purely domestic energy source, it will lead to an increase in self-sufficiency, which is important from the perspective of energy security.

(2) Long-duration energy storage (LDES) for maximum utilization of variable renewable energy

Figure 3-1-4 shows the major areas that need to be addressed in expanding the adoption of renewable energy and making best use of it.

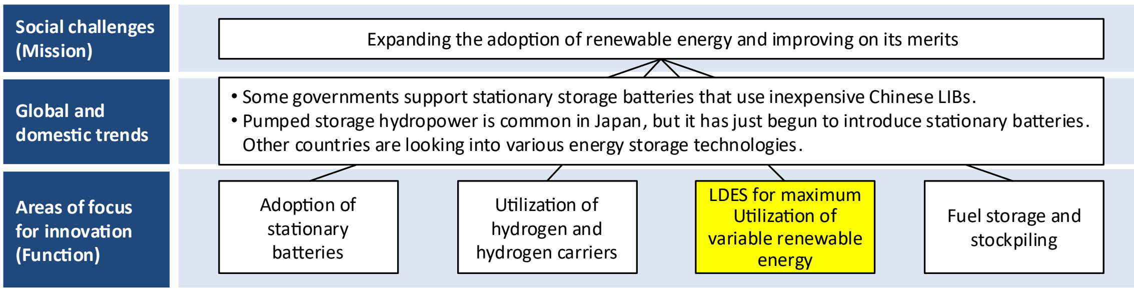


Fig. 3-1-4: MF logic model of renewable energy

We propose LDES for maximum utilization of variable renewable energy as a frontier area, with specific methods including storage by thermal and mechanical energy. This judgment was reached after sorting energy storage by how much can be obtained and how long it keeps (output time). An area with a long output time is an area where efforts are insufficient, such as storage batteries not being suitable, as reflected in Figure 3-1-5.

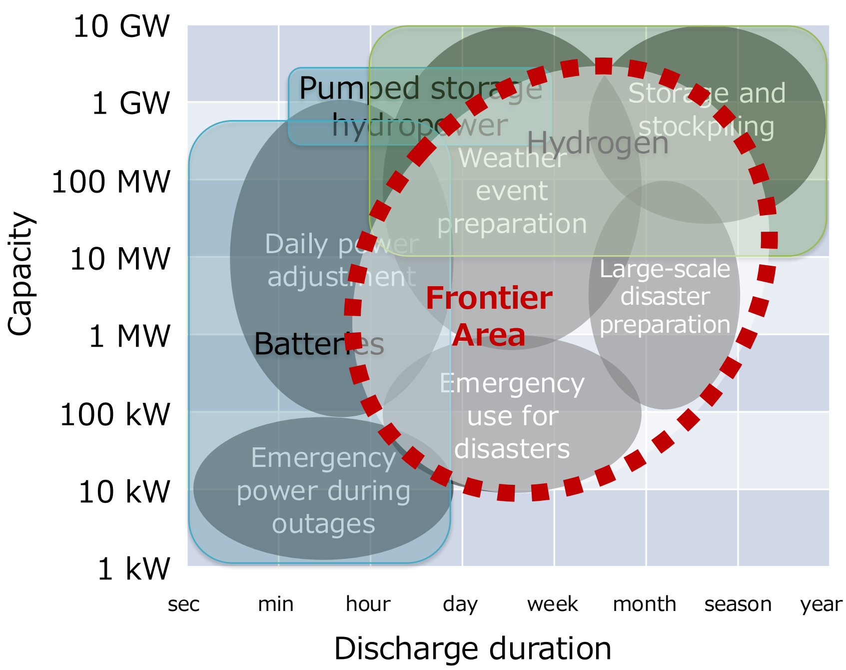


Fig. 3-1-5: Frontier areas of energy storage technology

The energy storage market is expected to reach $204.8 billion by 2033, up from $58.9 billion in 2024, and has enormous potential. LDES has been attracting the attention of government agencies and venture companies, with the United States, Europe, and China rapidly accelerating research and development in innovative technologies.

Japan possesses high-efficiency heat pump technology and high-performance thermal insulation technology. The technological strengths may be drawn on for the practical application of high-efficiency thermal energy storage. This is also important from the perspective of energy security because it does not require specific mineral resources in contrast to LIBs.

3.1.3 Examples of Specific Steps to Take

(1) Utilization of unused subsurface resources

Specific examples of utilization of unused subsurface resources include supercritical geothermal power generation and geologic hydrogen. Supercritical geothermal power generation uses water that is drawn underground by plate tectonics and is in a supercritical state at extremely high temperature and pressure as a geothermal resource. More than 15 regions in Japan have been identified with a high probability of having supercritical geothermal reserves. In the future, exploratory wells will be needed to verify the potential of supercritical water. High-temperature and high-pressure drilling technology should also be developed such as high-temperature cement, corrosion-resistant casings, subsurface cooling technology, and drill bits.

Figure 3-1-6 looks at the geologic hydrogen production process. Geologic hydrogen is thought to be formed by the reaction of underground peridotite with water to form serpentine. In order to increase the amount of recoverable hydrogen, it is important to understand the formation mechanism, such as what type of geology can store it and for how long until it is released into the atmosphere. We must also develop technologies to artificially boost hydrogen production. At the same time, it is necessary to evaluate the environmental impact of hydrogen mining and potential leaks, and consider measures to reduce those impacts.

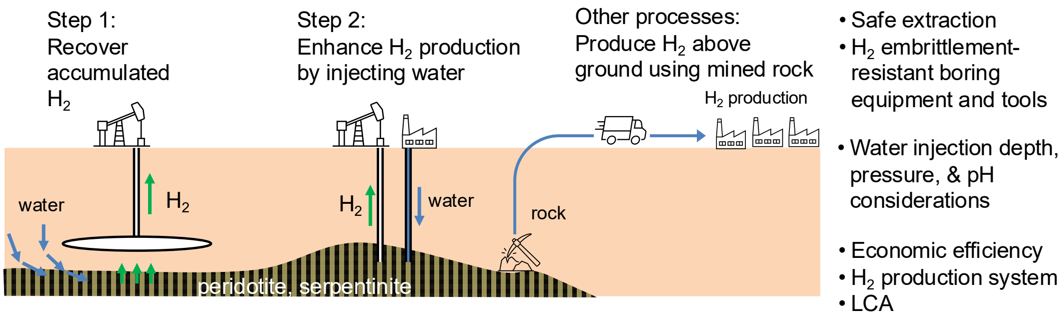


Fig. 3-1-6: Geologic hydrogen recovery and enhanced production processes

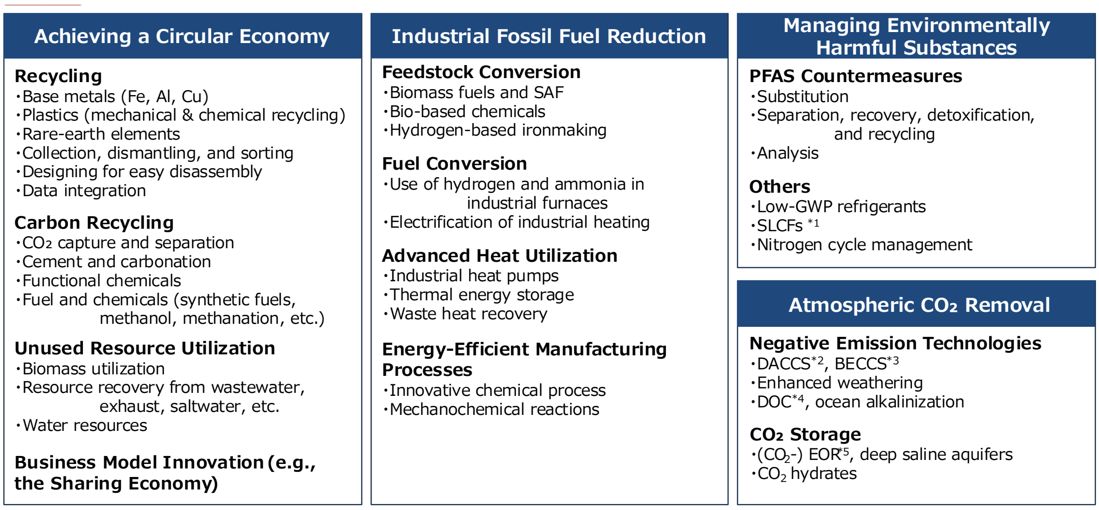
(2) Long-duration energy storage for maximum utilization of variable renewable energy

In order to maintain output control when using variable renewable energy, surplus power is stored as heat or chemical energy and either used as heat or supplied to the grid when needed. To advance thermal storage, we must find efficient ways to convert electricity into heat, develop sensible and latent heat storage media, and improve the methods and efficiency of heat-to-power conversion. In addition, we must develop thermal insulation technology that keeps the heat storage media at a high temperature, improve its durability affected by repeated temperature changes, and develop materials.

3.2 Environment and Green Chemistry Field

3.2.1 Field Overview

Figure 3-2-1 provides an overview of the environment and green chemistry fields. The realization of a circular economy is highlighted as one of the three key social systems for achieving the sustainable society described in Section 2. Accordingly, *Innovation Outlook Ver. 1.0* focuses on promoting the realization of a circular economy within the environment and green chemistry fields.



*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

Fig. 3-2-1: Overview of the environment and green chemistry fields

3.2.2 Social Challenges and Frontier Areas: Base Metal Recycling; A fundamental shift from fossil-based carbon sources in chemical production

In Japan, the circular economy has traditionally been considered from the perspective of adderssing social challenges such as waste reduction and resource security, but in recent years climate change mitigation—specifically, reducing CO_2 emissions by curbing the extraction and consumption of new resources—has come into the picture. Producing base metals (like iron, aluminium and copper) and plastics emits a large amount of CO_2, and recycling is being reconsidered as a way to procure raw materials. Recycling these materials is also important because they have a high weighted Herfindahl-Hirschman Index (HHI), which is one of the indicators of procurement risk, among the materials with high CO_2 emissions during production as shown in Figure 3-2-2. In fact, the market for the use of recycled materials is expanding, and the International Energy Agency (IEA) estimates the ratio of recycled materials and scrap input will increase significantly [International Energy Agency, 2023] (Fig. 3-2-3). Therefore, base metal and plastic recycling should be addressed.

