RITE Today

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Annual Report

Research Institute of Innovative Technology for the Earth

■ Feature ■ Acquisition of New Large National Projects and Future Research and Development Prospects

RITE Today 2024 Vol.19

Contents

The Establishment of the CCS Business Act Will Mark a Major Milestone for Social Implementation of CCS in Japan

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Carbon dioxide capture and storage (CCS) technology has been considered to be one of the important technologies that curb the increase in atmospheric CO_2 concentration and contribute to tackling global warming. For nearly 30 years since its founding, RITE has engaged in research and development on CCS. RITE has been highly regarded for the development of CO_2 separation and capture technologies and fundamental technologies concerning the underground storage of CO_2 and the elevation of those technologies to practical application levels through verification tests conducted in Nagaoka City, Niigata Prefecture.

Now, CCS is going to enter a new stage. In the 213th ordinary session of the Diet, the Bill for the Act on Carbon Dioxide Storage Businesses (CCS Business Act) was passed into law. The establishment of the CCS Business Act, which provides a legal framework concerning the licensing system for CCS businesses and the ownership of CO_2, will be an important milestone for social implementation of CCS in Japan. This Act is expected to accelerate CCS projects by private sector in Japan, enabling the commencement of CCS on a commercial level by around 2030. To establish CCS as a new industry, moreover, it is indispensable to address a wide variety of challenges, including developing technologies, ensuring economic efficiency, and fostering social acceptability. With the CCS Business Act as momentum, Japan should seek to foster companies that play a key role in the CCS value chain and create an industrial base with an eye toward the overseas expansion of CCS business.

The full-fledged social implementation of CCS would be a major step toward the realization of carbon neutrality by 2050. IEA analysis shows that CCS will help reduce annual CO_2 emissions by 3.6 billion to 7.2 billion tons by 2050. The Japanese Ministry of Economy, Trade and Industry has set a target of reducing 0.12 billion to 0.24 billion tons of CO_2 per year by 2050 with CCS. To carry out such large-scale CCS projects, risk management for safely storing CO_2 underground becomes important. To do this, it is necessary to select the right storage sites by accurately investigating the underground geological conditions of potential sites and, based on the evaluations, conducting a long-term simulation of injected CO_2 behavior. In addition, continuous monitoring of the CO_2 storage reservoirs should be conducted to ensure that CO_2 is stored as intended. RITE's R&D results in this field and the findings obtained through its verification tests in Japan and abroad will be utilized for the risk management of CCS business in the future.

To implement CCS projects, it is indispensable to obtain understanding and cooperation from local communities, in addition to ensuring technological safety. To establish CCS as an effective means against global warming and as a new industry in Japan, it is vital to resolve technological challenges and move forward steadily while gaining public trust. For the sound development of CCS projects, at the same time, it is necessary to develop, in addition to engineers, human resources equipped with the ability to approach issues from diversified perspectives, including global environment protection and social acceptability. Cooperation between the public and private sectors is essential in promoting CCS-related education and human resource development. In this respect, the role of RITE is very important. I sincerely hope that the results of the R&D conducted thus far by RITE will be able to contribute to Japan and the world as a key technology to both tackle climate change and encourage economic growth in the future.

Acquisition of New Large National Projects and Future Research and Development Prospects

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1. Introduction

Biomanufacturing is expected to contribute to carbon neutrality for the realization of a sustainable society. This technology uses biological processes to produce products independent of fossil fuels. An example is carbon recycling that uses CO_2 to directly feed microorganisms and will convert atmospheric CO_2 into useful compounds and contribute to the reduction of greenhouse gases. Products such as bio-plastics and biofuels made from renewable resources such as biomass resources have a lower environmental impact than conventional petroleum-based products. The widespread use of these products is expected to reduce the carbon footprint of the entire industry.

The Research Institute of Innovative Technology for the Earth (RITE) has been working on producing biofuels and green chemicals through research and development of smart cell and biorefinery technologies. In FY2023, RITE was entrusted with the Green Innovation Fund (GI) Project and Research and Development of Technologies to Promote Biomanufacturing, taking a new step toward realizing a sustainable society. These projects will develop carbon-recycling technologies to produce chemicals and fuels from CO_2 and biomass resources. In the future, RITE aims to contribute to realizing a carbon-neutral society by building an innovative manufacturing method to produce high-value–added chemicals from diverse biomass resources and CO_2, with biomanufacturing technology at its core. This initiative can be expected to become the industrial foundation for the next generation as a sustainable manufacturing process that replaces the conventional manufacturing process that use fossil resources as raw materials.

In this special issue, the efforts of RITE in the GI Fund Project and Research and Development of Technologies to Promote Biomanufacturing will be introduced after an overview of the current trends in biomanufacturing.

2. Global trends in biomanufacturing

Biomanufacturing is gaining worldwide attention as a sustainable manufacturing method and is experiencing intensifying competition, especially in Europe and the United States.

In the U.S., a presidential decree on the promotion of biotechnology and biomanufacturing has been signed, stating that biomanufacturing will replace one-third of the manufacturing industry within the next 10 years, with the market size estimated to reach approximately \$30 trillion[1]. These policies indicate a policy of expansion and intensive investment in biomanufacturing.

In Europe, emphasis is being placed on the formation of international rules for creating a recycling-oriented society, and environmental regulatory strategies such as the adoption of the "Draft New Regulation on Packaging and Packaging Waste"[2] and the revision of the European Renewable Energy Directive (RED III)[3] are being used to provide direction for biomanufacturing and to promote the bioeconomy.

In Japan, to secure competitiveness in this field, the

New Energy and Industrial Technology Development Organization (NEDO), a national research and development corporation, has been implementing the "Development of Highly Functional Materials Production Technologies Using Plants and Other Organisms (Smartcell Project, FY2016–2020)"[4] to build unique and efficient gene design and recombination technologies by combining biotechnology and digital technology, and has produced many results[5]. This concept and its results have been carried over to the current "Development of Production Technology for Biobased Products to Accelerate the Realization of Carbon Recycling (Biomanufacturing Project, FY2020–FY2026)"[6] and other projects. RITE has participated in these projects and developed several core technologies that are now being used to develop current technologies (see Research and Development Activities of the Molecular Microbiology and Biotechnology Group, RITE).

In October 2020, then Prime Minister Suga declared the goal of carbon neutrality (zero overall greenhouse gas emissions) by 2050. In June 2021, the government formulated a "Green Growth Strategy"[7] and created a 2 trillion yen GI Fund[8] at NEDO as a budget for addressing global warming as an opportunity for growth.

Furthermore, in June 2022, Prime Minister Kishida announced the "Grand Design and Implementation Plan for New Capitalism."[9] This states that bold and focused investment will be made in biomanufacturing, a research field that can pursue both economic growth and solutions to social issues on a global scale.

Based on these policies, in 2023, NEDO launched the "Green Innovation Fund Project/Development of Production Technology for Biobased Products to Accelerate the Realization of Carbon Recycling" and the "Research and Development of Technologies to Promote Biomanufacturing" to support the diversification of raw materials and products for biomanufacturing and the advancement of production technology, as well as the development of domestic platforms to design and develop efficient material production microorganisms based on the outlook for future industrial structure[10].

RITE has proposed and been adopted for these two projects in collaboration with companies, and is carrying out the projects. The following is an introduction of the contribution of RITE to these projects.

3. GI Fund Projects*

3.1. Project overview

The Green Growth Strategy was formulated to meet the Japanese Government's 2020 target of achieving carbon neutrality (zero greenhouse gas emissions overall) by 2050, and the GI Fund was established at NEDO in 2020 as one of the initiatives to achieve this target. In 2023, as part of the GI Fund project, NEDO announced that this would launch the "Promotion of carbon recycling using CO_2 as a direct raw material through biomanufacturing technology" (total budget: 176.7 billion yen), and six themes were selected. The main feature of the GI Fund project is that this uses "CO_2 carbon as a direct raw material," rather than the conventional biomanufacturing by microorganisms from "biomass resources."

Therefore, the aim is to contribute to achieving carbon neutrality through the development and social implementation of new biomanufacturing products using CO_2 as a raw material and to change the industrial structure through the conversion of CO_2 into resources.

RITE, in collaboration with Sekisui Chemical Co., Ltd. is currently implementing the "Green Innovation Fund Project: Promotion of Carbon Recycling Using CO_2 as a Direct Raw Material through Biomanufacturing Technology, Development and Improvement of Microorganisms Capable of Producing Materials from CO_2, Development and Verification of Manufacturing Technology Using Microorganisms Capable of Producing Materials from CO_2, Development and Demonstration of

Microorganisms that can Produce Materials from CO_2, Development and Commercialization of High-value–added Chemicals using CO_2 as a Raw Material through Biomanufacturing Technology" (project period: 8 years from FY2023 to FY2030).

3.2. Challenges in biomanufacturing from CO_2 by microorganisms

The acetate-producing bacteria (e.g., CO-assimilating bacteria) used in this project by RITE/Sekisui Chemical Co., Ltd. can efficiently fix gases with the lowest ATP energy consumption among the seven previously reported metabolic pathways that enable gas fixation, including CO_2. Therefore, useful substances can be efficiently produced using gas as a raw material. The disadvantages are that most acetic acid-producing bacteria are anaerobic, requiring dedicated anaerobic culture facilities and culture knowledge, as well as the development of genetic modification tools and technology to construct smart cells from acetic acid-producing bacteria. These aspects will be addressed through research and development by RITE under the GI Fund project.

For many years, RITE has enabled the production of various useful chemicals and biofuels from sugar feedstock derived from various biomass resources using Coryneform bacteria.

3.3. Themes contributed by RITE

Figure 1 shows the research and development image of this project conducted by RITE and Sekisui Chemical Co., Ltd. Sekisui Chemical Co., Ltd. converts CO_2 to CO with high efficiency by using a chemical catalyst, which has a high energy level (easily used by living organisms). RITE converts CO to polymer raw materials for epoxy resin in a bioprocess using acetate-producing bacteria (e.g., CO-assimilating bacteria, etc.). The resulting polymer raw materials are photodimerized and epoxidized by Sekisui Chemical Co., Ltd. to produce heat-resistant adhesives. This high-value–added heat-resistant adhesive is used for specialized bonding of components that require heat resistance, such as smartphones, aircraft, and automobiles. After use, the adhesive can be combusted into CO_2, and the same scheme can be used for resource recycling. The production cost of the adhesive is expected to be 1.2-fold less than that of the current product.

RITE will use the smart cell technology and bioproduction technology it has developed to date to develop strains that can convert CO to polymer raw materials (by developing genetic recombination tools for CO-assimilating bacteria and constructing production strains for intermediate and polymer raw materials from CO), which are the most important issues, using CO-assimilating bacteria, which are acetic acid-producing bacteria,

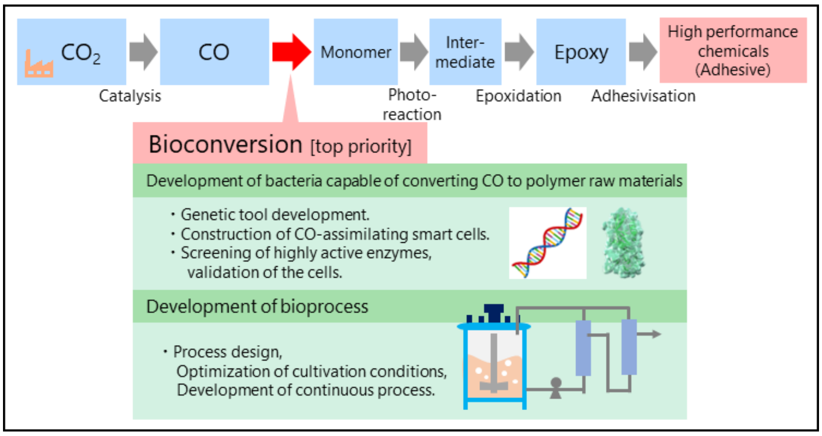

Fig. 1 Image of commercialization of high value–added chemical products from CO_2 by biomanufacturing technology

and developing bioproduction processes for polymer feedstock (process design, optimization of culture conditions, and developing continuous processes), mainly on a laboratory scale.

3.4. Future perspectives

Many refuse combustion facilities in Japan are of the "complete combustion type," and if NOx and SOx are removed according to established methods, exhaust gas mainly comprising CO_2 can be obtained. Since there are approximately 10,000 such facilities in Japan, the technology developed in this project could be applied to waste treatment facilities nationwide. In addition to these facilities, if CO_2 emitted from steel mills, thermal power plants, factories, and other facilities can be efficiently used for biomanufacturing, this would contribute to promoting carbon recycling and to the domestic carbon fixation and transporting biomass resources, rather than using sugar and other materials derived from biomass resources. This could also contribute to reducing CO_2 emissions. In Japan, where edible and non-food biomass resources are not abundant, the ability to use atmospheric CO_2 as a resource is advantageous from the perspective of securing future raw materials.