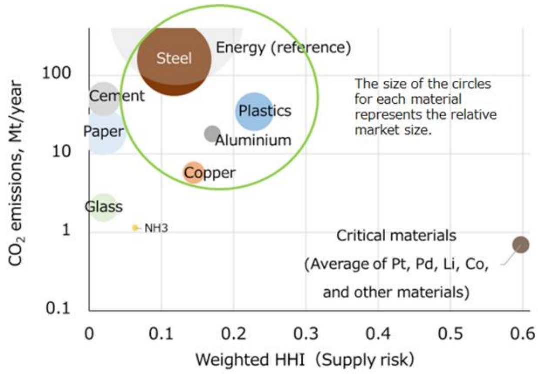


Fig. 3-2-2: CO_2 emissions during production of major materials in Japan, procurement risks, and market size

Source: created by TSC based on various materials

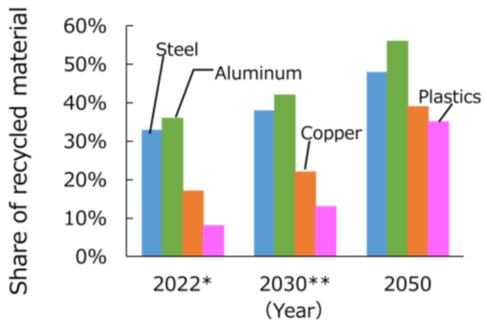


Fig. 3-2-3: Current status and outlook for recycled material or scrap input ratio during manufacturing

Source: created by TSC based on IEA materials[4]

If we look at manufacturing from the perspective of fossil fuel-based resource consumption, which is closely related to CO_2 emissions, we see that the chemical industry, producers of materials such as plastics, use more of these resources as raw materials and energy than the steel or cement industries do. The backbone of chemicals is hydrocarbons, and even if energy consumption is reduced and decarbonization achieved, the use of carbon as a raw material is unavoidable. Analysis of the IEA's scenario shows that oil demand is expected to decline significantly in the fuel sector, but not as much in the chemical sector, and the move away from fossil-based carbon sources in chemical production is an urgent issue. In the circular economy, carbon recycling is regarded as important for reducing CO_2 emissions and making effective use of carbon resources, but it is rarely employed at present due to economic unfeasability. Since both plastic recycling and carbon recycling can be regarded as ways to move away from conventional fossil-based sources in chemical production, defossilization of carbon sources for chemicals is an area that should be addressed.

[4] A Global Pathway to Keep the 1.5 °C Goal in Reach 2023 Update (IEA, 2023), Recycling of Critical Minerals（IEA, 2024）

(1) Base metal recycling

Base metals are located upstream of the supply chain and are the basic materials that are the source of competitiveness. Aluminum and copper are used in solar power generation and electric vehicles, and future demand is expected to increase thanks to the green transformation. To increase the amount of materials recycled, innovation must focus on the quality of scrap raw materials and improving recovery systems to allow use of low-quality, impurity-containing scrap, which has been underutilized to date. Since Japan has historically been a world leader in recycling, there is a chance to take advantage of its strengths, such as established systems for source separation.

(2) A fundamental shift from fossil-based carbon sources in chemical production

The chemical industry provides high-performance, value-added materials that are the source of the domestic industry's competitiveness. However, as the IEA's future outlook assumes that fossil fuel sources will continue to be used as raw materials for chemicals, conversion of carbon sources will be challenging. Innovative carbon recycling technologies that use lower-grade waste plastics must be made economically feasible and put into practical use. From the perspective of economic security, we note that China has implemented chemical manufacturing technology that uses coal-derived methanol. As that poses a threat to the green chemical market, which uses CO_2 as a raw material, carbon recycling technology should be put into use as soon as possible.

Figure 3-2-4 shows these two frontier areas to be focused on.

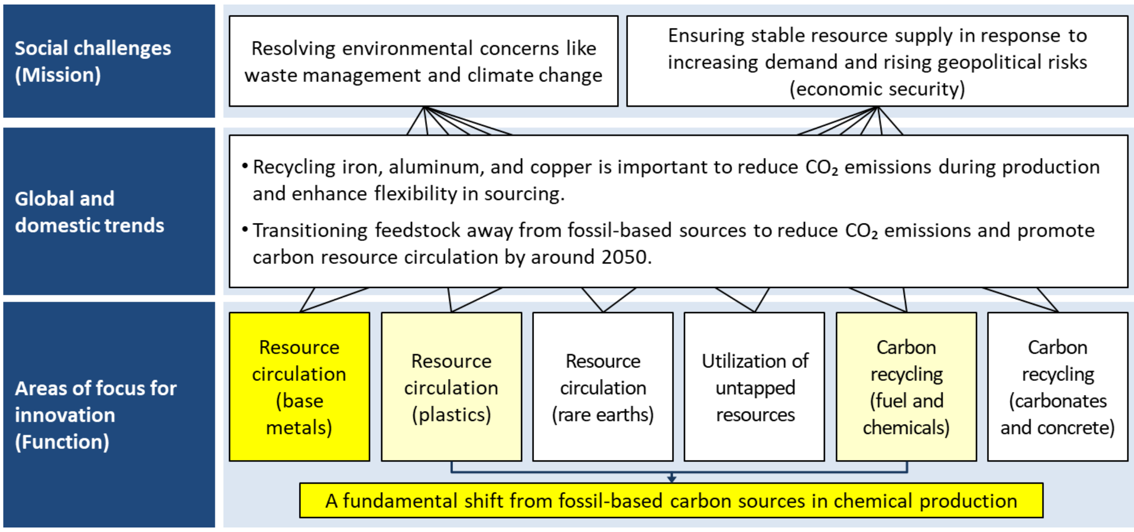


Fig. 3-2-4: MF logic model of the circular economy field

3.2.3 Examples of Specific Steps to Take

(1) Base metal recycling

In order to maximize base metal resource recycling at an early stage, innovative technologies and systems are needed throughout the entire process, including collection of waste products, dismantling, crushing, sorting, recycling, and recycled materials processing. In the sorting process, using AI imaging data can improve sorting accuracy. Reactants can be employed in the recycling process to aid the removal of impurities. Finally, suppressing physical degradation by adding reinforcing agents and dispersing trace crystalline impurities will assist in the processing process.

(2) A fundamental shift from fossil-based carbon sources in chemical production

Figure 3-2-5 shows a technical system for defossilizing carbon sources of chemical production.

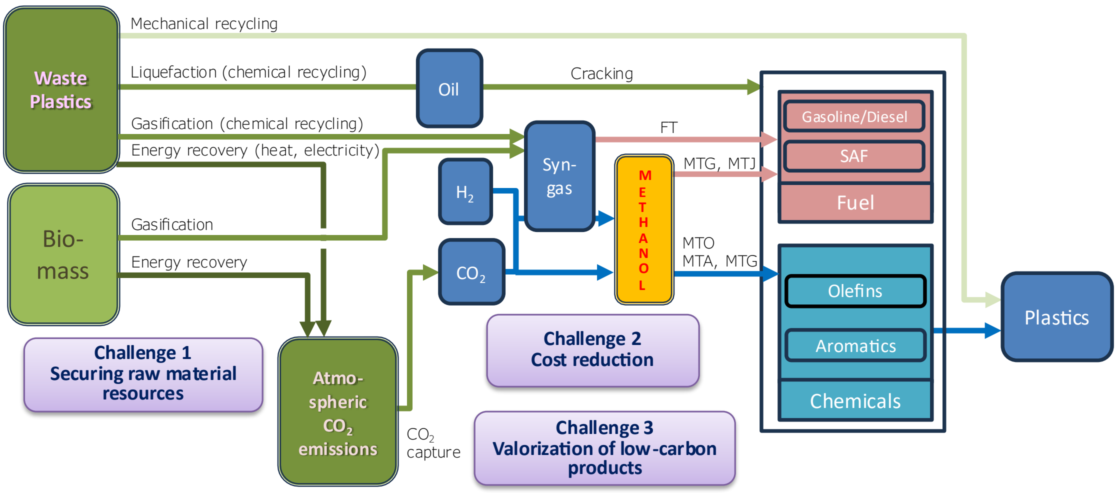


Fig. 3-2-5: Technical system for defossilizing carbon sources in the chemical production

To secure sufficient raw material resources, it is essential to expand the usable volume of biomass and plastic waste. In plastic recycling, it is necessary to establish quantitative standards for assessing the grade of waste plastics after dismantling, crushing, and sorting. as well as developing technologies for circular chemical recycling that can produce chemical feedstocks from low-grade plastic waste. In carbon recycling, while there are few quantitative constraints on the availability of CO_2 as a feedstock, technological development is needed to significantly reduce the costs associated with CO_2 capture and utilization. Figure 3-2-6 shows where various carbon technologies stand in terms of their Technology Readiness Levels (TRLs), with Level 7 being demonstration level. While it is important to scale up mature technologies and improve processes, immature technologies with the potential to exceed mature ones must also be promoted. Thus, not only do we need to develop technology, but we must also make the shift from fossil-based sources to low-carbon products economically feasible.

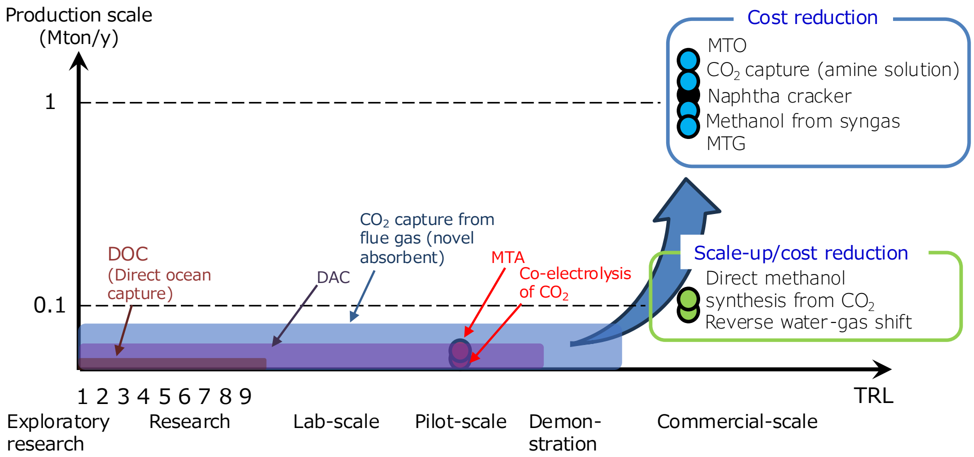


Fig. 3-2-6: Example of R&D themes for carbon recycling technology in chemicals

3.3 Agri-Food Tech Field

3.3.1 Field Overview

Demand for food is expected to surge as the global population grows, and there are concerns over an increase in the number of people who experience chronic hunger or protein malnourishment. Add in external factors such as climate change and international conflicts, and food insecurity becomes apparent as a global concern.

In Japan, it is estimated that the number of core persons mainly engaged in farming will decrease by a quarter over the next 20 years. Agricultural production is threatened on various fronts, including delays in digital transformation, the high dependence on overseas materials and energy, and reliance on imported food. It is necessary to consider multiple perspectives, including mitigating environmental impacts, in order to improve the sustainability of domestic agriculture.

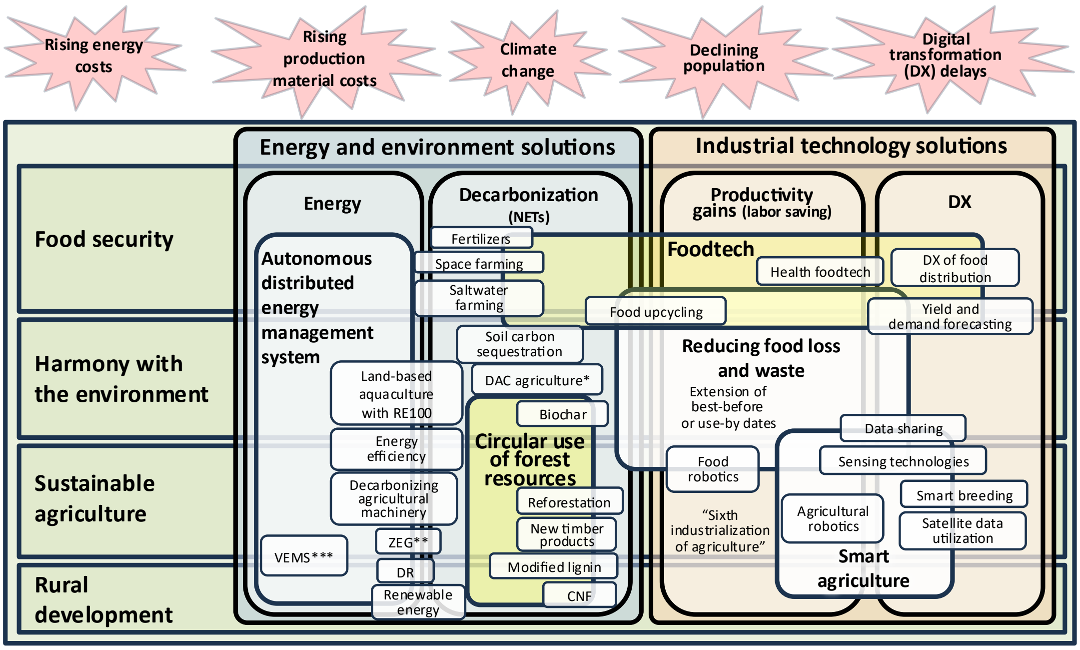


Fig. 3-3-1: Overview of energy, environmental, and industrial technologies in the agri-food tech field

* 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.

3.3.2 Social Challenges and Frontier Areas: Health Foodtech; Circular Use of Forest Resources

The ideal society from the point of view of agri-food tech is one in which everyone is healthy, and no one has to worry about where their next meal is coming from (see the 12 visions of society to achieve in the *Prosperous Future Report* presented in Section 2.) Japan's challenge is to build a robust supply chain linking procurement, production, distribution, processing, and consumption, so that food supplies are stable, continuous, and sustainable.

In addition, dependence on food imports for domestic consumption should be reduced as much as possible to strengthen food security. Enhancing the food self-sufficiency rate so that demand can be met domestically is an important social challenge. Internationally, securing not only sufficient quantities of food but also their quality, including access to healthy diets, has become a major challenge. By supplying high-quality (e.g., highly nutritious) food that meets consumer needs, we improve dietary habits, leading to healthy eating and extended life expectancies.

Solutions to the social challenges in building sustainable food systems, strengthening food security, and ensuring healthy diets are listed next. Table 3-3-1 is organized into three sections:

1. Environmental improvement: solutions related to the sustainability of food production and harmony with the environment
2. Securing quantity: solutions related to the enhancement of the food self-sufficiency ratio and food security
3. Ensuring quality: solutions related to food quality and safety

Table 3-3-1: Organization of the agri-food tech field

	Function (F)	Future prospects	Innovations	Japan's strengths	Difficulties for private sector	Specific examples	Areas of interest
Environment	**Boosting agriculture workforce**	Essential part of food supply chain	-	-	++ Government policies	· Business support (finance, training, etc.)	
Environment	**Reducing environmental impacts**	++	+ IPM, RNA-based pesticides, etc.	++	+ Initiatives by public sector	· IPM · RNA-based pesticides · Bio stimulants	
Environment	**Mitigating GHGs**	+++ Expand carbon credit market	++ New materials	+++ Abundant forest resources	++	· Biochar · Reducing methane from rice paddy soil · Elite trees · New timber products · Blue carbon · Carbon credits	Circular use of forest resources
Environment	**Domestic energy and farming material supplies**	++	++	++	++ Locality-specific initiatives	· Village EMS (community EMS targeting rural areas) · Heat pumps · Phosphorus recovery from raw sewage sludge	
Quantity	**Enhancing DX** **Improving productivity**	+++ Expand smart agriculture market	++	+++ Many patent holders (Kubota, Iseki, etc.)	++ Standardization	· Data-based decision support systems for agriculture · Variety development · Harvesting robots · Autonomous tractors	Smart agriculture
Quantity	**Reducing food loss and waste**	++ Ongoing efforts	++	+++ Preservation and packaging technologies	++ Difficulty with data sharing	· Packing · Yield forecasting · Demand forecasting · Raising awareness · Reviewing business practices · Donations	
Quality	**New food businesses (foodtech)**	+++ Expand domestic and export food markets	++	+++ Strong position in some fields (cell culture, genome science)	++ Need for regulation	· Alternative proteins · Land-based aquaculture · Aquaponics · Space agriculture · Saltwater farming · Functional foods · Personalized nutrition	Health foodtech
Quality	**Improving health and nutrition**	+++ Expand domestic and export food markets	++	+++ Pioneering ways to cope with aging society	+++ Need consumer acceptance		

We qualitatively determined the impacts of each function and listed them as:

+++ strong impact
++ moderate impact
\+ weak impact
\- limited impact

Items that are key parts of the solution were identified, and their contributing technologies were aggregated as areas of interest. These were then organized into an MF logic model after considering the breadth of their applicability (Fig. 3-3-2).

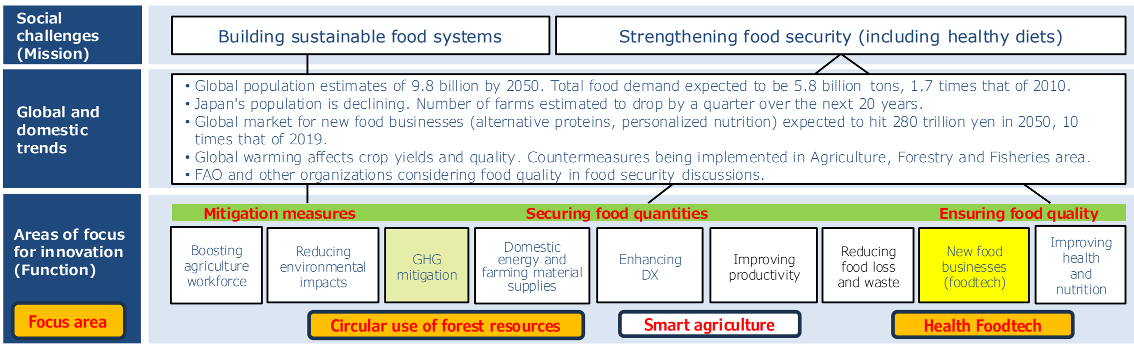


Fig. 3-3-2: MF logic model in the agri-food tech field

The circular use of forest resources (environmental improvement), smart agriculture (securing quantity), and health foodtech (ensuring quality) were identified as areas of focus. Various initiatives have already been made in smart agriculture, so we propose health foodtech and the circular use of forest resources as frontier areas.

(1) Health Foodtech

By grasping the functional labeling component and taste of foods, and by easily analyzing each person's genetic characteristics, nutrient intake, and biological data, we can provide food optimized for individuals to achieve their health goals.

The global foodtech market is expected to expand significantly in the future. Valuing the quality of food is one of the strengths of Japanese food products, and there is a chance that this can be relied on to provide added value.

(2) Circular use of forest resources

Global warming is already having a significant impact on crops through effects such as high temperature damage. Japan's abundant forest resources can act as carbon sinks to mitigate climate change and make food production a sustainable activity. To expand demand for forest resources that have absorbed CO_2, we should establish a production and distribution system and develop new value-added timber and, innovative wood-based chemical materials.

Modified lignin is a wood-based chemical material expected to be used in electronic substrates and automotive components, and estimates of future market value exceed 100 billion yen. Thinned trees and pruned branches can be used for biochar, a soil conditioner that has the effect of storing carbon in farm soil.

Methods for afforestation and reforestation are registered in the J-Credit Scheme[5] for carbon offsets, and it is expected that transactions will expand in the future.

[5] J-Credit is a carbon offset system used by the Japanese government. Credits certify greenhouse gas emission reduction or absorption through carbon sinks.

3.3.3 Examples of Specific Steps to Take

(1) Health Foodtech

Exploration of taste perception and visualization of flavor

There are technologies and devices that evaluate the sensory intensity of sweetness perceived by the tongue, as well as technologies and devices that use high-sensitivity spectroscopic analysis methods to non-destructively measure a food's functional labeling component. Since these can also monitor the condition of acids and sugars, they are expected to be applied to smart agriculture.

Personalized nutrition technology

The second phase of the Cross-Ministerial Strategic Innovation Promotion Program (SIP) included the theme Technologies for Smart Bio-Industry and Agriculture. This saw the design of a system for G-Plus certification[6] of foods which contain 17 nutritional components that show effectiveness in improving mild health ailments. It is possible to provide meals according to an individual's condition. Going forward, it will be necessary to collect and maintain data according to the target minor health concerns and changes in physical condition (see Figure 3-3-3).

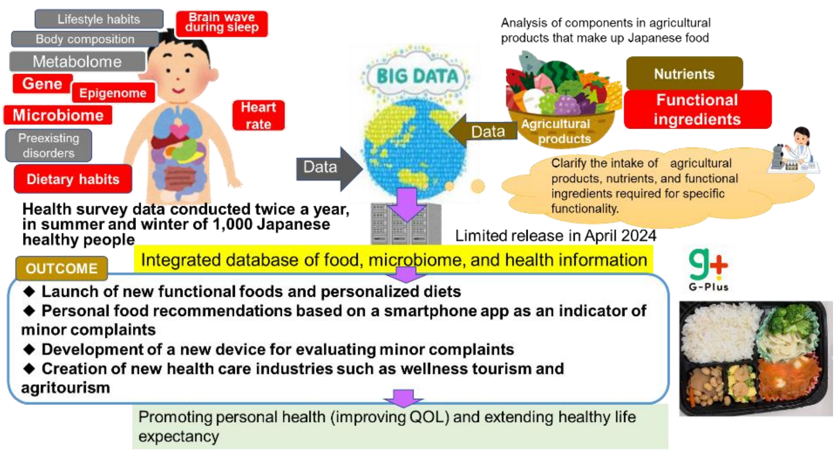


Fig. 3-3-3: Outline of initiatives in the second phase of SIP, Technologies for Smart Bio-Industry and Agriculture

Provided by The Food Research Institute of the National Agriculture and Food Research Organization

[6] G-Plus certified foods contain specified amount of five or more nutrients that have been shown through prior research to address minor health issues. Certification is provided by the Self-Care Food Council or compliant third parties.