In the future, new developments are expected to include the development of technology for continuous bioproduction of various high-value–added compounds from CO_2 at high concentrations and yields, and the selective bioproduction of highly functional and high-value–added compounds from CO_2 that are difficult to produce using chemical methods because of isomer by-products.

4. Research and Development of Technologies to Promote Biomanufacturing*

4.1. Project overview

The "Research and Development of Technologies to Promote Biomanufacturing" project launched in 2023 conducts development of technologies necessary to build a biomanufacturing value chain that uses diverse raw materials as input and diverse products as output. The project aims for both economic growth and solving social issues such as environmental problems by converting the manufacturing process to biomanufacturing and promoting the social implementation of biobased products. The project conducts the following: Developing technology for procuring raw materials for biomanufacturing, developing microbial-modification platformers that can promote social implementation of biobased products, developing improvement technology for microorganisms, and developing and demonstrating manufacturing technology for mass production.

Together with TAKASAGO INTERNATIONAL CORPORATION and TEIJIN LIMITED, RITE drafted and proposed a development plan to strongly promote the social implementation of biobased products, and the project was adopted.

4.2. Our theme

In our proposal, "Development of bio-upcycling technology to produce useful chemicals from unused raw materials," RITE develops strain-breeding technologies and establishes a strain-development base. The coproposers, TAKASAGO INTERNATIONAL CORPORATION and TEIJIN LIMITED, conduct practical development of bio-aroma ingredients and high-performance bio-fiber in their respective industrial fields of expertise.

More specifically, to produce results that are unique and industrially competitive compared with research and development in biomanufacturing in Japan and around the world, we will conduct research and development focusing on the following items.

i. Food waste and surplus biomass currently being discarded will be positioned as unused domestic resources, and technology will be developed to process them into raw materials for fermentation.

ii. We will also develop breeding techniques and establish a base for developing microorganisms that can utilize raw materials derived from unused resources and produce even chemicals that are toxic to living microorganisms.

iii. By establishing large-scale production technology and purification technology, we will develop manufacturing technology for useful chemicals.

iv. We will conduct Life Cycle Assessment (LCA) on the manufacturing process of biobased products from unused resources to clarify the environmental performance, such as the CO_2 reduction effect, of converting from conventional petrochemical methods to biobased methods (Fig. 2).

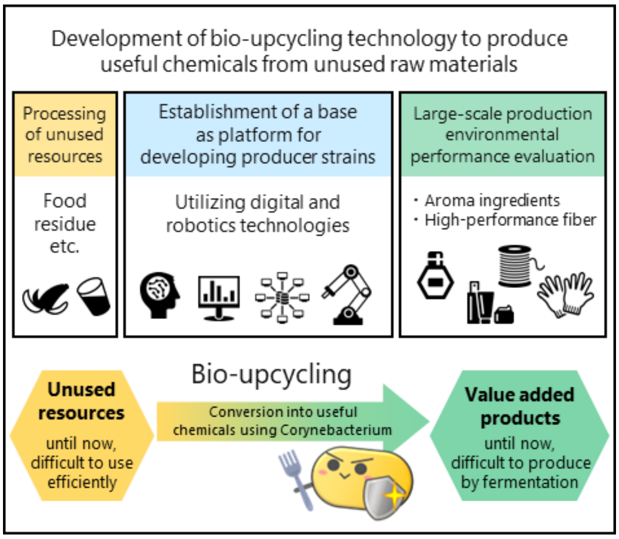

Fig. 2 Overview of RITE's theme

4.3. RITE's challenge to become a strain-development platform

A platform operator (platformer) is a company or organization that provides the foundation for users, such as individuals or companies, to develop their businesses. As the number of users increases, the amount of information stored on the platform increases and can be analyzed and used to expand business. Amazon, Google, and Apple are representative examples of platform operators that have a huge impact on their respective markets. The strain-development platformer referred to here is an organization that provides a service for developing high-performance producing strains. This service is the core of commercializing chemical production technology using microbial fermentation.

RITE has developed various producing strains through national projects and corporate joint researches. Since developing these strains requires advanced biotechnology, companies without experience face extremely high hurdles, including initial investment, training of engineers, and acquiring knowledge. For this reason, many companies hesitate to enter the biomanufacturing industry. Strain-development platformers are commissioned to develop and provide strains that can produce chemical products desired by these companies. These strain-development platformers strongly promote the conversion of manufacturing processes to biomanufacturing and the social implementation of biobased products. However, very few organizations that currently operate in Japan that can do this. RITE aims to become an organization that revitalizes the entire bioindustry as a bacterial strain-development platformer by fully using the microbial fermentation production technology we have accumulated over the years.

4.4. Future perspectives

The use of biotechnology has extremely high expectations for supporting a shift toward biomanufacturing using unused resources that can simultaneously solve the dual challenges of environmental problems and domestic economic growth. Strain-development platformers play an important role in achieving these changes, and the role of RITE as such a platformer is expected to make the following contributions.

1. Discovering and improving new microbial functions: The RITE platformer can explore new microorganisms and microbial functions and discover strains with useful properties. This is expected to improve existing

microorganisms and create more efficient and environmentally friendly bioprocesses.

2. Use of sustainable resources: The RITE platformer can develop microorganisms to utilize renewable raw materials. Technologies that generate energy, such as bio-fuel, using non-food or discarded biomass as raw materials are attracting attention as a sustainable energy source.

3. Collaboration with industry: The RITE platformer is expected to collaborate with industry to provide practical solutions through promoting applied research and commercializing production using newly developed production microorganisms.

4. Human resource development: The RITE platformer has a role in nurturing the next generation of researchers and engineers. This includes spreading knowledge and developing biotechnology by sharing research results to the extent possible.

The RITE platformer takes advantage of its characteristics as a Public Interest Incorporated Foundation, allowing the conduct of research and development and human resource development without conflicts of interest. RITE will solicit joint research not only from specific companies but also from a wide range of industries and contribute to create a sustainable society by bringing to the world many bioproducts derived from unused and renewable resources (Fig. 3).

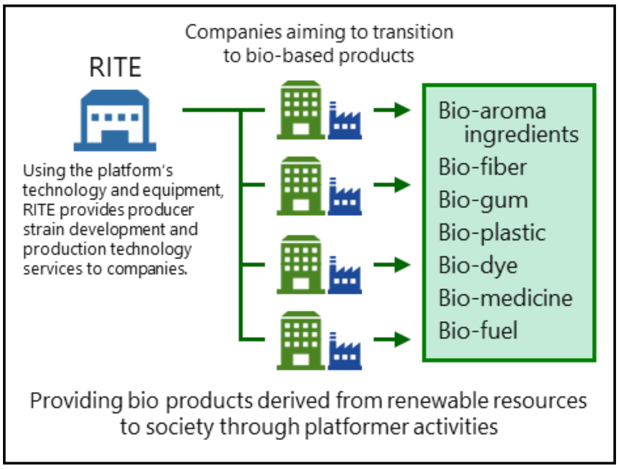

Fig. 3 Social contribution through RITE platformer activities

5. Closing remarks

Innovation in biomanufacturing technology is an essential element in building a new industrial structure and accelerating sustainable economic development. RITE will not only develop these technologies but will also focus on addressing the challenges faced in social implementation and promote the spread of biomanufacturing. Therefore, RITE plans to construct two new research facilities that will integrate technology and equipment. Each corresponds to the two new projects described in this feature.

The research building to be developed under the GI Fund project will be equipped with facilities specializing in fermenting polymer feedstock from CO and developing associated bioprocesses. This research building is scheduled for completion this year (FY2024) and will considerably accelerate the development of technology for the fermentation production of high-value–added compounds from CO.

The Research and Development of Technologies to Promote Biomanufacturing is also moving forward with plans to construct a dedicated experimental building that will integrate platform functions. Incorporating digital robotics technology to enable the breeding of ultraefficient high-producing strains of bacteria. Since multiple strain development requested by companies will be conducted simultaneously, the structure will be designed with sufficient consideration for information security. Construction on this site is expected to begin this year.

By promoting the GI Fund Project and the Research and Development of Technologies to Promote Biomanufacturing in this special feature and by progressing the activities in the respective dedicated research buildings on track, RITE aims to explore the feasibility of manufacturing processes that do not depend on fossil fuels and contribute to environmental conservation by reducing CO_2 emissions.

These activities are important steps toward building a recycling-oriented society and achieving carbon neutrality by 2050. RITE will continue to pursue the further evolution of biomanufacturing, and the realization of a sustainable society brought about by this. We sincerely hope that RITE's efforts will serve as a foundation for building a better environment for future generations.

We hope that this special issue of RITE will help spread awareness of our activities and inspire people to work together to create a sustainable future.

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* This article is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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Research Efforts to Realize a Carbon-neutral Society

The Research & Coordination Group has four major functions to 1) explore new R&D topics while looking at domestic and overseas policies and technology trends, and propose and implement new research themes by taking advantage of the research potential of RITE; 2) support the government with regard to IPCC (Intergovernmental Panel on Climate Change), and facilitate collaboration with international organizations, such as ISO (International Organization for Standardization); 3) promote the dissemination of RITE's technologies and develop human resources for the future; and 4) promote the practical application of technologies through collaboration with the industry. We, together with research groups, have been actively working on policy support, technology development and the creation of innovation in order to pursue both global environment protection and economic development.[1)]

The following is an overview of the Japanese government's actions taken toward carbon neutrality in FY2023.

The Bill for the Act on Promotion of Smooth Transition to a Decarbonized Growth-Oriented Economic Structure (GX Promotion Act)[2)] approved by the Cabinet in February 2023 was passed into law in May 2023. Based on the GX Promotion Act, the Strategy for Promoting Structural Transition Based on Decarbonization (GX Promotion Strategy) was approved by the Cabinet in July 2023[3)]. In addition, the Carbon Management Subcommittee established under the Natural Resources and Fuel Committee of the Advisory Committee for Natural Resources and Energy started discussions on issues toward CCS commercialization in September 2023, and it prepared a summary entitled "What Institutional Measures Related to CCS Ought to Be"[4)] in January 2024. In February of the same year, the Bill for the Act on Carbon Dioxide Storage Businesses (CCS Business Act) was approved by the Cabinet[5)], and it was submitted to the 213th ordinary session of the Diet and passed into law.

1.1. GX Promotion Act

With investment competition toward green transformation (GX) being accelerated worldwide, Japan, in both the public and private sectors, needs to invest more than 150 trillion yen in GX over the next 10 years to fulfill its international pledges, including achieving carbon neutrality by 2050, strengthen its industrial competitiveness, and achieve economic growth. To these ends, the GX Promotion Act requires the government to (1) formulate and implement a GX Promotion Strategy, (2) issue GX economy transition bonds, (3) introduce growth-oriented carbon pricing, (4) establish the GX Promotion Organization, and (5) conduct progress evaluation and necessary review.

(1) Formulation and implementation of the GX Promotion Strategy

The government formulates and implements a strategy to promote GX in a comprehensive and systematic manner.

(2) Issuance of GX economy transition bonds

The government issues GX Economy Transition Bonds, which was started from FY2023 for a 10-year period, to support upfront investment to realize the GX Promotion Strategy.

(3) Introduction of growth-oriented carbon pricing

Added value is provided to GX-related products and businesses by pricing CO_2 emissions. Starting in FY2028, the government will impose a fossil fuel levy on fossil fuel importers in accordance with the amount of CO_2 derived from fossil fuels that is imported. Starting in FY2033, the government will allocate CO_2 emission allowances to power generators for a partial fee and levy a specific business operator burden fee in accordance with the amount.

(4) Establishment of the GX Promotion Organization

The GX Promotion Organization has been established with the approval of the Minister of Economy, Trade and Industry. Major functions of the GX Promotion Organization are support for private companies' investment in GX (financial support (debt guarantee, etc.)), collection of fossil fuel levies and contributions from specific business operators, and the operation of an emission trading system (allocation of emission allowances for specific business operators, bidding, etc.).

(5) Progress evaluation and necessary review

Based on the implementation status of GX investment, etc. and economic trends related to CO_2 emissions in Japan and overseas, measures are examined and necessary review is conducted based on examination results. The detailed system design for the fossil fuel levy and the emissions trading system are reviewed, including concrete measures for the full-scale operation of the emissions quota trading system, and necessary legislative measures are taken within two years after the enforcement of this Act.

1.2. GX Promotion Strategy

In July 2023, the GX Promotion Strategy was approved by the Cabinet based on the GX Promotion Act. The following are the Strategy's two key pillars:

(1) For ensuring a stable energy supply, Japan will advance decarbonization efforts toward GX, including a shift to renewable energy, nuclear power and other decarbonized electric sources that contribute to increasing Japan's energy self-sufficiency, in addition to thorough energy savings.