(2) Circular use of forest resources

Reforestation

This includes digitization of forest information using laser measurement data and drones, breeding “elite trees,” and development of container seedling propagation technology.

Biochar

The goal is to develop and demonstrate high-performance biochar that imparts microbial functions and improve crop yields.

Urban construction using wood

This includes development and implementation of wood utilization techniques aimed at storing large amounts of carbon in the long term, such as wooden high-rise buildings.

This also includes visualizing and measuring wood quality using X-rays for timber. Additionally, visualizing the internal structure of hardwood trees and logs can also be used in high-end furniture production.

3.4 Digital Field

3.4.1 Field Overview

As shown in Figure 3-4-1, the digital field consists of IT fields such as AI that generate and process data, application fields such as automotive and robotics that utilize IT, and basic technology fields such as electronics and semiconductors that support IT.

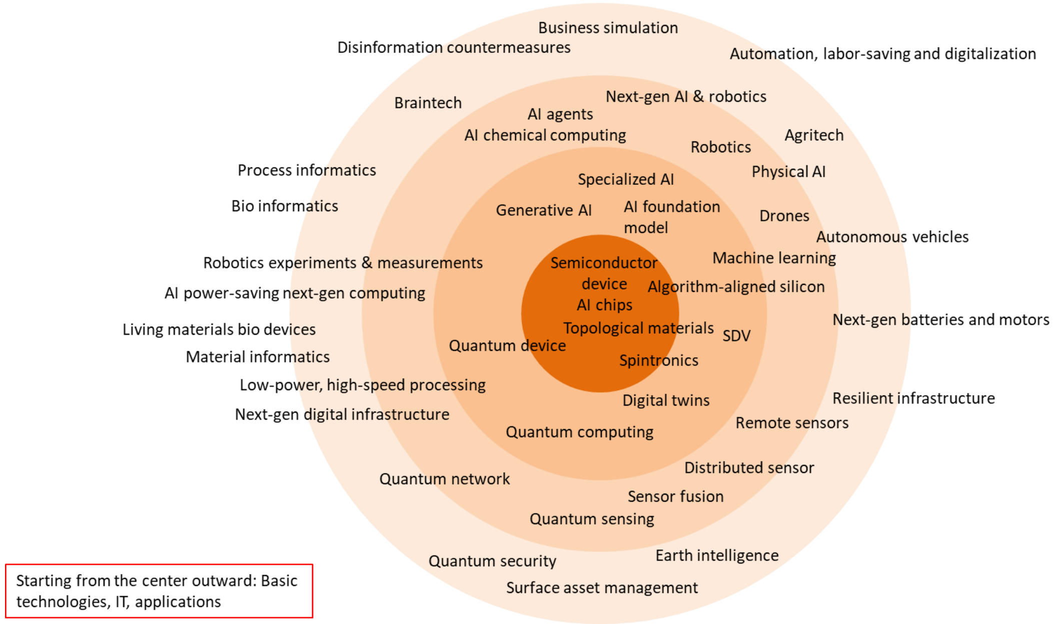


Fig. 3-4-1: Overview of the digital field

3.4.2 Social Challenges and Frontier Areas: Low-Power, High-Speed Processing; Social Infrastructure Monitoring and Forecasting; Automated, Digitalized and Efficient Workforce

The digital field has a hand in solutions to almost all social challenges, including those addressed by other fields.

We first pulled out the functions that may be achieved using technologies related to the digital field from among those necessary to solve social challenges. Next, for each function, we evaluated the magnitude of its social impact using the six directions of the core value compass from the *Prosperous Future Report* discussed in Section 2. Then we estimated when each function is expected to be ready for real-world social implementation based on the concept of Technology Readiness Levels. Figure 3-4-2 shows the functions plotted by date of readiness and magnitude of social impact.

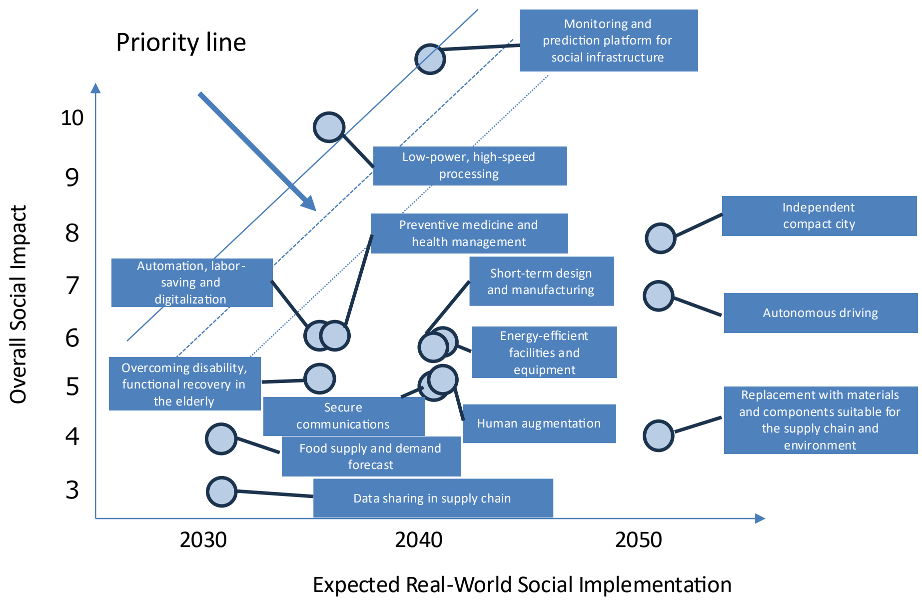


Fig. 3-4-2: Social impact of functions and estimated realization dates

Looking at the functions, we chose the following to be prioritized as frontier areas: low-power, high-speed processing; a monitoring and prediction platform for social infrastructure; and automation, labor-saving, and digitalization. These have a significant impact on society and can be implemented in the near future.

(1) Low-power, high-speed processing

Generative AI has developed rapidly in recent years. It is expected to boost economic development, strengthen the industrial base, and make significant contributions toward solving social challenges such as work style reform and the decline in the working population. On the other hand, the development and use of generative AI consume enormous amounts of electricity, and in order to achieve carbon neutrality by 2050, this must be drastically reduced. Specifically, in addition to reducing power consumption in data centers, it is important to develop innovative AI chips and systems that can operate generative AI using less power even on local edge devices, where its use will increase in the future. Figure 3-4-3 shows our logic model related to low-power, high-speed processing.

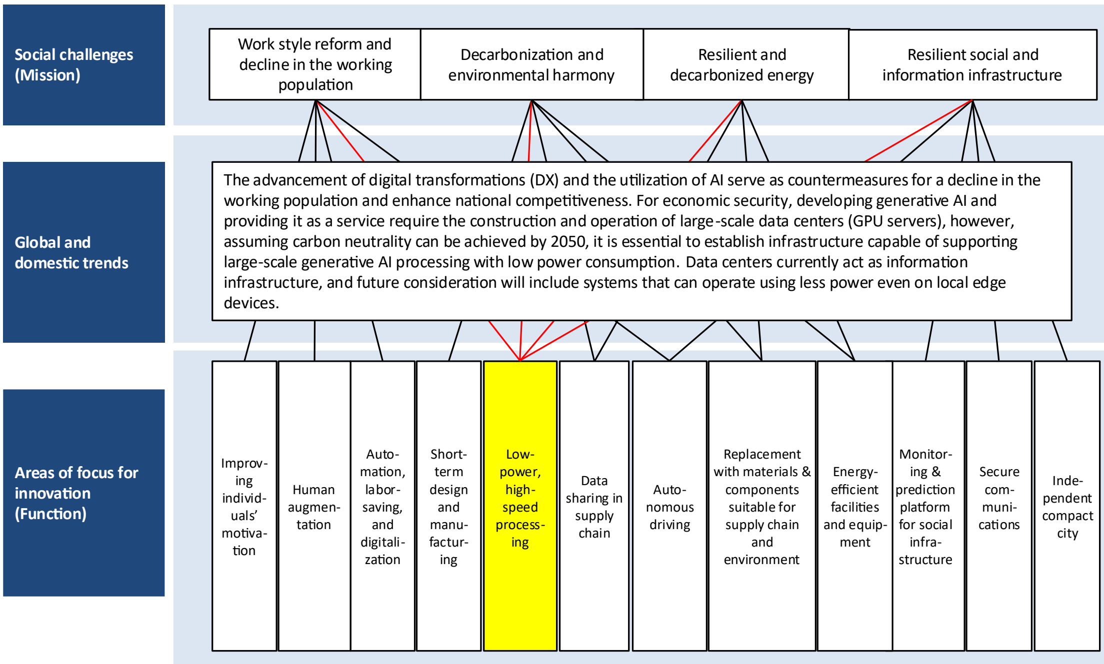


Fig. 3-4-3: MF logic model in the area of low-power, high-speed processing

(2) Monitoring and predicting platform for social infrastructure

In recent years, natural disasters have become even more severe, and minimizing their damage is important not just to save lives but from the perspective of economic security. However, a monitoring and prediction platform for resilient social infrastructure should not be limited to disaster prevention and mitigation, since incorporating maintenance and operation into the economic cycle under normal circumstances will enhance the robustness of the system. Japan has experienced many natural disasters and is well-positioned to make use of accumulated data. Figure 3-4-4 shows our logic model for a monitoring and prediction platform for social infrastructure.