(2) For achieving GX, Japan will implement “growth-oriented carbon pricing initiatives,” including support for bold upfront investment by using the GX economy transition bond, etc., incentives for upfront investment in GX by carbon pricing, and the use of new financial means.

1.3. CCS Business Act

To achieve carbon neutrality by 2050, it is an important challenge to achieve GX in areas where decarbonization is difficult. As a means to promote decarbonization after the use of fossil fuels and materials in such areas, it is indispensable to introduce CCS (carbon dioxide capture and storage), a technology that is used to capture and store CO_2 underground, as a solution.

Aiming to create a business environment in which private companies are able to launch CCS businesses in Japan by 2030, the government will establish a licensing system for storage business, etc. necessary for creating the business environment while maintaining public safety and preserving the marine environment.

(1) Establishment of a licensing system for trial-drilling and storage business and the development of business regulations and safety regulations pertaining to storage businesses

① Establishment of a licensing system for trial-drilling and storage business

- The Minister of Economy, Trade and Industry designates an area where the reservoir may exist as a "specified zone," announces an open call for trial drilling and CO_2 storage projects in a specified zone, and grants permission to the most appropriate applicants.

- For those granted permission as stated above, a right is established for trial drilling (the right to excavate land to check whether the stratum is appropriate for a reservoir) and a storage business (the right to store CO_2 in the reservoir). To ensure the stable storage of CO_2, the rights for trial drilling and storage are a "deemed real right."

- A holder of digging right under the Mining Act may conduct trial drilling or a storage business with the permission from the Minister of Economy, Trade and Industry in areas (mining sites) other than specified zones as stated above.

- Conventionally, the storage of CO_2 in a sea area required the permission of the Minister of the Environment pursuant to the provisions of the Act for the Prevention of Marine Pollution and Maritime Disasters. Under the CCS Business Act, however, the procedures to obtain the permission are integrated so that the Minister of Economy, Trade and Industry may grant the permission after gaining consent from the Minister of the Environment through prior consultation. Accordingly, the licensing system for undersea storage of CO_2 emission under the Act for the Prevention of Marine Pollution and Maritime Disasters was abolished.

② Development of regulations for storage business operators

- A specific implementation plan for trial-drilling and storage projects requires the approval from the Minister of Economy, Trade and Industry.

- Business operators are obliged to monitor the temperature and pressure of the storage reservoir so that the leakage of stored CO_2 can be identified.

- To secure funding necessary for monitoring and other operations conducted after the stop of CO_2 injection, business operators are required to set aside reserves, etc.

- If certain requirements are met, such as stability of the stored CO_2, management of storage sites, including monitoring, can be transferred to the Japan Organization for Metals and Energy Security (JOGMEC). To secure funds for post-transfer management operations, storage business operators are obliged to contribute funds to JOGMEC.

- Storage business operators are prohibited from refusing CO_2 storage requests from CO_2 emitters without justification and from discriminatory treatment of certain CO_2 emitters, and they are required to provide notice of fees, etc.

- Safety and security regulations are imposed on storage business operators, including obligations to comply with technical standards, submit a work plan, and develop safety measures.

- If a third party suffers damage as a result of an event specific to a trial drilling or storage project, liability for damages (i.e., non-fault liability) is imposed on storage business operators, irrespective of intent or negligence, from the perspective of relief for victims.

(2) Development of business regulations and safety regulations pertaining to CO_2 pipeline transport operations

① Establishment of a notification system for pipeline transport operations

- Those who transport CO_2 via pipelines for the purpose of storing CO_2 in a reservoir are required to submit notification to the Minister of Economy, Trade and Industry.

② Regulation imposed on pipeline transport operators

- Pipeline transport operators are prohibited from refusing requests for CO_2 transport from CO_2 emitters without justification and from discriminatory treatment of certain CO_2 emitters, and they are required to provide notice of fees, etc.

- Safety and security regulations are imposed on pipeline transport operators, including obligations to comply with technical standards, submit a work plan, and develop safety measures.

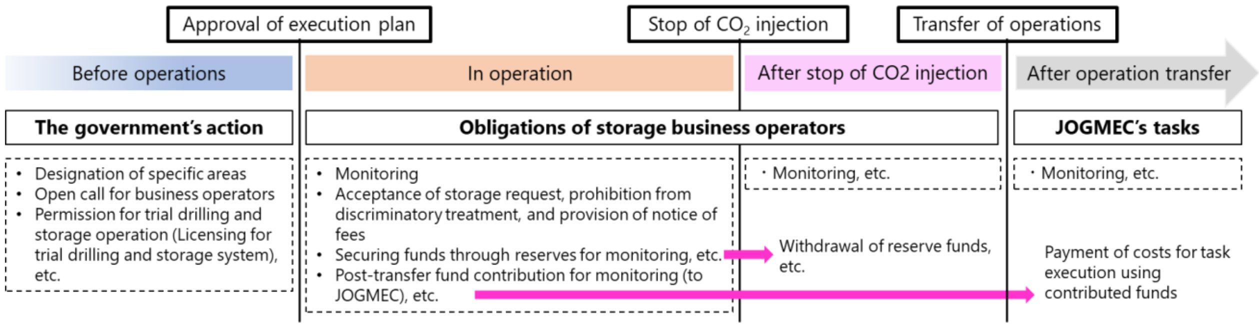


Figure 1 Flowchart for storage operations

2. Research study activities

In FY2023, we were entrusted with the " Study Project on Measures for Stable Fuel Supply (study on the improvement of the CCS business environment and the development of a CCS Action Plan with an eye toward achieving carbon neutrality by 2050)," a research project commissioned by the Ministry of Economy, Trade and Industry. To review the "CCS Action Plan" in the Final Summary by the CCS Long-term Roadmap Study Group[6], we conducted a study concerning cost targets and technology development guidelines.

Below is an outline of the CCS cost structure study conducted to discuss technology development policy (= cost reduction measures) to achieve cost targets.

Table 1 Policies discussed for formulation of the CCS Action Plan[6]

Items	Policies Discussed
Annual storage amount targets	**Elaborate the annual storage amount targets to be achieved by 2050 based on views and opinions from individual industrial sectors,** and make the targets more elaborate according to the progress of decarbonization efforts, including energy savings, electrification, and hydrogenization.
Cost targets / technology development guidelines	After reviewing CCS cost targets as needed, **develop technology development guidelines for achieving the targets set**, and make the guidelines more elaborate according to the progress of cost reductions.
Suitable site investigation plan	**Consider conducting investigation on the geological structure of coastal regions** while continuing to estimate the location of suitable sites for CO_2 storage in areas on which data exists. **Give further consideration to a method to evaluate risk from a geologic fault** in a geological structure investigation.

2.1. Understanding of CCS cost structure

2.1.1. Trial calculation (example)

Figure 2 shows an example of a trial calculation, in which a coal-fired power plant (CFPP) and a natural gas combined cycle power plant (NGCC)—for both of which there is a relatively large amount of cost data—are CO_2 emission sources. Other conditions set here are pipeline transport and liquefied CO_2 transfer by ship, as well as CO_2 injection for storage from a land area and injection in a sea area (grounding and floating).

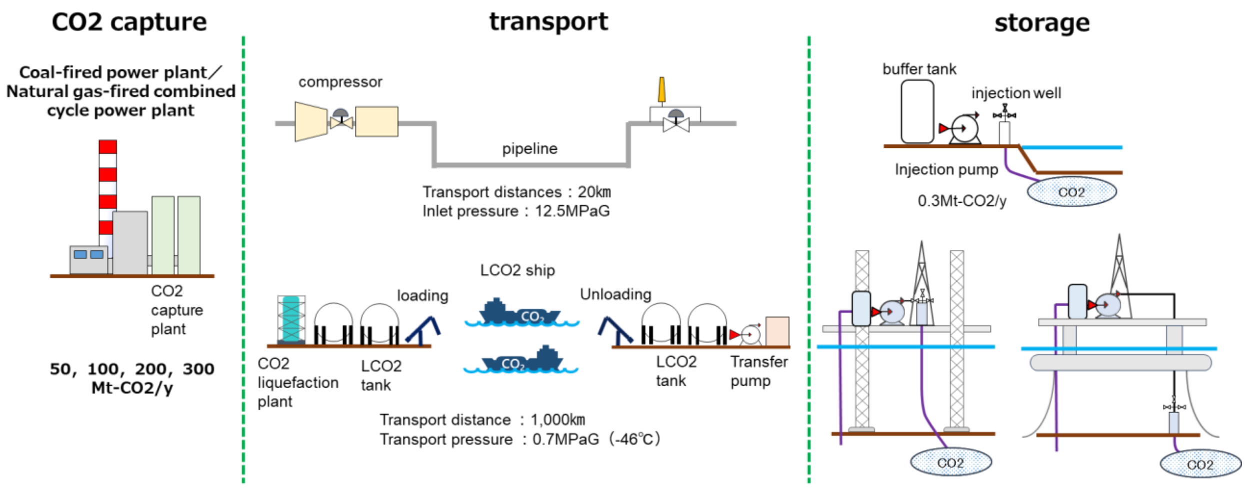


Figure 2 Example of trial calculation (a combination of separation & capture, transport, and storage)

2.1.2. Points to note regarding trial calculation and major preconditions

This time, a trial calculation was conducted, with the amount of CO_2 as a variable, under the preconditions set arbitrarily by RITE based on public data. It should be noted that this is not a cost estimate based on a specific site, piece of equipment, etc., and that in each of separation/capture, transport and storage, no consideration is given to constraints on land, land costs, reserve funds, or compensation costs.

Table 2 Major preconditions for trial calculation of CCS costs

Items	Description
Project period	Operation period (20 years) / post site closure management (20 years)
Trial calculation year, exchange rate, etc.	Cost base: 2023 Exchange rate: ¥139/US$ (average for the first half of 2023)[7)] Discount rate: 5% External electricity costs: ¥20/kWh Coal price: ¥26,000/t (Sept. 2023)[8)] LNG price: ¥88,000/t (Sept. 2023)[8)]
Emission sources	CFPP (CO_2 level: 12% - 13%) NGCC (CO_2 level: 3% - 4%) Capacity factor: 70%
Annual CO_2 recovery amount	0.5 million, 1 million, 2 million, 3 million ton CO_2/year
CO_2 separation and capture facilities	CO_2 recovery rate: 90% Chemical absorption method (amines) * Renovation costs for common facilities and existing facilities not

	included
Pipeline transport facilities	CO_2 transport pressure: 12.5 MPaG * Compression power (Calculated for two-stage compression)
Liquefied CO_2 transport facilities	Liquefaction equipment (directly cooled) * 0.7 MPaG, - 46°C
	Storage/loading equipment (land) * Pier not included
	Unloading/storage equipment (land) * Pier not included
	Boosting equipment for transfer to injection equipment
CO_2 carrier	Standard value: - 46°C (upper limit: - 43°C, lower limit: - 50°C) Design pressure: 1.0 MPaG * Type of ship: up to 50,000 ton class
Other	Renovation costs for existing facilities, reserve funds, general administration costs and miscellaneous costs NOT included

2.2. Outline of trial calculation results

2.2.1. CO_2 separation and capture costs (Figure 3, 4)

In both CFPP and NGCC, the percentage of capital expenditure becomes smaller with increasing CO_2 recovery amount. In terms of economies of scale, effects are higher in CFPP than in NGCC. In the case of CFPP, the percentage of capital expenditure is high, irrespective of the amount of CO_2 recovery, which is followed by absorbent/industrial water and renewable energy. In the case of NGCC, however, the percentage of capital expenditure becomes high when the CO_2 recovery amount is 0.5 million tons and 1 million tons, and in the case of other recovery amounts, the percentage of renewable energy costs is high. When the CO_2 recovery amount is the same, NGCC, whose emissions flow rate is higher, has a higher percentage of blower pump power than CFPP.