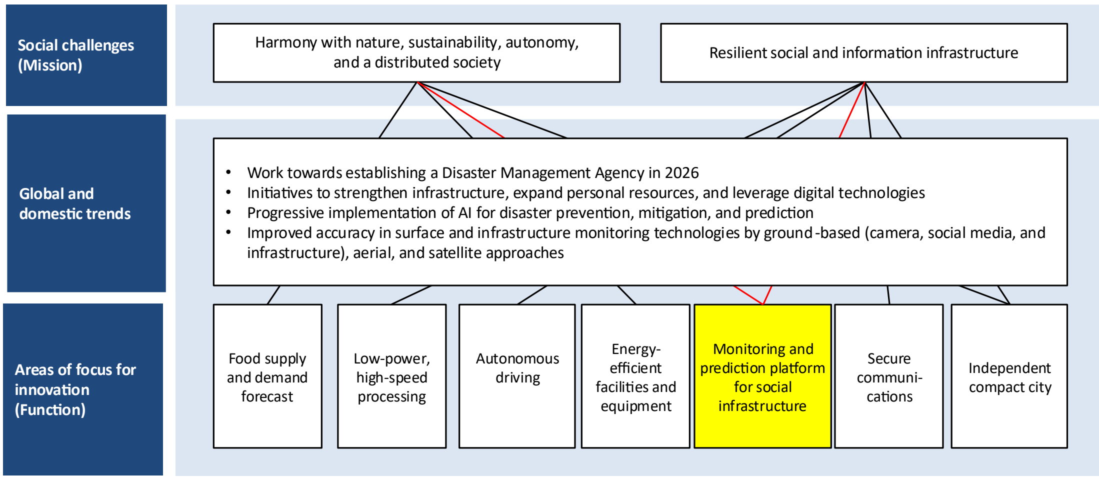


Fig. 3-4-4: MF logic model for social infrastructure monitoring and predicting platform

(3) Automation, labor-saving, and digitalization

A decline in the working population and the aging of society has made it harder to pass on the knowledge and skills of engineers and to secure workers in manufacturing, logistics, construction, nursing care, and agriculture. We can address these and other challenges by formalizing experienced workers' wealth of knowledge and developing technologies for automated, efficient labor by transferring that knowledge to AI agents and robots that utilize generative AI. Japan has a large share of the industrial robotics market, and together with a culture of meticulous service, there is a chance to leverage these strengths. Figure 3-4-5 shows our logic model for automation, labor-saving, and digitalization.

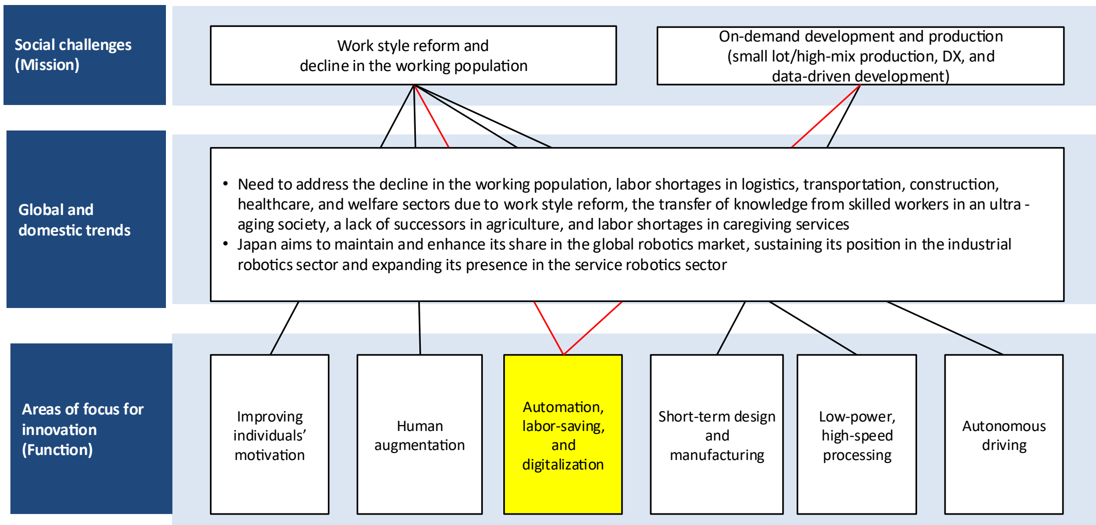
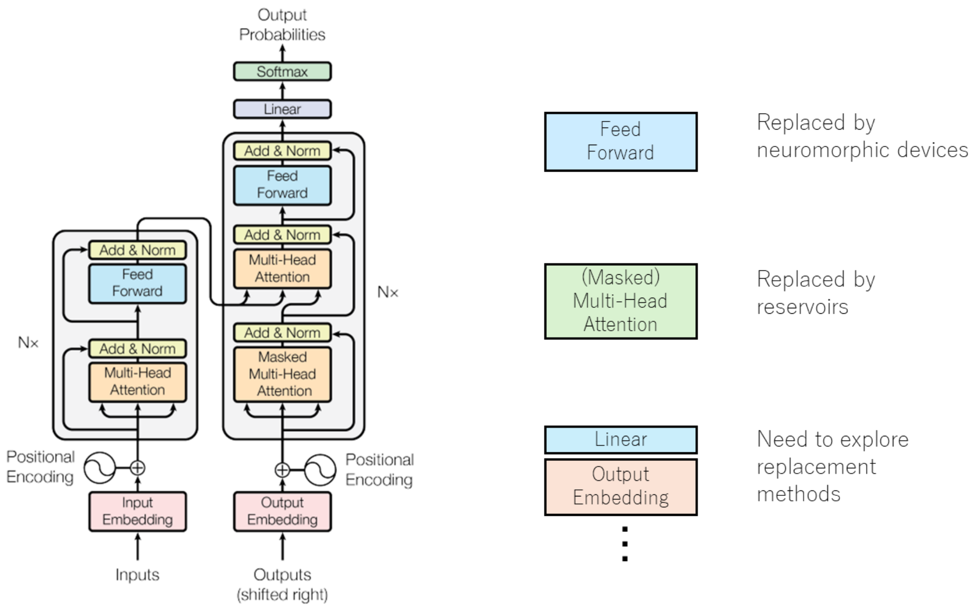


Fig. 3-4-5: MF logic model in the area of automation, labor-saving, and digitalization

3.4.3 Examples of Specific Steps to Take

(1) Low-power, high-speed processing

The transformers used in generative AI combine complex functions, and although it is difficult to achieve power saving with a single technology, it may be possible to implement a power-saving system using neuromorphic devices and reservoirs (Fig. 3-4-6). In addition, general purpose, arithmetic-based computers running on spintronics and photonics instead of conventional electronics can be useful.



(a) The Transformer-model architecture

(b) Alternative system implementation for innovative power saving

Fig. 3-4-6:(a) The Transformer-model architecture
and (b) Alternative system implementation for innovative power saving
of Generative AI

Source :(a) Attention Is All You Need (Google,2017)[7]

[7] https://arxiv.org/pdf/1706.03762

(2) Monitoring and predicting platform for social infrastructure

We can strengthen the resilience of social infrastructure by building a digital twin system that integrates data on devices, facilities, and infrastructure for use in a range of activities, such as urban development planning, day-to-day monitoring, and risk assessment in the event of a disaster (Fig. 3-4-7).

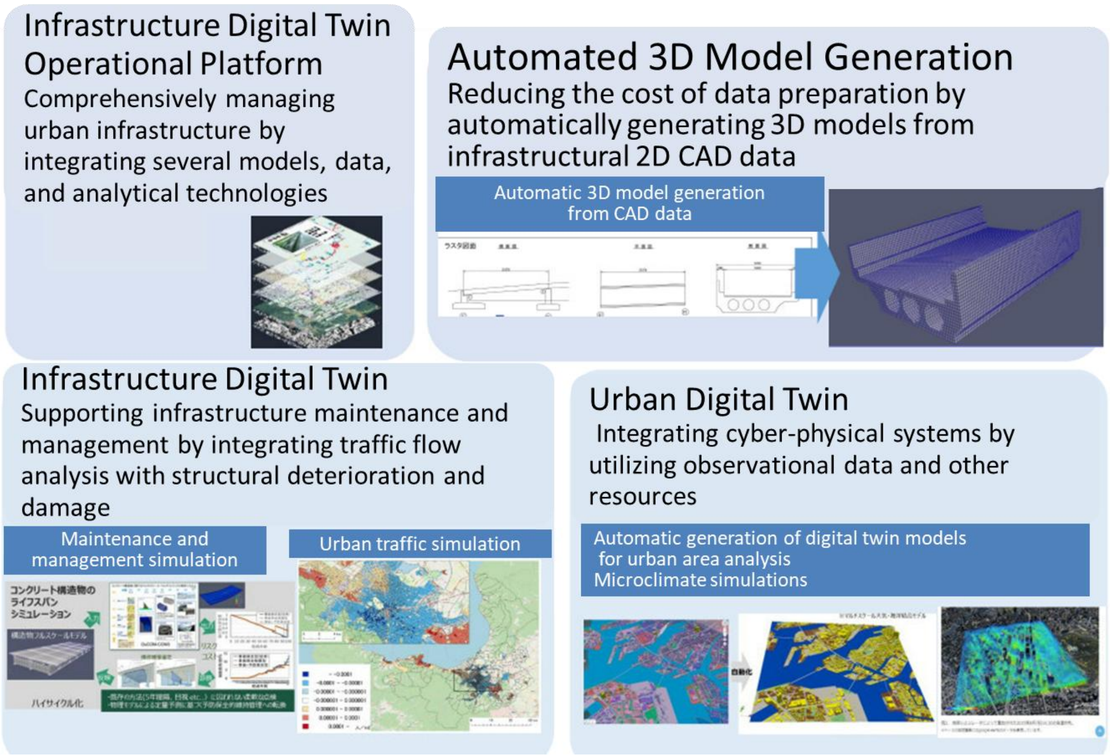


Fig. 3-4-7: Example of R&D related to monitoring and predicting platform for social infrastructure

Source: Strategic Innovation Promotion Program (SIP), *Building a Smart Infrastructure Management System: Kickoff Symposium Material*[8] (English translation by TSC)

[8] https://www.pwri.go.jp/jpn/research/sip/offerform/kickoffsympo_006.pdf (PWRI, 2023) Japanese only

(3) Automation, labor-saving, and digitalization

We will build an AI agent that incorporates the expertise of experienced workers with the help of generative AI that analyzes, models, and formalizes not only typical industry data, but recorded data such as interviews with workers. The generalization ability of an AI agent makes it possible to pass on the tricks of the trade from skilled workers to new employees or transfer them to robots that perform desired tasks. We will build multifunctional autonomous robots, including humanoid robots (Fig. 3-4-8) that can work in a variety of environments, handle a range of work capacities, speak naturally, and offer user-friendly, human-like interfaces using brain-computer interface technology as examples while developing new markets for robots.

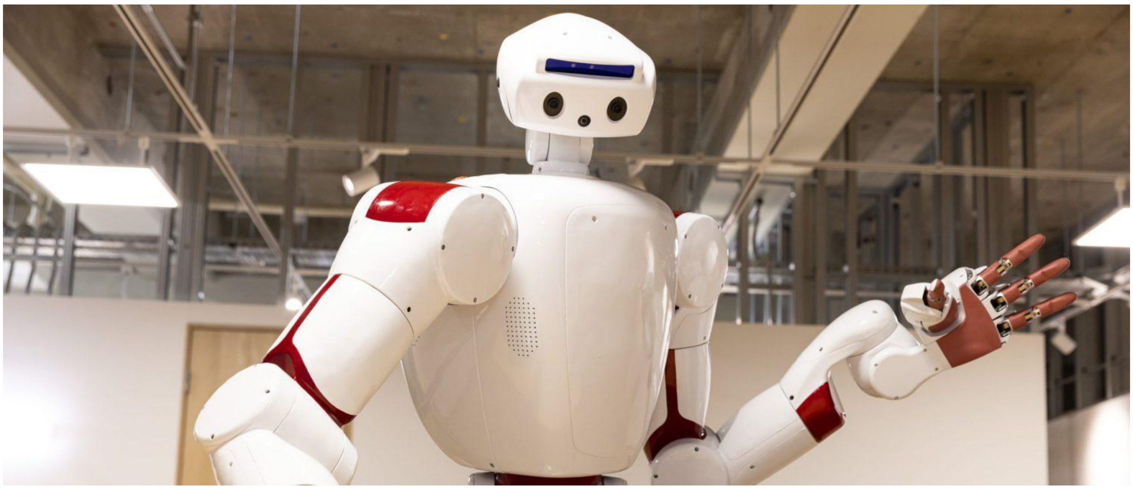


Fig. 3-4-8: Robot developed under R&D related to automation, labor-saving, and digitalization

Provided by JST Moonshot Research & Development Program *"Goal 3"* (SUGANO Shigeki PJ)

3.5 Materials Field

3.5.1 Field Overview

Our definition of materials is not simply substances used to make products and components, but also the equipment and devices that use them. When we consider the materials industry, the manufacturing process technology is also included. Therefore, the materials field includes a wide variety of items and technologies, as shown in the field overview in Figure 3-5-1.

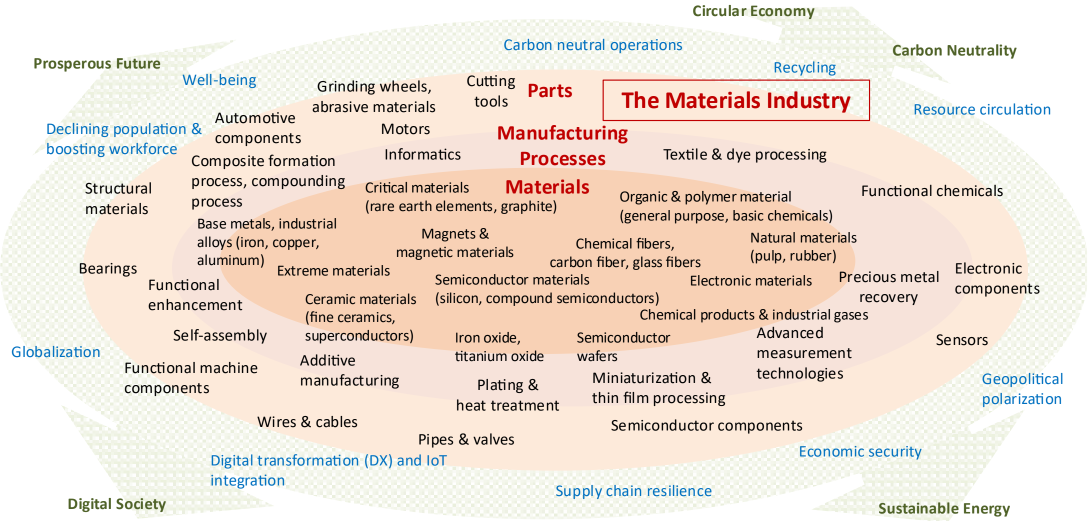


Fig. 3-5-1: Overview of the materials field

In the *Materials Innovation Strategy* announced in April 2021 [Council for Integrated Innovation Strategy, 2021]:

- The history of mankind is also the history of the development of iron, metals, plastics, ceramics, electronics, and other materials, and so materials are the backbone of the world
- Materials have changed the world many times in the past
- Japan has excelled in stacked development and has created innovative materials by refining its technology

In short, materials play a fundamental role in the physical aspects of human society, and Japan has played a major role in their research and development. It is necessary to continue to fulfill this role for the future.

3.5.2 Social Challenges and Frontier Areas: Extreme Materials

Materials are expected to contribute to the realization of all the visions of the future presented in the *Prosperous Future Report* and have the potential to become the foundation for innovation in industries such as energy and resources for a sustainable society and infrastructure industry for a secure society, etc. In other words, it is considered appropriate to set "realization of a sustainable society through the creation of core industries and technologies" among the 12 social visions presented in the *Prosperous Future Report*, as a fundamental social challenge to be solved by the materials industry.

We can classify the business model of the materials industry into three types: high-performance materials, superior grade materials, and general-purpose materials. Japan's materials industry is competitive in high-performance materials. Therefore, continuous production of high-performance materials is key to Japan’s winning strategy.

This is discussed in *Materials Innovation Strategy*. In addition, the strategy identifies the following key technology area [Integrated Innovation Strategy, 2021]:

- Materials with extreme functions
- Materials that can express advanced functions
- Materials that use quantum and electronic control to express innovative functions
- Materials that enable innovative energy conversion
- Basic technologies for advanced materials cycles

As a result of TSC’s research, we highlighted some areas where materials (such as heat resistance, strength, corrosion resistance, optical properties, magnetism, thermal and electrical conductivity, etc) have extreme functions, or where materials are used in extreme conditions (ultra-high temperatures, extra-high voltages, ultra-high magnetic fields or plasma environments.) This is called extreme materials and is proposed as a frontier area.

Figure 3-5-2 shows the MF logic model in the materials field based on the previous information.

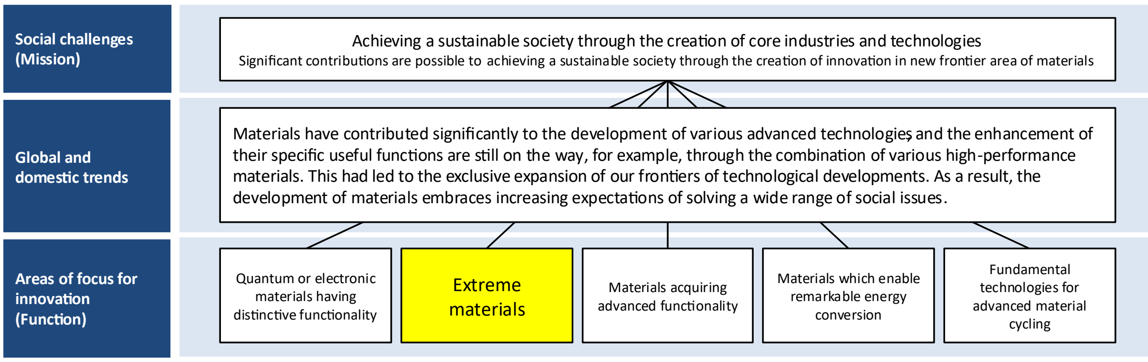


Fig. 3-5-2: MF logic model in materials field

The market for extreme materials has a higher growth rate than markets for other materials. In addition, Japan has a large share of this market and many patent applications are filed by Japanese companies, making it an area where Japan’s strengths should be utilized.

3.5.3 Examples of Specific Steps to Take

When considering initiatives in the field of extreme materials, it is important not only to pursue performance in extreme conditions, but also to select materials with a foreseeable potential for social implementation and develop technologies that leverage Japan’s strengths in extreme conditions to avoid winning in technology but losing in business. As a result of analyzing Japan's strengths from the perspective of market prospects and innovation of technologies and ideas (literature, number of patents, technology and policy trends, etc.), *Innovation Outlook Ver. 1.0* has decided to focus on "high-temperature superconducting conductors" and "ultra-high-performance optical materials (power lasers)".

(1) High-temperature superconductors (HTS)

HTS tapes can stably maintain a superconducting state in high magnetic fields. The high magnetic field state caused by high-temperature superconductivity dramatically improves the strength of conventional magnets and is expected to be used in a wide range of applications, such as improving the resolution of MRI and other fields, miniaturizing powerful motors, applying them to aircraft power sources, and developing powerful magnets for confinement of nuclear fusion plasma.

One example of HTS tape is REBCO (REBa2Cu3Oy; rare earth, barium copper oxide), which excels at generating a strong magnetic field. The tape-shaped wire is made by growing complex oxide crystals on a metal substrate using a technique such as vapor deposition (Fig. 3-5-3).

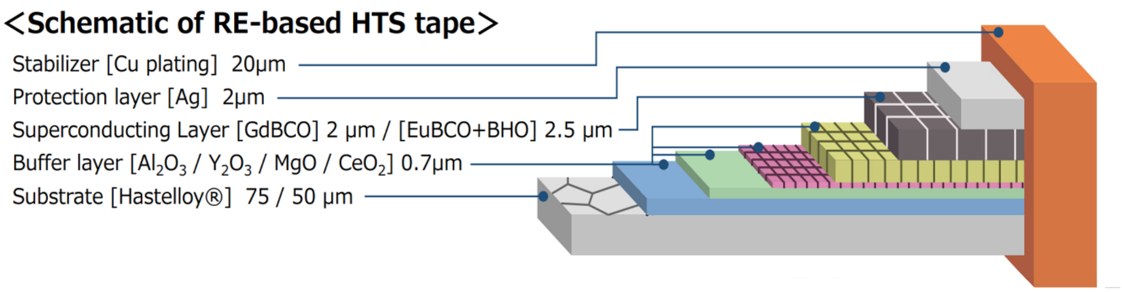


Fig. 3-5-3: Schematic diagram of REBCO tape rod structure
Source: Introduction of Fujikura RE-based High Temperature Superconductor [9]

HTS tape (tape length: ~1 km) is used for academic research but is not widely used in industrial applications. Since HTS tape is brittle on itself, an easy-to-handle, cable-type conductor is required to efficiently manufacture magnet coils. In addition, for widespread adoption by industry, both AC and DC coils are needed, which requires AC loss.

Although Japan companies have a high presence in HTS tape manufacturing, it is considered necessary to further develop and implement high-temperature superconductor technology and social implementation to further maintain and strengthen Japan's industrial competitiveness.

[9] https://www.fujikura.co.jp/products/superconductors/images/Fujikura_superconductor_202508_EN.pdf (Fujikura Ltd.,2025)

(2) Ultra-high-performance optical materials (high-power lasers)

High-power lasers are expected to be used in applications such as processing difficult-to-machine materials, wireless energy transmission, removing debris from outer space, and modifying metal surfaces.

Figure 3-5-4 shows an example of a high-power pulsed laser developed by a leading optical equipment and materials manufacturer as part of a NEDO project.