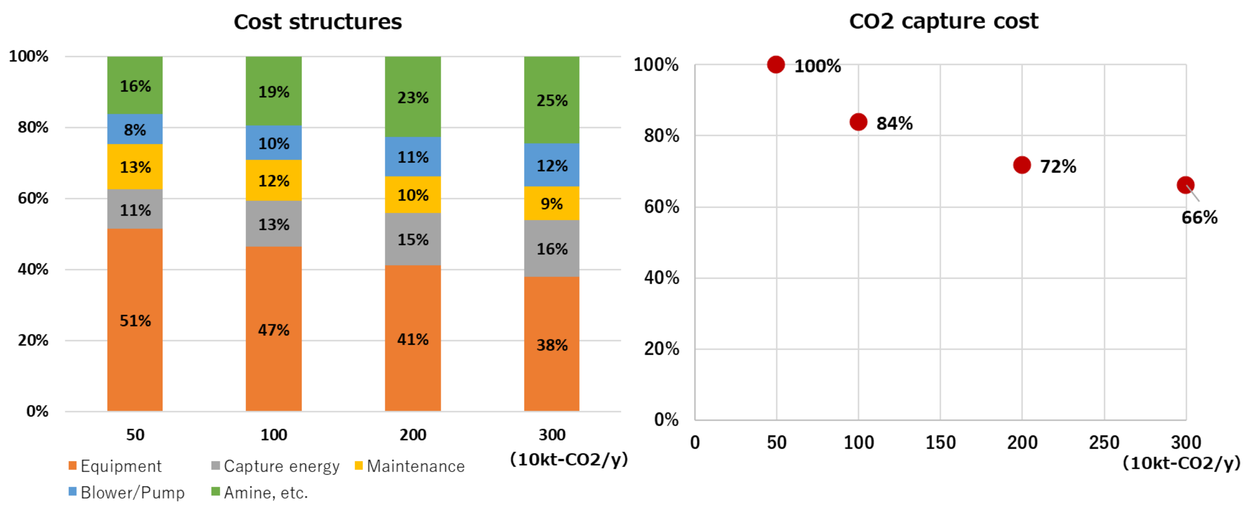


Figure 3 CO_2 capture (Cost structures) ※coal-fired thermal power plant

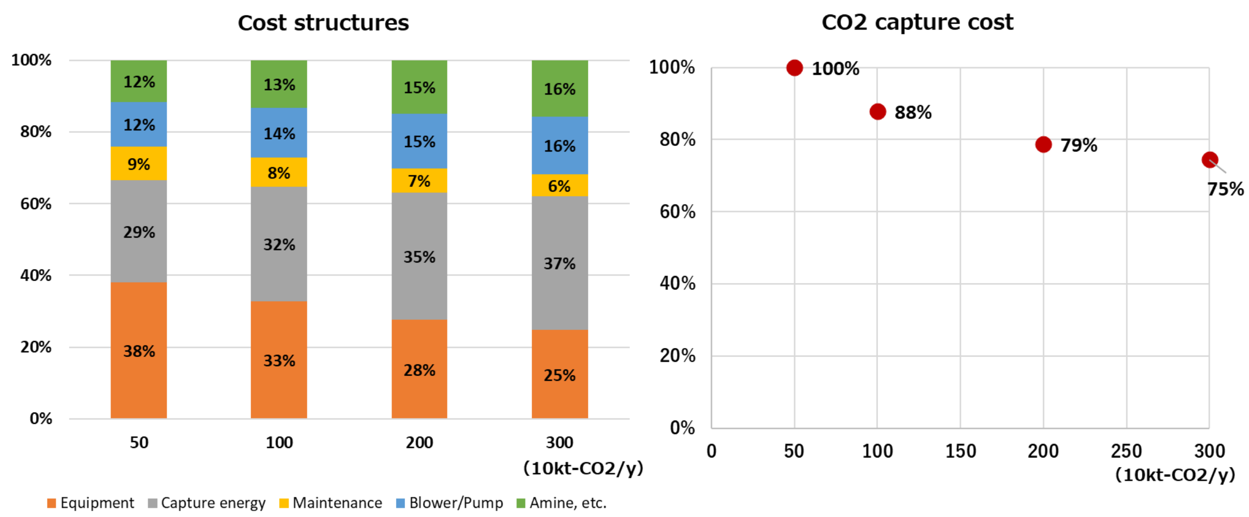


Figure 4 CO_2 capture(Cost structures) ※Natural gas-fired combined cycle power plant

2.2.2. Transport costs (Figure 5, 6)

In both pipeline transport and liquefied CO_2 transport by ship, the percentage of capital expenditure becomes smaller with an increasing CO_2 transport amount. In terms of economies of scale resulting from expanded transport scale, pipeline transport and liquefied CO_2 transport by ship showed about the same results.

In pipeline transport, the percentage of electricity costs for compressor (compression power) is high, irrespective of the amount of transport, with about 70% for 3 million tons of transport.

In liquefied CO_2 transport by ship, the percentage of electricity costs for liquefaction is high, irrespective of the amount of transport. With external electricity costs of ¥20/kWh set as a precondition, each energy cost became high.

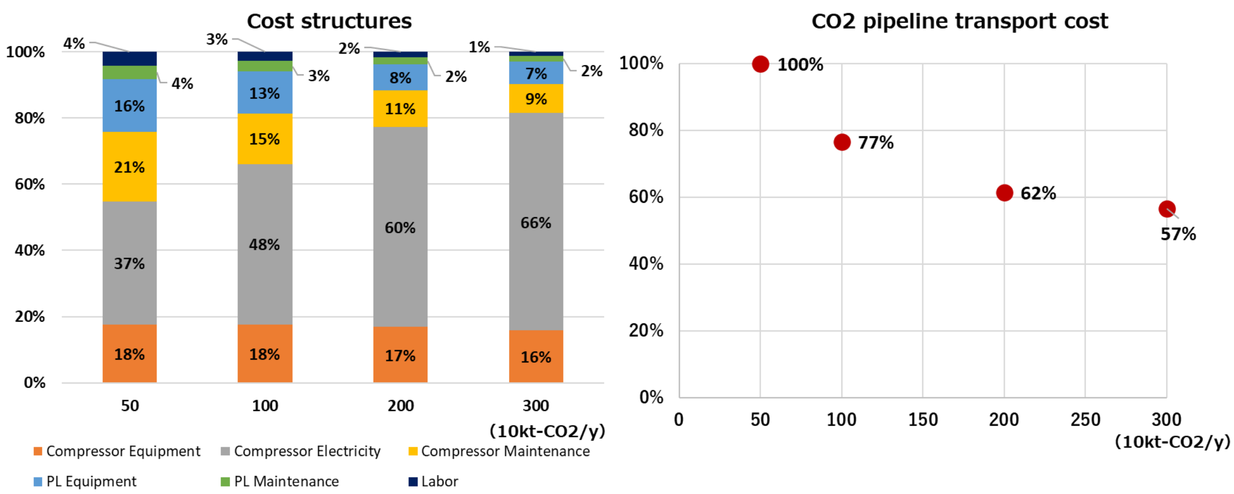


Figure 5 CO_2 Pipeline transport(Cost structures)

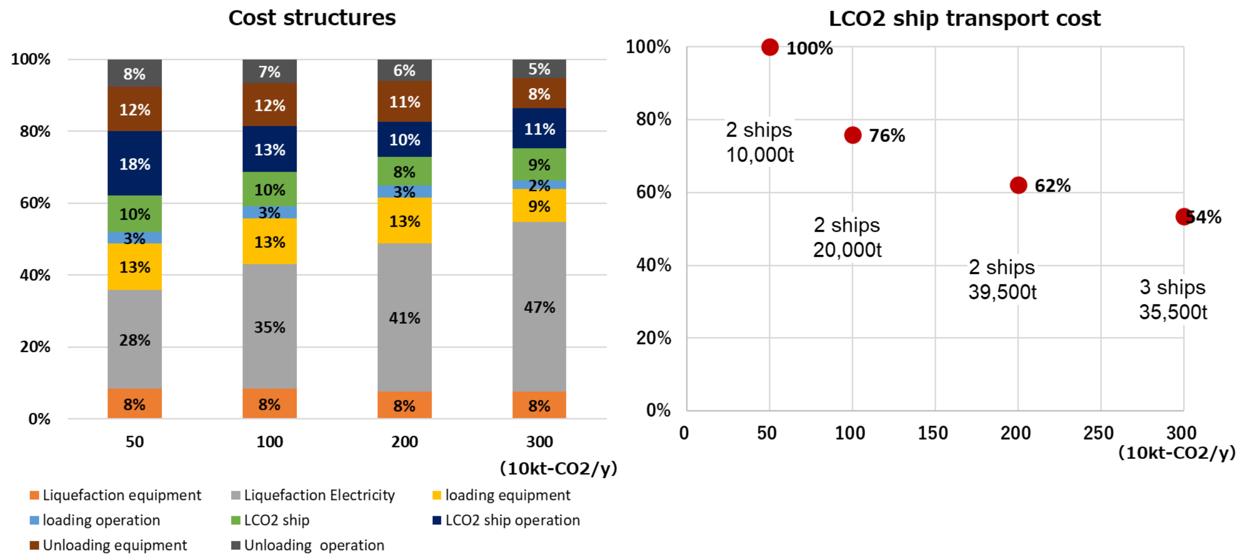


Figure 6 LCO₂ Ship Transport (Cost structures)

2.2.3. Storage and monitoring costs (Figure 7, 8, 9)

The percentage of drilling costs in any area of land, sea (grounding), and sea (floating).

In the case of land area, the percentage of injection monitoring costs is second highest, behind drilling costs. For the sea area (grounding and floating), the percentage of costs for grounding base and floating base is high.

For the sea area (grounding), the third highest is injection monitoring costs, but for the sea area (floating), it is costs for undersea equipment. The percentage of capital expenditure (CAPEX) is relatively higher than separation/capture and transport.