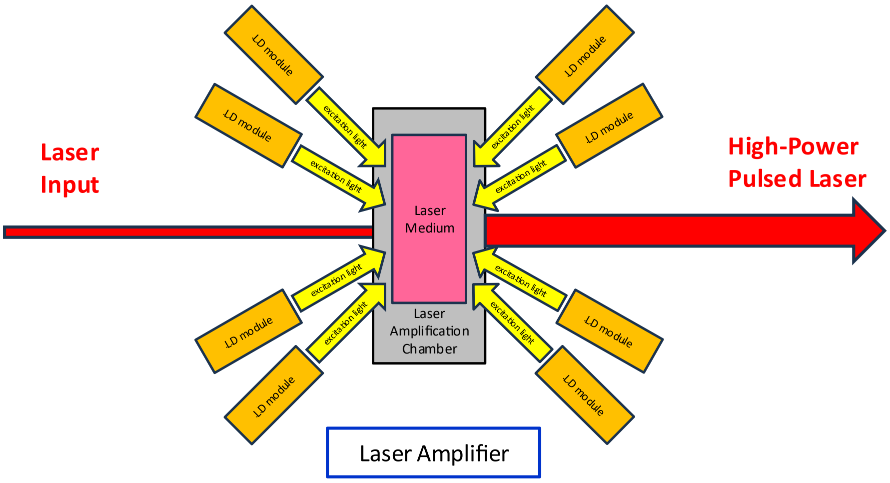


Fig. 3-5-4: Development example of high-power pulsed laser

The development of laser-related materials (optical materials and devices) requires the conversion of high pulse energies of several 100 joules or more and the response to further high energy increases. A laser medium or optical component require high-power and high-efficiency materials, high thermal conductivity and light-gathering capabilities to withstand the heat generated at output, wavelength compatibility, high shape processability, bondability to other materials, high mechanical strength, corrosion resistance in harsh environments, resistance to optical damage, and reliability.

Leading optical equipment and materials manufacturers in Japan are tackling to solve these problems. Recently, with growing global attention on laser fusion, academic institutions and startups may also play a role in the development of high-power lasers.

3.6 Bioeconomy Field

3.6.1 Field Overview

With the growing interest in sustainable development, the bioeconomy—an economic system that uses biological resources and biotechnology to create materials, products, and services—is gaining prominence.

The solutions created by the bioeconomy can be broadly divided into three main fields: industrial (white biotechnology), health and medical care (red biotechnology), and agriculture, forestry, and fisheries (green biotechnology). As shown in the field overview in Figure 3-6-1, there are a wide range of support technologies, and fusion with fields such as digital technology, chemistry, and engineering is indispensable for real-world social implementation and industrial acceleration.

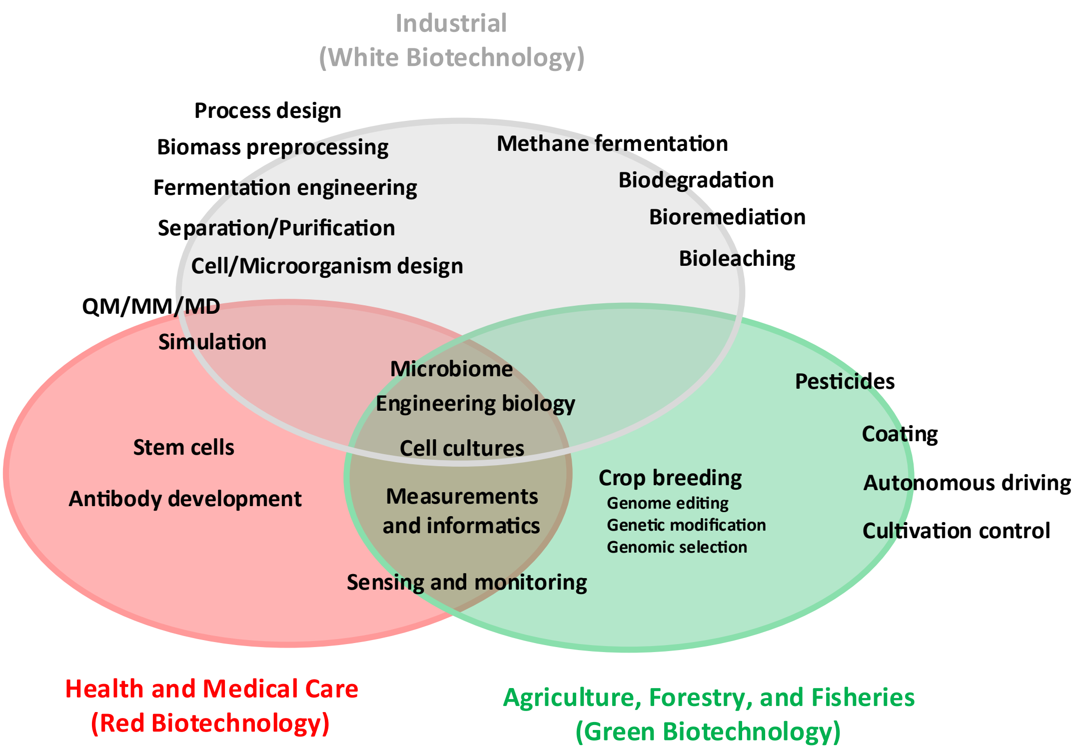


Fig. 3-6-1: Technology landscape of the bioeconomy sector

3.6.2 Social Challenges and Frontier Areas: Transition From Fossil Fuels to Renewable Bio-Based Materials; Advanced Sensing of Biological and Environmental Information; Control of Living Organisms and the Environment

The four main social challenges in bioeconomics are realizing carbon neutrality, achieving a circular economy, becoming nature positive, and creating a healthcare economy. The value provided that contributes to solving these challenges was extracted and is organized as an overhead view of the MF model in Figure 3-6-2.

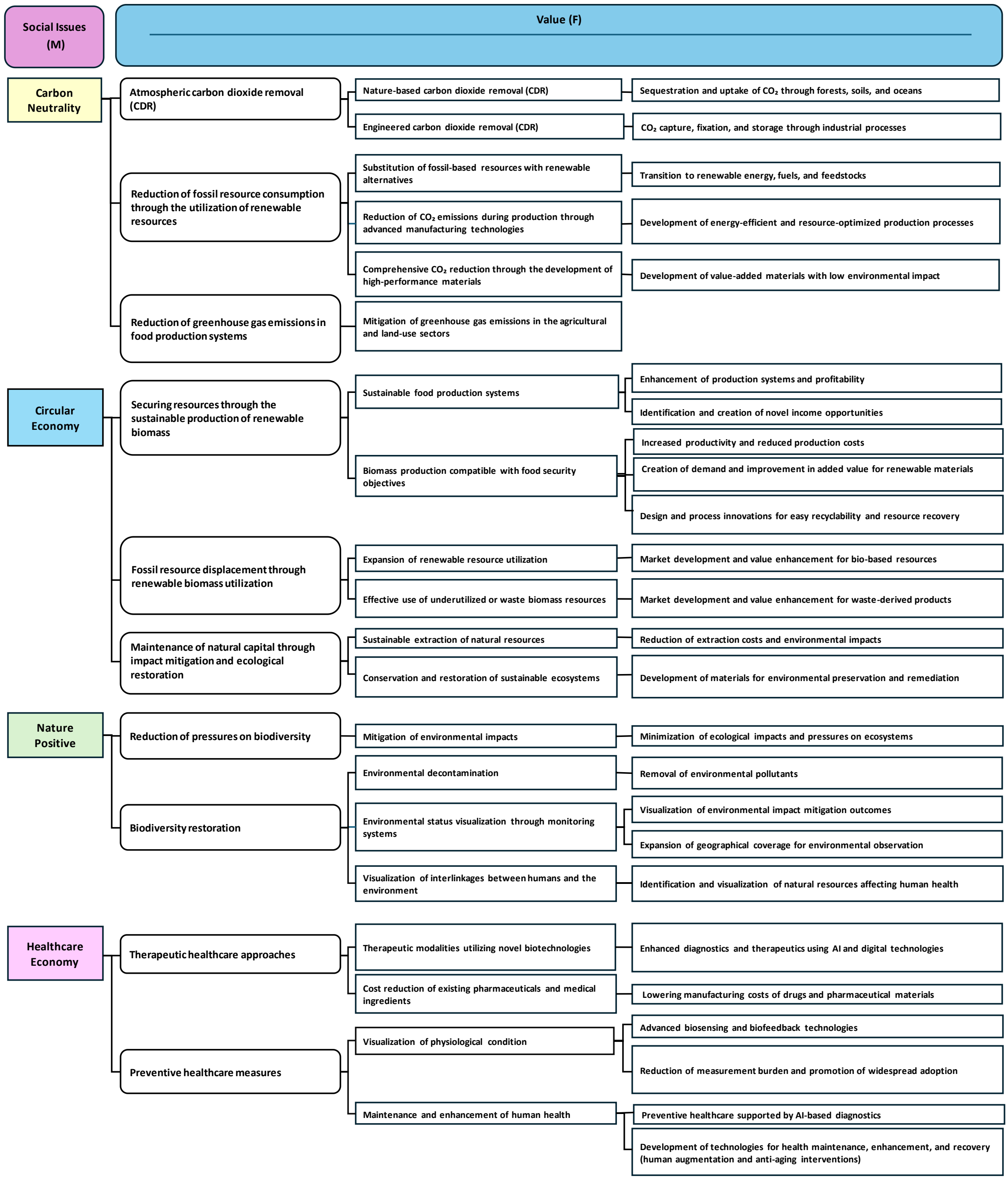


Fig. 3-6-2: Overview of the MF model

The value provided for carbon neutrality includes removing CO_2 from the atmosphere and reducing the use of fossil fuels through the adoption of renewable resources. In relation to the bioeconomy, atmospheric CO_2 can be addressed through absorption and fixation by forests and oceans and microorganisms that use CO_2 as a raw material to produce useful substances. The fossil fuels that power industry and food production can be replaced with renewable resources such as biomass.

The value provided for the circular economy includes the production and use of renewable resources, the subsequent reduction in the use of fossil fuels, and the maintenance of natural capital. Specifically, it is important to manufacture biofuels and bioplastics using raw materials from renewable resources such as inedible biomass, develop high-value-added materials by applying advanced precision fermentation to the process, and to utilize biomimicry.

The value provided for the realization of nature positivity is biodiversity; namely, maintaining, restoring, and reducing burdens on it. In other words, it is necessary to reduce environmental impacts based on monitoring the natural environment.

As described above, the use of renewable resources and the reduction of environmental impacts are related as common values that contribute to solving the problems of carbon neutrality, the circular economy, and nature positivity. The healthcare economy will employ highly sensitive, real-time methods for measuring and controlling the body's condition using biological functions. This overlaps with environmental monitoring, a method for achieving nature positivity, where a reduction of environmental impacts is based on monitoring.