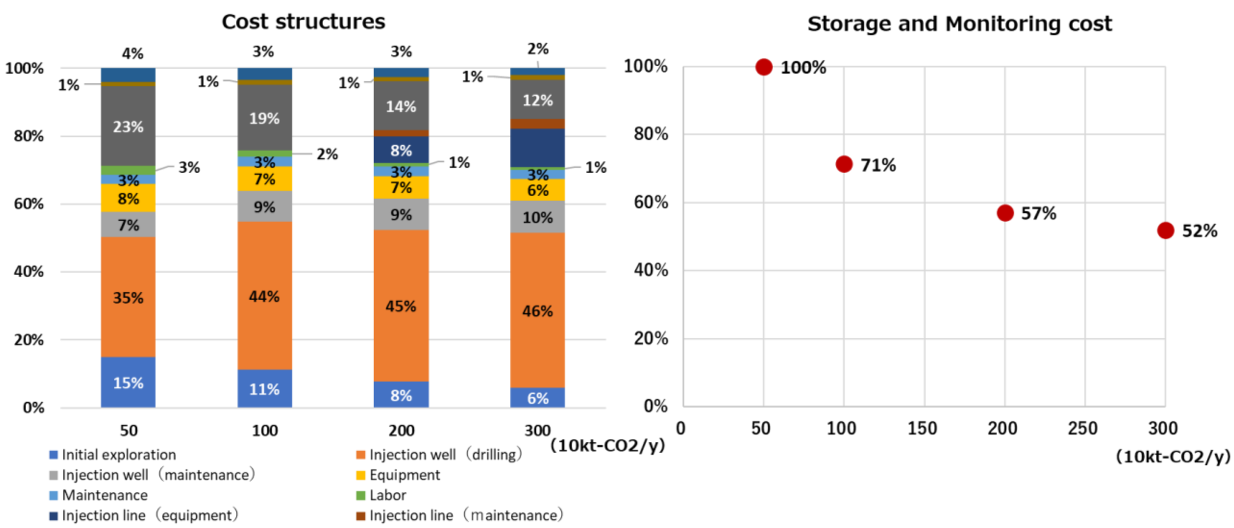


Figure 7 Storage and Monitoring (Cost structures) ※Onshore

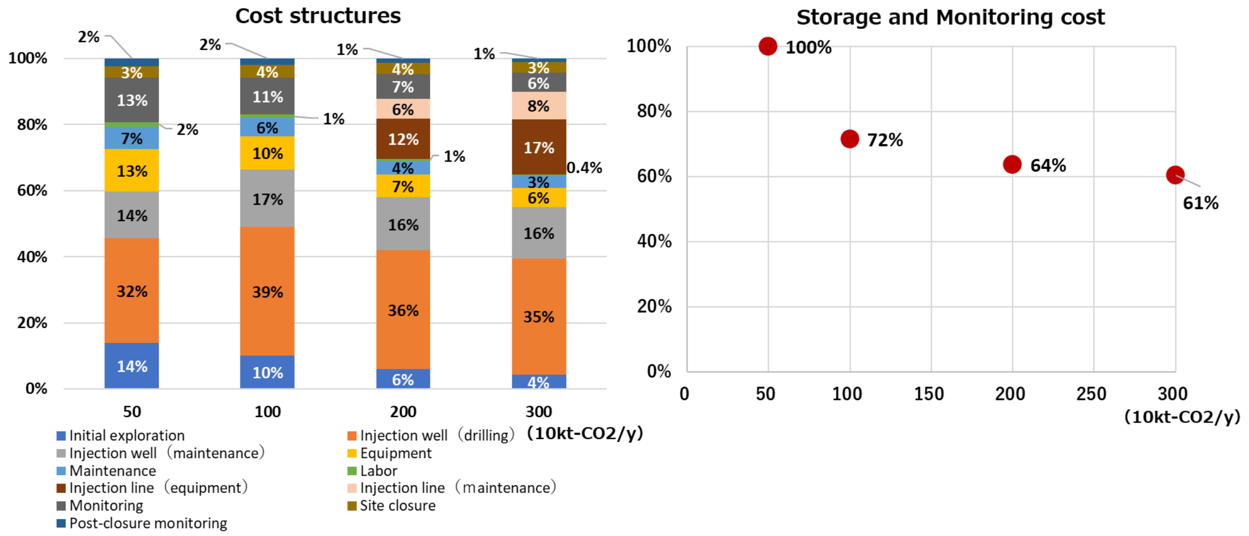


Figure 8 Storage and Monitoring (Cost structures) ※Jack-Up

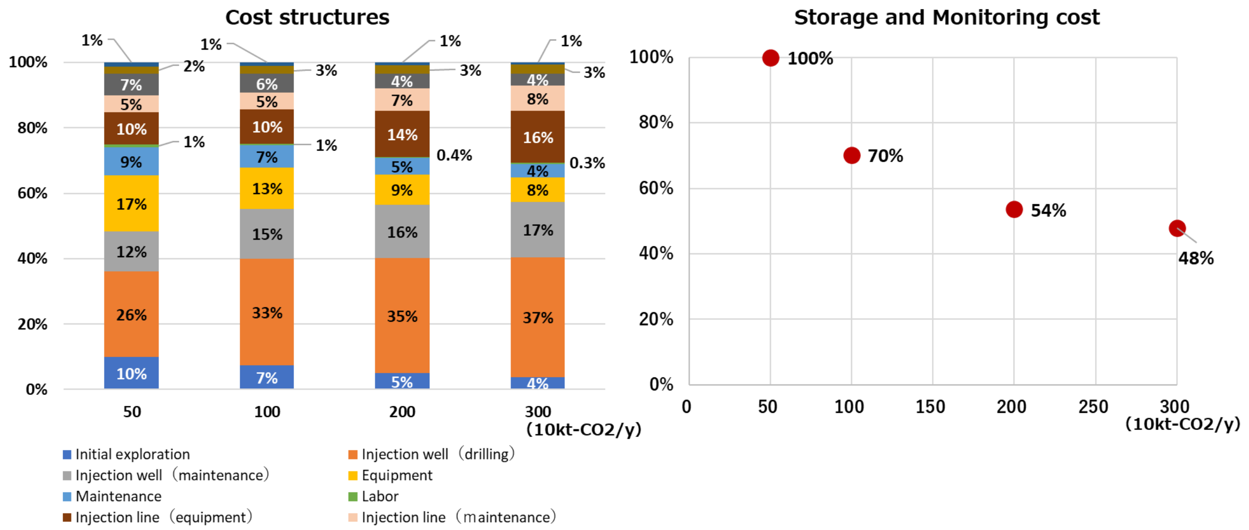


Figure 9 Storage and Monitoring (Cost structures) ※Semi-sub

2.3. Summary

For CCS in Japan, operating expenditure (electricity and fuel costs, etc.) for CO_2 separation and capture and transport is relatively high. So, it is an effective way to develop energy-saving equipment and a technology to utilize waste heat. With regard to storage, the percentage of CAPEX (drilling costs, platform, undersea equipment, etc.) is relatively high. So, it is important to discuss cost reduction measures for CAPEX.

This time, the trial calculation of CCS costs was conducted for a project that is implemented in an integrated manner—from separation/capture to transport and storage. However, when a CCS project is expanded to the several hundred million yen level, the optimization of a CCS project as a whole needs to be considered in order to reduce costs.

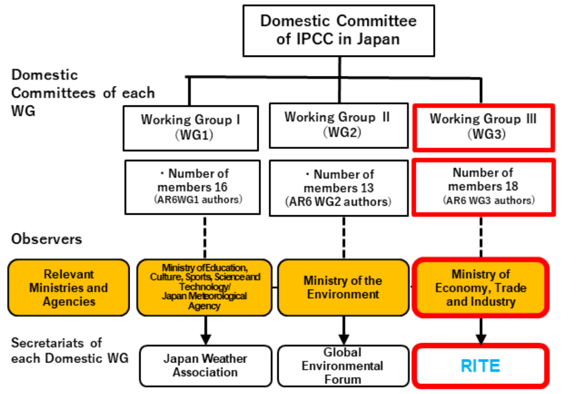
3. Promotion of international partnership

3.1. IPCC (Intergovernmental Panel on Climate Change)

The IPCC has been established in 1988 with a view to conducting a comprehensive assessment from scientific, technical, and socio-economic perspectives on climate change, impact, adaptation and mitigation measures by anthropogenic sources, jointly by the United Nations Environment Program (UNEP) and by the World Meteorological Organization (WMO). The IPCC examines scientific knowledge on global warming and makes the reports prepared by three WGs, - Physical Science Basis (WG1), Impacts and Adaptation, and Vulnerability (WG2), and Mitigation Measures (WG3).

In the IPCC, the experts chosen among each country make the reports, based on the literature or the scientific observation data and evaluate / examine the scientific analysis, social economic influence and countermeasures to control climate change. This outcome is to have a high influence on international negotiations since the scientific basis is also given to the policies of each country.

RITE plays the central role of domestic support secretariat of mitigation measures (WG 3) (Figure 10). The IPCC launched a new structure for the Seventh Assessment Cycle (AR7) in July 2023, and decided to provide the Working Group reports, a Special Report on Climate Change and Cities, a Methodology Report on Short-Lived Climate Forcers (SLCF), and a Methodology Report on Carbon Dioxide Removal Technologies (CDR) and Carbon Capture Utilization and Storage (CCUS), and has begun its work. RITE has also been supporting METI through information gathering, analysis, report, advise, etc.



* Members of each working group (WG 1, WG2, WG3) consist of AR6 and SR authors.

Figure 10 Committee structure and RITE

3.2. ISO

ISO (International Standard Organization) is an organization composed of 170 standardization bodies of various countries that gives the common standards and promotes global trade. It can provide safe, reliable, and high-quality products/service by utilizing ISO standards.

In the world, a number of CCS verification projects on a commercial scale are implemented, and inter-national collaboration is under way. International standardization of CCS can contribute to the wide-spread of safe and appropriate CCS as it can ensure internationally agreed knowledge on safety and environmental aspects.

RITE is a domestic deliberation organization on ISO / TC 265 (Carbon dioxide capture, transportation, and geological storage) and is in charge of a secretariat of WG 1 (capture). Through these activities, we are actively involved in the international standardization on design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the CCS field (Figure 11).

As of the end of March, 2024, thirteen standards related to the CCS have been published from ISO / TC265 and eight documents are currently under development. The launch of a new project is also being considered, and TC265 has become more active in recent years. In particular, CO_2 ship transportation is attracting attention as a powerful means of transportation from emission sources to CO_2 storage site. Development of Technical report related to CO_2 ship transportation began in 2022, and it is currently in the final stage.

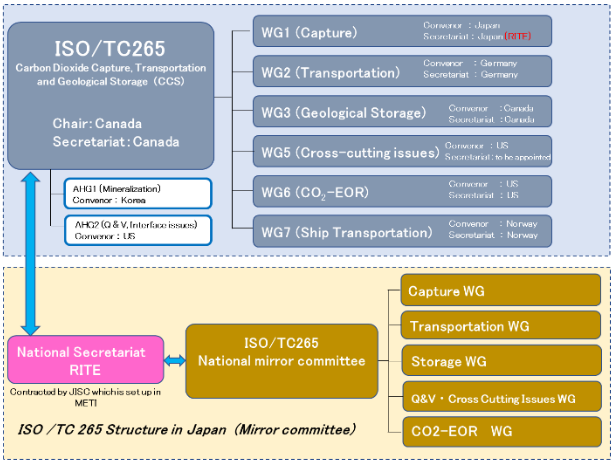


Figure 11 ISO/TC265 structure

4. Human development and industry collaboration

4.1. Human development

RITE conducts various human resource development activities to foster the next generation of re-searchers. Here, human resource development activities are explained separately for elementary, junior high and high school students and universi-ty/graduate school students.

<Elementary, junior and high school students>

It is important to educate the next generation about the issue of global warming. At RITE, we are: i) accepting field trips for elementary, junior and high school students using research facilities; we are working to respond to class requests. In 2023, 133 students from 6 schools visited RITE. In the class, CCS technology will be picked up from the research conducted by RITE, and the mechanism of global warming will be explained as knowledge, and the possibility of leakage through the clay layer (shielding layer) even if CO_2, which is the main greenhouse gas, is stored underground. In addition, activities are based on a learning cycle, such as deepening understanding through consideration and exchange of opinions (Figure 12).

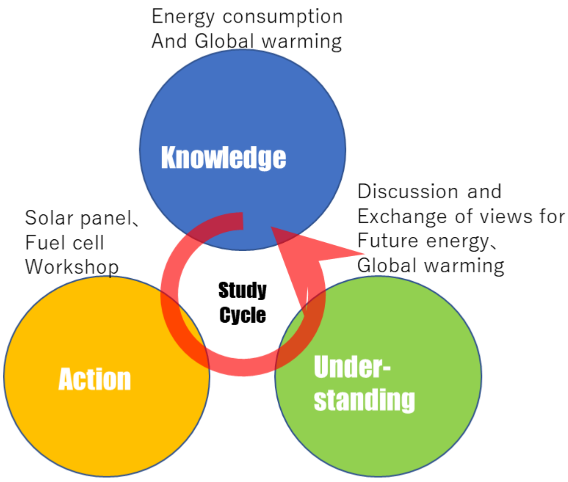


Figure 12 Human resource development by RITE
（Elementary, Junior and high school students）

<University & Postgraduate student>

As part of efforts to develop human resources who will support next-generation research and technology, RITE promotes educational partner-ships with universities and graduate schools. We are developing education at universities and re-search guidance at research institutes (Figure 13). For example, Nara Institute of Science and Technology (NAIST) has set up a university-collaborated laboratory in the bio-science field at RITE. We are promoting research and education aimed at realizing are cycling-oriented and low-carbon society using renewable resources. In addition, we have established a collaborative laboratory with the materials creation science area of the NAIST, and are promoting research and education on CO_2 separation and recovery technology.

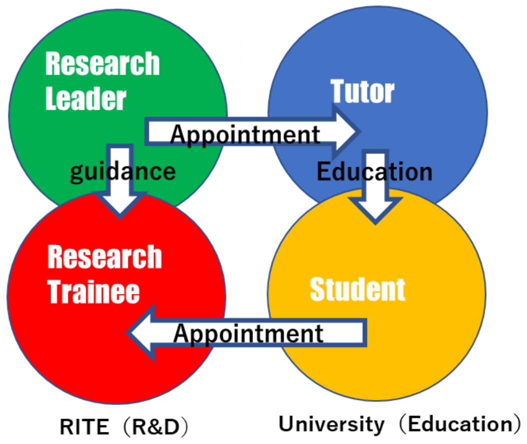


Figure 13 Human resource development by RITE (University ＆ Post graduate students)

4.2. Intellectual property and industry collaboration

RITE strategically and efficiently acquires and manages intellectual property rights such as pa-tents and know-how regarding the results of re-search and development, etc., and actively utilizes them for the public interest. The aim is to advance and improve industrial technology that contributes to the conservation of the global environment.

The acquisition of such research results as intellectual property creates opportunities for industrial collaboration with companies, etc., and through joint research and joint applications, further intellectual property is generated through a virtuous cycle that contributes to society. At RITE, we focus on the di-verse functions of intellectual property rights and strategically promote intellectual property activities while taking into consideration the market and other research and development trends.

As part of the promotion of intellectual property strategies, the "Patent Deliberation Committee" was established with RITE executives as members and the public relations and industry collaboration team as the secretariat. The main agenda is the acquisition and management of intellectual property such as patent applications and examination requests, patent right maintenance, and intellectual property strategies such as approval of license agreements.

As of the end of March 2024, of the patents for which RITE is the sole or joint applicant, 16 domestic applications and 18 foreign applications are pending patent applications, and the registered rights are maintained. It holds 71 domestic patents (including 7 under license to companies) and 49 foreign patents (7 of which are licensed to companies).