From this analysis, we propose the transition from fossil fuels to renewable bio-based materials, the advanced sensing of biological and environmental information, and the control of organisms and the environment as frontier areas in the field of bioeconomy (Fig. 3-6-3).

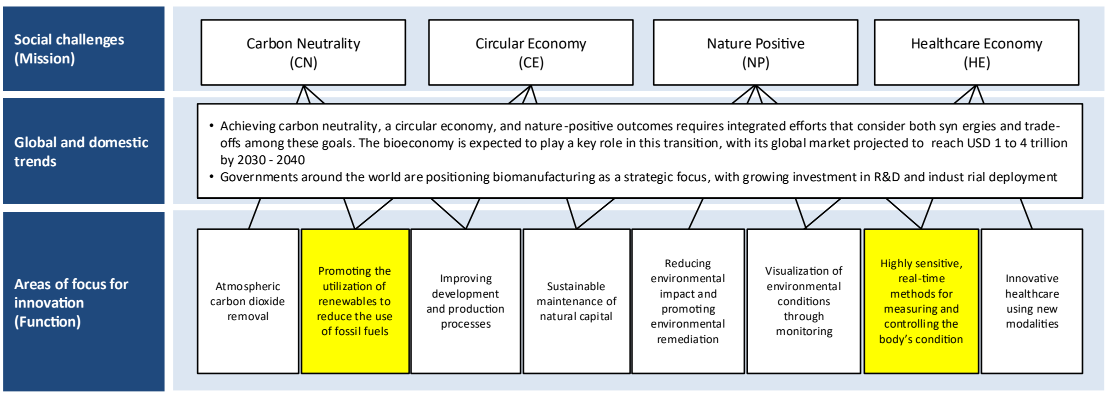


Fig. 3-6-3: MF logic model in the bioeconomy sector

The markets for biomanufacturing, which uses biomass as a resource, and healthcare, which uses advanced sensing and control, are expected to expand in the future. Innovation is needed for renewable resource production that is nature-based and negative-emission (such as forest and ocean biomass) as well as for advancements in sensing and control. Japan has many skilled researchers working on production through biotransformation, immunology in healthcare, and regenerative medicine, so there is an opportunity to draw on these strengths.

3.6.3 Examples of Specific Steps to Take

(1) From fossil fuels to renewable, bio-based materials through biomanufacturing

An effective means of transition from fossil fuel-based to renewable bio-based materials is biomanufacturing. Biomanufacturing is low-environmental impact production that makes full use of biotechnology while using biomass and other renewable resources as raw materials. It includes methods such as processing biomass chemically and reducing CO_2 into compounds such as methanol with hydrogen or light energy. However, there are challenges, as the issues in Figure 3-6-4 show.

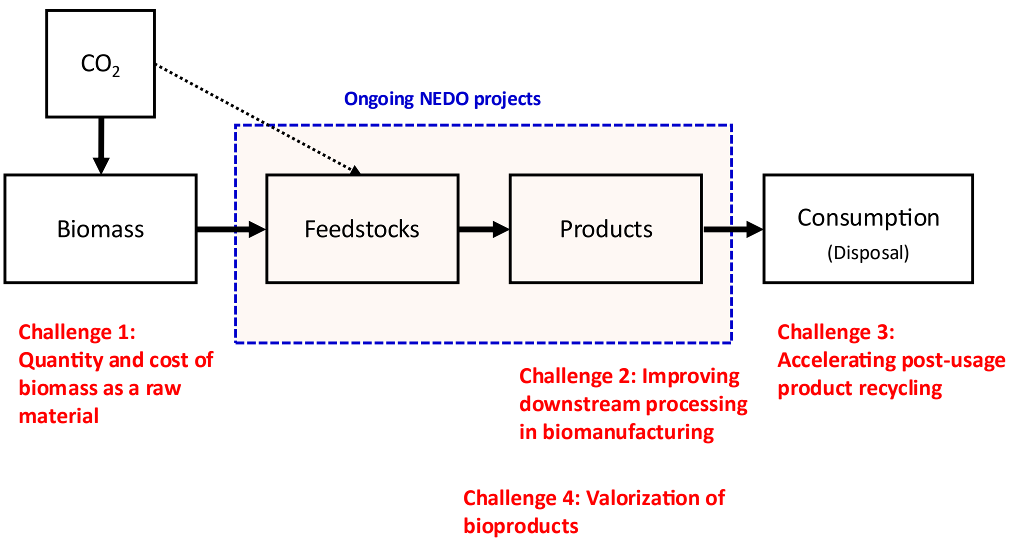


Fig. 3-6-4: Enabling technologies essential for the real-world social implementation of biomanufacturing

Challenge 1: Quantity and cost of biomass as a raw material

It is necessary to understand the amount, location, and composition of biomass, create a public perception of its value, improve the plants used for it with biotechnology, advance cultivation management technologies, and develop environmental impact monitoring technologies that can comply with new certification systems.

Challenge 2: Improving downstream processing in biomanufacturing

Since bioproducts are usually produced in aqueous solutions, it is necessary to improve the concentration of products and find new separation and purification technologies that lead to improved recovery rates.

Challenge 3: Accelerating post-usage product recycling

In order to recycle waste, products should be designed so they are easy to recycle. This can be done using material informatics technology. We must also create a system for collecting products after use.

Challenge 4: Valorization of bioproducts

In order to promote the significance and value of products, it is important to develop sensing and monitoring technologies that quantify the environmental impact. Rules are needed regarding the value of bioproducts.

(2) Sensing and controlling biological and environmental information through engineered living materials and living devices

Living organisms have evolved the ability to accurately sense environmental factors and biological information and respond to external and internal signals. We propose "engineered living materials" and "living devices" as effective means for sensing biological and environmental information and controlling living organisms and the environment. Engineered living materials are fully functional artificial cells or biomaterials designed to reproduce specific biological functions using a combination of cellular components. A living device uses biological functions integrated with electronic and mechanical systems.

Advances in molecular biology and digital technology have made possible research on artificial design of biomolecular systems and the construction of biomolecular networks in model cells. This synthetic biology approach has led to research on the production of materials. In Europe and the United States, attempts are being made to analyze cell functions in hopes of modularizing and reconfiguring them to create synthetic cells for industrial use (Fig. 3-6-5).

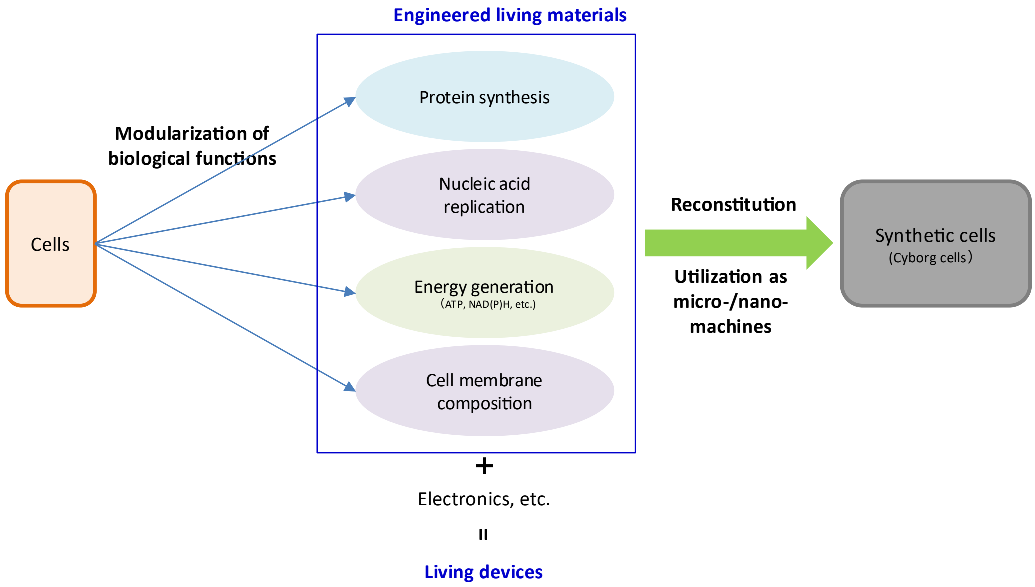


Fig. 3-6-5: Conceptual diagram showing modularization and utilization of biological functions and relationships between engineered living materials and living devices

One example of a living device is a sensor that measures the current generated by electrochemical interactions. Biological reactions are highly specific and sensitive. Smart bandages that detect the condition of an injured area and dispense medicine accordingly and biosensors with miniaturized, integrated biological elements and detectors are being developed.

Section 4. Future Challenges

Innovation Outlook Ver. 1.0 is the first offering of its kind from the NEDO Technology and Innovation Strategy Center. It was compiled after repeated trial and error while TSC was undergoing a major policy shift. We acknowledge that the following problems and issues exist and need to be addressed:

1. The results of studies for each technology field were integrated, but the logic of each technical field was not consistent, and the cross-disciplinary areas between technical fields based on value were not sufficiently examined.
2. The analysis was limited by the amounts of information, time, and resources available. There are areas that could not necessarily be covered, and depending on the field, it was not always possible to propose new areas to be tackled.
3. *Innovation Outlook Ver. 1.0* advocates the promotion of transformative innovation, but it focuses on proposing elements of technological development and may not sufficiently consider functions (F) that take into account rule formation, ecosystem construction, and social system transformation.
4. Uncertainty and major changes in economic and social conditions, such as we saw during the pandemic or as a result of geopolitical tensions, can shake the very foundations of social challenges. Disruptive innovation does not necessarily arise from social challenges, and that should be taken into account when using all logic models, including MFT frameworks.
5. Although the frontier areas are specific based on value, in order to realize the value, it is necessary to dig deeper into the five perspectives presented by METI. We must also consider more fully Japan’s strength in areas such as deep tech, as well as strategic indispensability, when looking at elements of technological development going forward.
6. While there is a tendency to emphasize the positive aspects of technology when proposing frontier areas, it is necessary to consider not only the direct but indirect effects, and also negative aspects.

It is our desire that the release of *Innovation Outlook Ver. 1.0* will prompt discussions among government agencies, industry players, and academic institutions. We look forward to receiving feedback and taking into account readers’ opinions as we work to create version 2.0 and beyond.

Acknowledgements and Permissions

Innovation Outlook Version 1.0
Executive Summary

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Technology and Innovation Strategy Center

Executive Director	Kikuo Kishimoto
Director General	Takefumi Tanabe Kenji Ueki (until June 2025)
Director General of Integrated Strategy Unit	Atsushi Sawada
Director General of Sustainable Energy Unit	Shigeki Hara
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Director General of Macroanalysis Unit	Hidenori Yamada
Director	Kazuaki Kohmoto

For inquiries about this document, please contact

Technology and Innovation Strategy Center   Tel: +81 044-520-5200

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