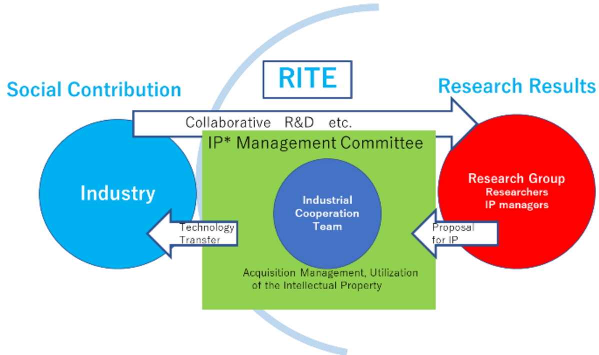


Figure 14 Strategic IP management and industrial collaboration

5. Conclusion

Toward the realization of carbon neutrality by 2050, the government has started the issuance of GX economy transition bonds and various GX promotion measures. With the enactment of the CCS Business Act, in addition, efforts have just been commenced to develop a business environment in which private companies are able to launch CCS business by around 2030. However, it is never easy to achieve carbon neutrality. To achieve this, RITE is required to play an active role in the social implementation of innovative environmental technologies. For practical application of CCS and other new technologies, it is essential to enhance public understanding. Taking advantage of the opportunity to display its DACCS (Direct Air Capture and Storage) technology at Expo 2025 Osaka, Kansai, Japan, RITE will make active efforts to enhance public understanding of the need to achieve carbon neutrality and the importance of CCS.

We at the Research & Coordination Group will also actively collect information on domestic and overseas policies and technology trends. With an eye toward realizing carbon neutrality by 2050, we, together with research groups, will actively implement and promote technology development and PR activities as well as industry-university cooperation activities. We believe that through RITE's concerted efforts to promote the social implementation of innovative environmental technologies, we will be able to contribute to carrying out RITE's mission: "to achieve the balance between the global environmental protection and economic growth."

Reference

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3) The Strategy for Promoting Structural Transition Based on Decarbonization (GX Promotion Strategy) (Cabinet approval on July 28, 2023)
4) Interim summary on "What Institutional Measures Related to CCS Ought to Be"
5) The Bill for the Act on Carbon Dioxide Storage Businesses (Cabinet approval on February 13, 2024) (https://www.meti.go.jp/english/press/2024/0213_003.html)
6) Final Summary by the CCS Long-Term Roadmap Study Group, Agency for Natural Resources and Energy (March 2024)
7) Mitsubishi UFJ Research and Consulting, Exchange Quotations, "Daily Exchange Quotations – since 1990," Checked in February 2024
8) Trade Statistics of Japan published by the Ministry of Finance, Exports and Imports Values by Commodity, World Monthly (Import), Checked in February 2024

Systems Analysis Group

Members (As of Apr. 2024)
Keigo Akimoto, Group Leader, Chief Researcher
Koya Yamada, Associate Chief Researcher
Kenichi Wada, Senior Researcher
Miyuki Nagashima, Senior Researcher
Takashi Homma, Senior Researcher
Fuminori Sano, Senior Researcher
Ayami Hayashi, Senior Researcher
Atsuko Fushimi, Senior Researcher
Noritaka Mochizuki, Senior Researcher (concurrent)
Tadashi Kuwatsuru, Senior Researcher
Yuko Nakano, Senior Researcher
Naoko Onishi, Senior Researcher
Teruko Hashimoto, Senior Researcher
Hitotsugu Masuda, Researcher
Teruhisa Ando, Researcher
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Kiyomi Yamamoto, Assistant Researcher
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Research Activities in Systems Analysis Group

The Systems Analysis Group aims to provide valuable information about response measures to global warming and energy issues through systematic approaches and analyses at both national and international levels.

Achieving the long-term 2°C or 1.5°C goals of the Paris Agreement is required. However, it is said that there is a large emissions gap between the current situation or the emission reduction targets submitted by each country in their Nationally Determined Contributions (NDCs) for 2030 and those long-term goals. It is important to present emission pathways and countermeasure scenarios for each sector quantitatively and consistently to limit temperature rise below 2°C or even 1.5°C, including transition periods such as 2030 and 2040. With this background, in FY2023, we have developed sectoral transition roadmaps for the world and Japan to achieve the 2°C and 1.5°C goals using the global energy and climate change mitigation assessment model DNE21+, which is published on the RITE website[1]. This report provides an overview of the analyses.

1. Development of long-term scenarios towards Carbon Neutrality (CN) and scenario assumptions

1.1. Background of developing transition roadmaps

It is necessary to strengthen measures in each sector to achieve the 2°C and 1.5°C long-term goals of the Paris Agreement and carbon neutrality (CN) early in the second half of the 21st century. Various possibilities have been presented such as in the IPCC AR6[2], including scenarios with high reliance on negative emissions through carbon dioxide removal (CDR) and scenarios with low reliance on negative emissions through the realization of a low energy demand society. Furthermore, transition pathways to CN realization are even more varied. For instance, emission reduction pathways for each industrial sector differ from sector to sector in terms of the lifetime of existing infrastructure and the difficulty of emission reduction measures. Uniform reductions may increase the cost of countermeasures and make emission reductions more difficult.

However, in the case where countries, industries, and companies take emission reduction measures at a slower rate than others, there is also a risk of being criticized as “greenwashing”. On the other hand, financial institutions and evaluation agencies do not necessarily have a sufficient understanding of the pathways for emission reductions that are consistent with the energy system as a whole, so quantitative information to make judgments about the appropriateness of investments is needed. Therefore, the Network for Greening the Financial System (NGFS) and other organizations are developing emission reduction scenarios using integrated assessment models that enable quantitative analysis[3]. On the other hand, these do not provide sufficient information on sectoral emission reduction pathways. The International Energy Agency (IEA) has also presented, but not enough information by country, especially for the 1.5°C scenario. Likewise, the report by the International Capital Market Association (ICMA)[4] also has issues regarding the consideration of regional and industrial characteristics. The Government of Japan has developed a transition roadmap for FY2021-22 to provide a specific direction for the transition toward achieving carbon neutrality, and to use this roadmap in transition finance. These also provide useful information, but at the same time, they were developed on a sector-by-sector basis, therefore, there is a need to further improve the accountability for consistency with the overall 2°C and 1.5°C emission reduction pathways, as well as consistency among sectors.

Therefore, we developed emission reduction scenarios, including transition roadmaps by sector, that are consistent with the 2°C and 1.5°C targets globally and with economic rationality while taking into account the differences among countries and sectors, using the global energy and climate change mitigation model: the DNE21+ model, which minimizes total energy systems costs for the period up to 2100.

1.2. Scenrio assumptions

For assuming scenarios for quantitative analyses using DNE21+, the NGFS scenarios[3] are basically referenced. NGFS develops Orderly scenarios and Disorderly scenarios, based on whether the transition will proceed orderly or not. Complying with this, we have developed our Orderly scenarios and Disorderly scenarios, as well as an additional scenario similar to Net Zero by 2050 (NZE)[5] by IEA. Outlines of the scenarios and assumptions for model analyses with the DNE21+ are shown in Table 1. In terms of temperature rises, two scenarios that are consistent with a 2°C target, and three scenarios consistent with a 1.5°C target are assumed. Global CO_2 emissions scenarios are assumed as shown in Figure 1.

Table 1 Assumed scenarios (outline)

Scenarios	Global average temp. increase	Policy speed#	CDR contribution	Renewables and BEV	Differences in policy intensity among regions	Relation to other scenarios		
						IPCC AR6 (IPCC 2022)	NGFS (2022)	IEA
Disorderly Below 2 °C	1.7 °C in 2100 (peak:1.8 °C)	Gradual (NDCs in 2030)	medium	Medium cost reductions	Large (major developed countries: CN by 2050)	Likely below 2 C, NDC [C3b]	Disorderly: Delayed Transition	APS (WEO 2022)
Orderly Below 2 °C	1.7 °C	Rapid	Small	High cost reductions	Small (equal MAC among countries)	Likely below 2 C with immediate action [C3a]	Orderly: Below 2C	SDS (WEO 2021)
Disorderly 1.5 °C	1.4 °C in 2100 (peak:1.7 °C)	Gradual (NDCs in 2030)	Large	Medium cost reductions	Large (major developed countries: CN by 2050)	1.5 C with high overshoot (IMP-Neg) [C2]	(Disorderly: Divergent Net Zero)*	
Orderly 1.5 °C	1.4 °C in 2100 (peak:1.6 °C)	Rapid	Medium	High cost reductions	Medium (major developed countries: CN by 2050)	1.5 C with no or limited overshoot [C1]	Orderly: Net Zero2050	
1.5C-CO2_CN	Approx. below 1.5 °C	Rapid	Small (Near-zero of CO_2 by sector)	High cost reductions	Large (major developed countries: CN by 2050)	1.5 C with no or limited overshoot [C1]		NZE

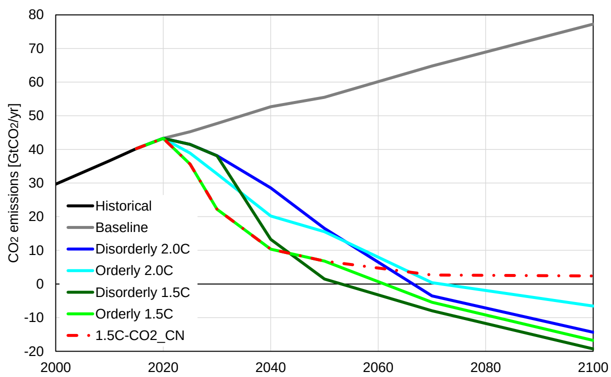

Figure 1 Global CO_2 emissions pathways

2. World

2.1. Scenario analysis using DNE21+

This section describes the scenarios for the world.

Figure 2 shows the global GHG emissions by sector. Earlier CO_2 reduction from the power generation sector is shown to be economically rational compared to other sectors.

Figure 3 shows the global electricity supply. While coal power generation is significantly suppressed even in 2030, several scenarios can be seen where gas power generation with CCS increases more than in the baseline, indicating the transition to gas is proceeding. For Orderly scenarios where relatively lower expansion rates of CO_2 storage are assumed, the introduction of gas power with CCS is smaller compared to Disorderly scenarios, and solar photovoltaics (PV) and wind power with further cost reduction assumed will increase instead.

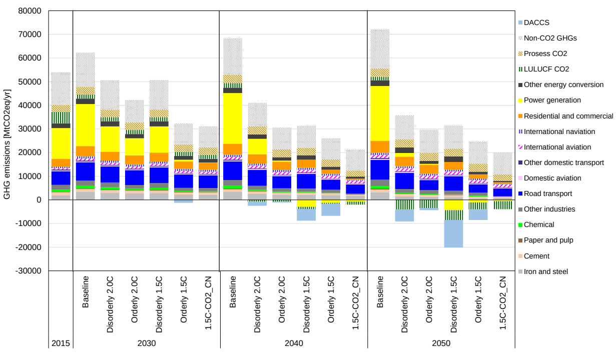

Figure 2 GHG emissions (world)

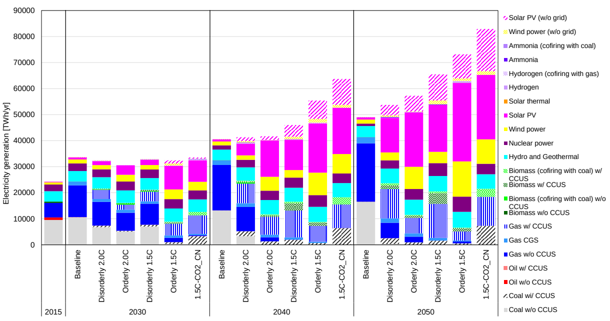

Figure 3 Electricity supply (world)

Figure 4 shows the global final energy consumption in the industry sector. Similar to the power generation sector, coal consumption decreases, and consumption of gas and electricity increases. The decrease in coal consumption is relatively smaller compared to the power generation sector because coal usage is needed for crude steel production by the blast furnace/basic oxygen furnace (BF-BOF) in the iron and steel sector. Compared to the analysis results for Japan shown later, consumption of hydrogen, ammonia, and synthetic methane (e-methane) is relatively smaller as many countries have larger potentials for domestic renewable energies, renewable energies over cross-border interconnection, and domestic CO_2 storage. However, in the 1.5C-CO_2_CN scenario where large deployments of CDR are constrained, those consumption is substantial.

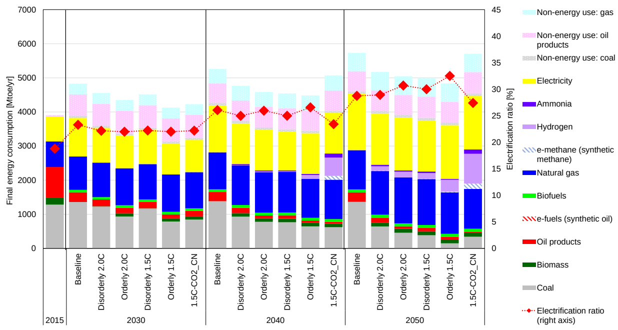

Figure 4 Final energy consumption in industry (world)

2.2 Comparison with other scenarios

Comparisons with existing international scenario analyses are described below. As described below, scenario analyses by RITE are highly consistent with them and have high explainability, with small variations due to the differences in models and assumptions.

Figure 5 shows the comparison of global CO_2 emissions by sector with those by IPCC. The sectoral CO_2 emissions in DNE21+ scenario analyses are almost consistent with those in IPCC and encompass their upper and lower limits, with a few exceptions of exceeding their ranges in the transport and the residential and commercial sectors. A major factor of residual emissions in these sectors slightly exceeding IPCC scenario ranges may be whether CDRs, especially direct air carbon capture and storage (DACCS) are considered in the models or not (Figure 6).

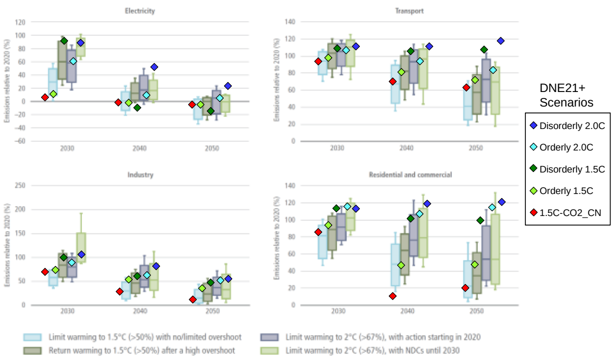

Figure 5 Comparison with global CO_2 emission scenarios of IPCC

Source) IPCC AR6[2], with DNE21+ scenarios plotted
Note) Boxes indicate 25th and 75th percentiles, while whiskers indicate 5th and 95th percentiles in IPCC scenarios.

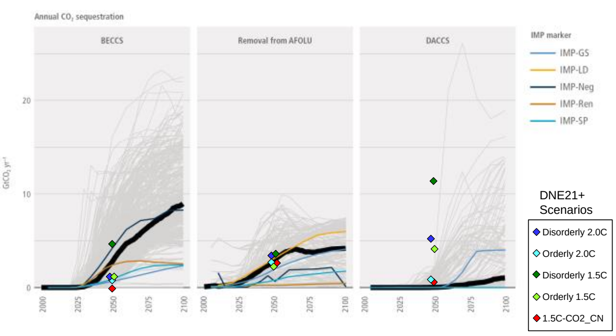

Figure 6 Comparison with global CDR scenarios of IPCC

Source) IPCC AR6[2], with DNE21+ scenarios plotted (only for 2050)
Note) As for IPCC AR6, only the scenarios categorized as C1-C3 are shown.

Figure 7 shows a comparison with NGFS in carbon prices (CO_2 marginal abatement costs; MAC) in each scenario. For 1.5°C scenarios, carbon price levels in DNE21+ scenarios are almost consistent with those in NGFS scenarios, with a tendency of slightly lower MAC as DACCS are considered in the DNE21+ model. Comparisons of MACs with scenarios in the IPCC report are shown in Figure 8. Many models in the IPCC report estimate them under the condition of MACs being globally equalized. MACs in DNE21+ scenarios are consistent with those in the IPCC report. While many IPCC scenarios do not assume DACCS, DNE21+ does assume DACCS, thus leading to slightly lower MACs in 2050 compared to those in the C1 scenario in IPCC.

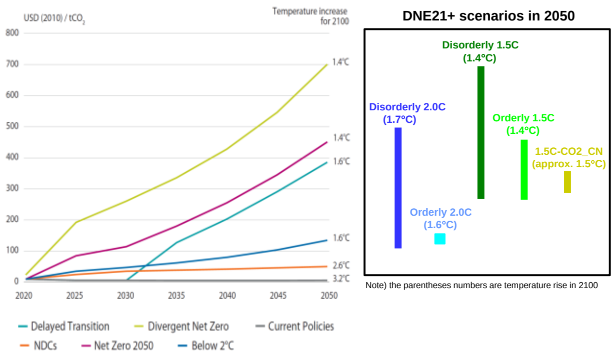

Figure 7 CO_2 marginal abatement costs: compared with NGFS

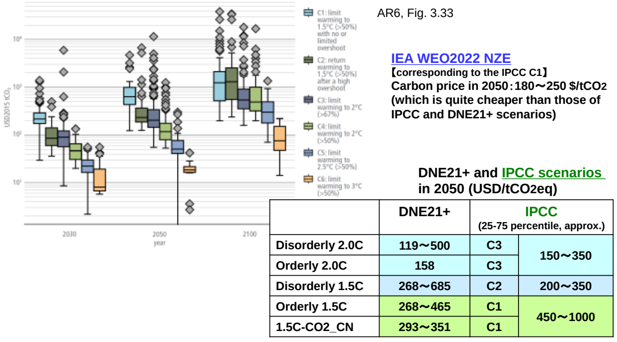

Figure 8 CO_2 marginal abatement costs: compared with IPCC

3. Japan

This section describes the quantitative scenario analysis for Japan.

3.1. GHG emissions

Figure 9 shows Japan's GHG emissions by sector. For three scenarios where net-zero emissions of GHG are achieved by 2050 (Disorderly 2.0C and Disorderly/Orderly 1.5C), measures such as DACCS, land-use CO_2 (CO_2 sequestration by afforestation), and net negative emissions of CO_2 in the power sector (achieved with biomass with CCS (BECCS) and e-methane with CCS) are introduced. For the Orderly 2.0C scenario where net-zero emission of GHG by 2050 is not assumed and global cost minimization (equal MACs across countries) is assumed, a reduction of approximately 70% compared to

2013 is shown to be cost-efficient. In this case, residual CO_2 emissions from the power sector or iron and steel sector are allowed.

Figure 10 shows the balance between CO_2 capture and storage/utilization in Japan. In 2030 and 2040, CO_2 captures from coal and gas power plants or BF-BOF are introduced. For some scenarios, captures from biomass power plants and DAC are introduced in 2040 and their amount increases in 2050. In the 1.5-CO_2_CN scenario, BECCS and e-methane with CCS in the power sector, and DACCS are not allowed (CCU that utilizes CO_2 captured by DAC is allowed), therefore CO_2 captures from coal (including biomass co-firing) and gas power plants and cement sector are observed even in 2050.

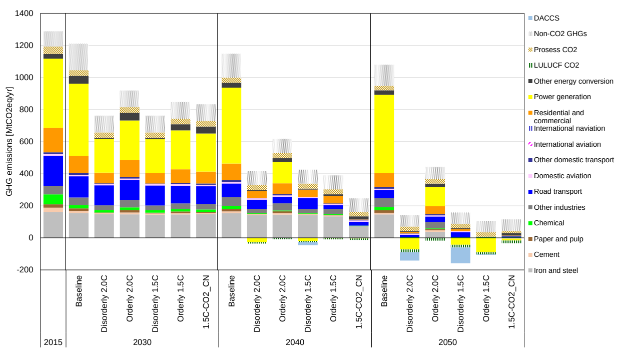

Figure 9 GHG emissions (Japan)

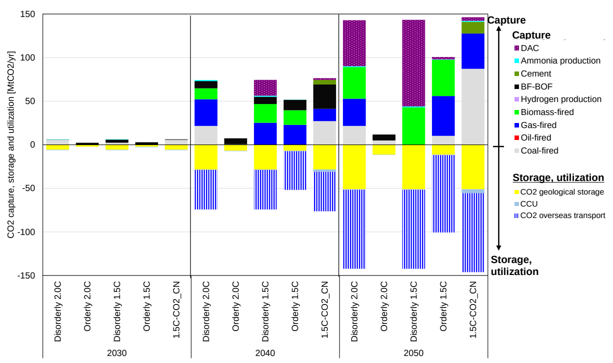

Figure 10 CO_2 balance (Japan)

3.2. Primary energy supply, electricity, and other energy conversion

Figure 11 shows the primary energy supply in Japan. Japan's potential for renewable energy and CO_2 sequestration is not large compared to its energy demand, therefore, importing and using carbon-neutral fuels such as e-methane, e-fuels, and biofuels as well as hydrogen and ammonia are evaluated as cost-effective. In Orderly 2.0C with emission reductions of around 70% below 2013 levels by 2050, those amounts are relatively small, and it is overall cost-effective to deepen emission reductions in other countries to achieve the global 2°C target, leaving coal and gas supplies without CCS.

Figure 12 shows the amount of electricity generated. To promote electrification, the total amount of electricity generated increases, especially under the severe emission reduction scenario. In addition to expansions of renewable energy sources (e.g., solar PV) and utilization of CCS, power generation using imported hydrogen and ammonia is being promoted to reduce CO_2 emissions. It is noted, e-methane is used for gas power generation with CCS in 2050 in all scenarios except Orderly 2.0C and 1.5C-CO_2_CN. In the Disorderly scenarios, since variable renewable energy (VRE) is assumed to be relatively high, imported from overseas hydrogen and ammonia (since a high rate of expansion of CO_2 storage is assumed, it is easier to produce blue hydrogen and blue ammonia abroad) tend to be used for power generation. On the other hand, in the Orderly scenarios, the use of VRE, which is expected to become even cheaper, is relatively expanded, while power generation using hydrogen and ammonia is rarely seen. The latter is because the expansion rate of CO_2 sequestration is assumed to be low, making production overseas difficult. Note that 1.5C-CO_2_CN constrains the use of BECCS and e-methane with CCS to be unavailable, resulting in the deployment of coal power with CCS.

Figure 13 shows the CO_2 emission intensity in the power sector for each scenario. Although the power source composition is different in Disorderly 2.0C/1.5C and Orderly 1.5C as mentioned above, there is no significant difference in the transition of the CO_2 emission intensity, and it is evaluated to be cost-effective overall to achieve net zero GHG emissions around 2040 in the power sector.

Figure 14 shows a comparison of the cumulative CO_2 emissions in the power sector for 2020-2030 with the Government of Japan Roadmap[6], which is slightly below the five DNE21+ scenarios, consistent with the 2°C and 1.5°C emission reduction pathways. Between 2031 and 2050, the government Road map is within the range of the five DNE21+ scenarios, which is consistent.

As for hydrogen-based energy, hydrogen can be produced domestically by water electrolysis in Orderly 2.0C/1.5C and 1.5C-CO_2_CN, where further cost reduction of VRE is expected, while in other scenarios, it is exclusively imported from overseas. In 2030 and 2040, most of it is used in power generation, but by 2050, it is used in direct reduced iron (DRI) production in the iron and steel sector. As for ammonia, blue ammonia produced overseas is used in the power generation sector, partly because the cost reduction of VRE is relatively slow in Disorderly 2.0C/1.5C. It is also used in industrial sectors such as petrochemical sector as carbon-neutral fuel. e-methane is used in the residential and commercial sectors, other industrial sectors, and the power sector (with the introduction of CCS, it is practically a negative emission like BECCS). The e-methane is mainly produced overseas where renewable energy costs are low, and imported, however, under the 1.5C-CO_2_CN, domestic production using innovative methanation technology is also observed. Imported e-fuels other than e-methane are also used.

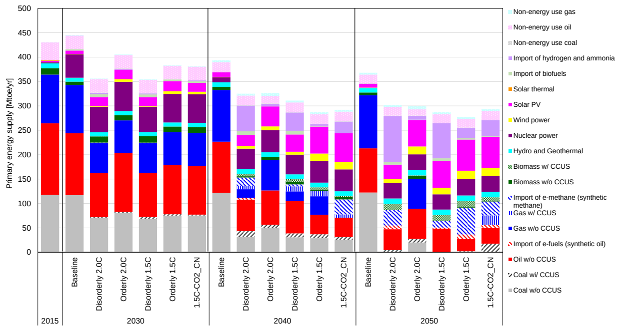

Figure 11 Primary energy supply (Japan)

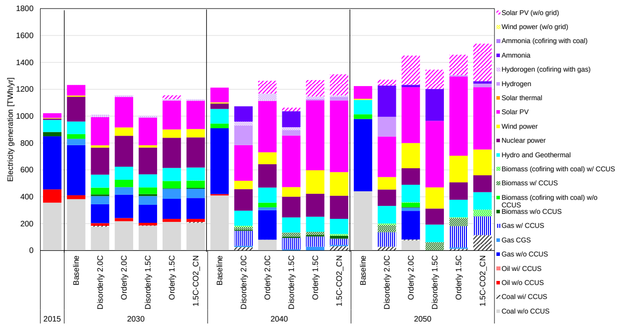

Figure 12 Electricity supply (Japan)

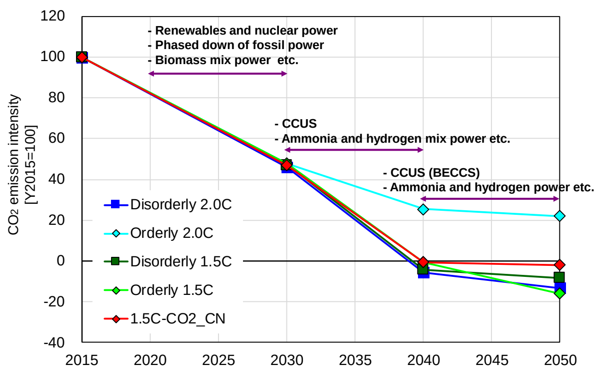

Figure 13 CO_2 intensity of electricity (Japan)

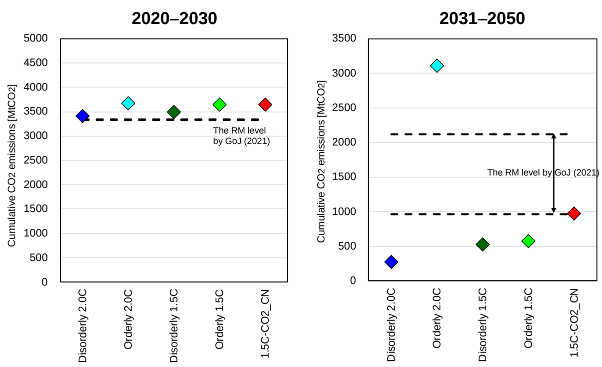

Figure 14 CO_2 emissions in power sector (Japan): comparison with the RM by GoJ

3.3. Gas and oil supply

Figure 15 shows the gas supply. Under Orderly 2.0C, the supply of natural gas supply keeps the current level or slightly decreases by 2050. Other scenarios predict greater uses of hydrogen or e-methane in 2040 and 2050. The choice between hydrogen and e-methane is sensitive depending on preconditions, such as the assumption of cost reduction timing. As in Figure 16, which shows CO_2 emissions in the gas sector, the CO_2 emission intensity is not improved in 2030 and 2040, compared to that in the power generation sector. Since natural gas has a low CO_2 intensity, its use is consistent with the 2°C and 1.5°C scenarios until around 2030 to 2040.

Figure 17 shows the oil (liquid fuels) supply. The oil use significantly decreases due to a decline in demand for transportation services, the improvements in vehicle fuel efficiency, and the shift to EVs, etc. in any scenario. This trend is notable particularly in Orderly 1.5C and 1.5C-CO_2_CN, which assumes high technological progress and cost reduction in renewable energy and EVs. The use of e-fuels can be also seen in 2050. Especially in Orderly 1.5C, in which the constraint on CO_2 storage expansion is assumed, oil is replaced with e-fuels more and more, as emission offset is limited and the price of e-fuels decreases due to further reductions in renewable energy costs.

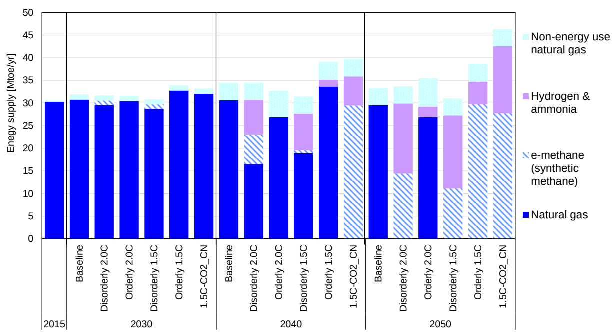

Figure 15 Gas supply (Japan)

Note) The uses in power, iron & steel, and petrochemical sectors are not included here and described in each sectoral analysis.

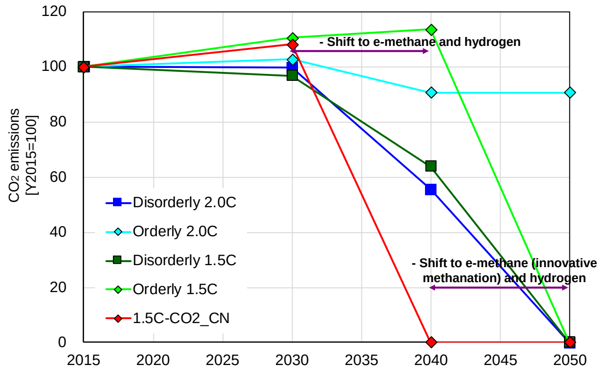

Figure 16 CO_2 emissions from gas (Japan)

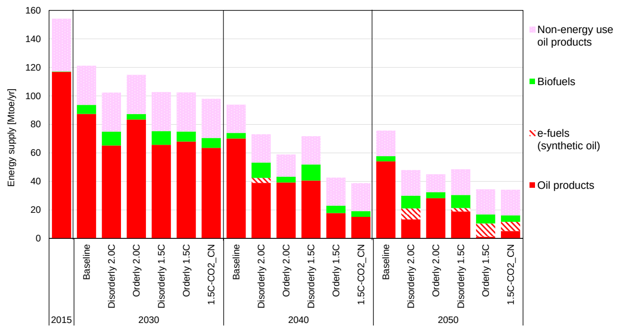

Figure 17 Oil (liquid fuels) supply (Japan)

Note) The uses in power sector are not included here.

3.4. Industry sector

Figure 18 shows the final energy consumption in industry. Coal use remains even in 2040 at a level close to that in 2030, for the usage in BF-BOF in the iron and steel sector. In 2050, there is no use of coal, and the uses of hydrogen, ammonia, and e-methane are observed in the scenarios other than Orderly 2.0C.

Figures 19 and 20 show the final energy consumption and crude steel production by technology in the iron and steel sector, respectively. As mentioned earlier, there is a considerable amount of coal used in 2040. There are also scenarios where BF-BOF steel manufacturing using external hydrogen, such as Super COURSE50, becomes economically efficient. In 2050, there is no use of coal, and the BF-BOF is completely replaced by hydrogen-using direct reduced iron (DRI) + electric furnace (EF) except for Orderly 2.0C, where total emission is predicted to be 70% lower than that in 2013.

The use of e-methane is used in the scrap EF process.

Figure 21 shows the CO_2 emissions intensity in the iron and steel sector. In any scenario, nearly zero emission is achieved in 2050 by introducing CCS in the BF after 2030, promoting the use of external hydrogen in some scenarios, and converting to the hydrogen-based DRI + EF from 2040 onwards. However, in Orderly 2.0C, where Japan does not make much progress in reducing CO_2 emissions, the BF-BOF without CCS continues to be used and some emissions remain even in 2050. Figure 22 shows a comparison of the DNE21+ scenarios and the roadmap formulated by the government of Japan for CO_2 emissions in the iron and steel sector. In the government's roadmap, while the upper limit for 2020-2030 has slightly higher emissions, other levels are within the range of the five DNE21+ scenarios and are consistent with the 2°C and 1.5°C emission reduction paths as a whole.

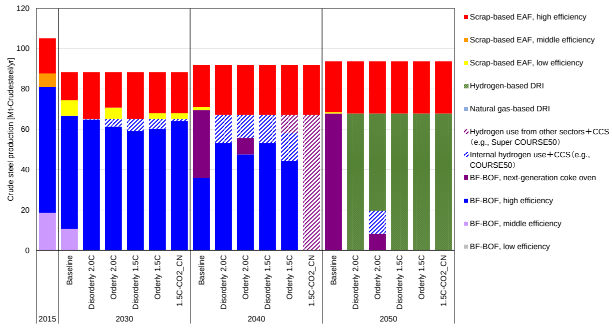

Figure 20 Steel production by technology (Japan)

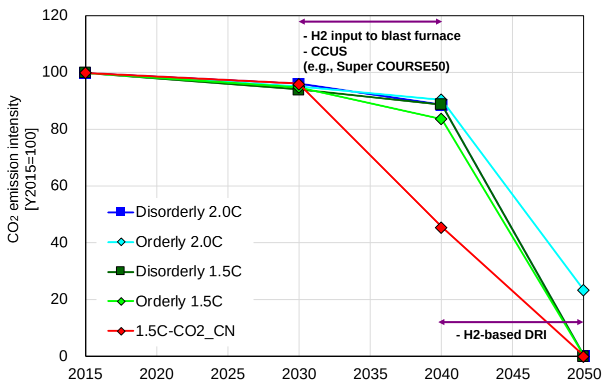

Figure 21 CO_2 intensity of iron & steel sector (Japan)

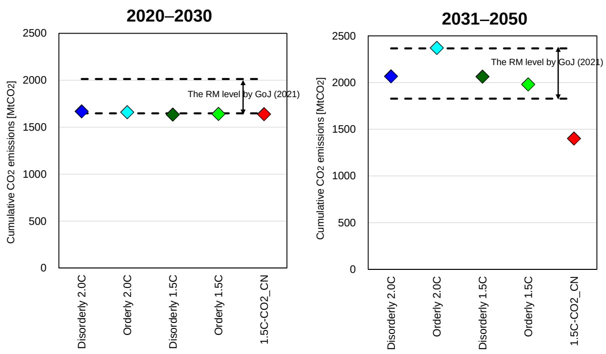

Figure 22 CO_2 emissions in iron & steel sector (Japan): comparison with the RM by GoJ

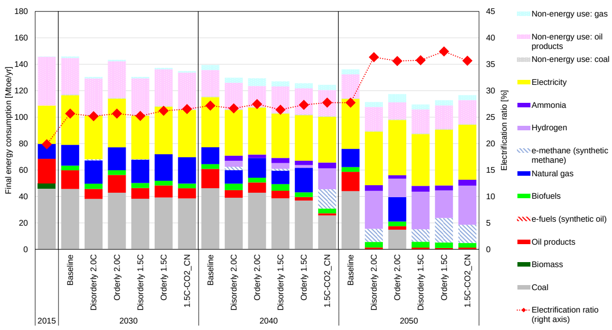

Figure 18 Final energy consumption in industry (Japan)

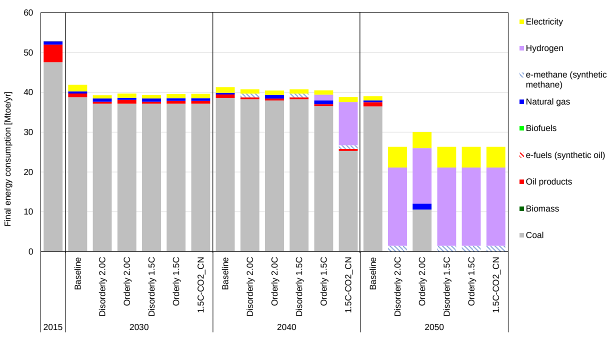

Figure 19 Final energy consumption in iron & steel (Japan)

Figure 23 and Figure 24 show the final energy consumption and clinker production by technology in the cement sector, respectively. A shift from to gas is considered to be cost-effective in 2030 except Orderly 2.0C. A shift to gas is further promoted towards 2040, and e-methane is the main source by 2050. In 1.5C-CO_2_CN, which restricts the use of CDR, the deployment of CCS progresses, and therefore energy consumption is higher than in other scenarios. Figure 25 shows the CO_2 emissions intensity of the cement sector. In scenarios other than 1.5C-CO_2_CN, no CCS implementation is seen, and emission including process-derived CO_2 remains even in 2050. Net zero emission is achieved in 1.5C-CO_2_CN by introducing e-methane with CCS (net negative emissions).

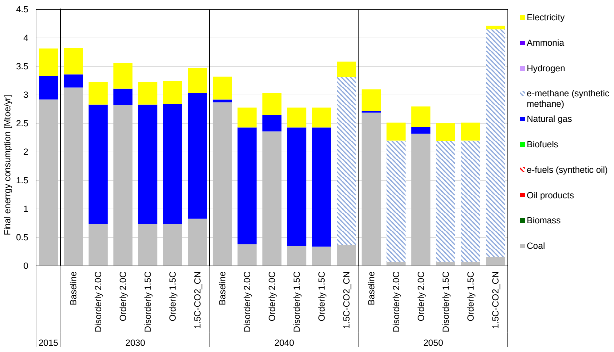

Figure 23 Final energy consumption in cement (Japan)

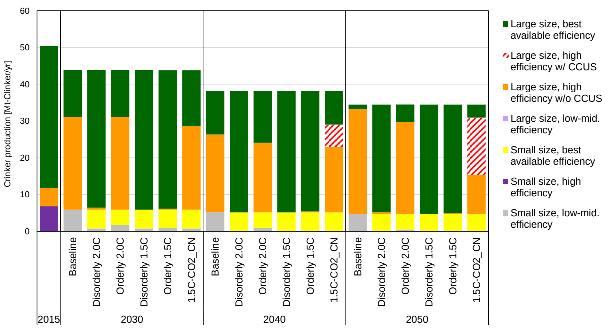

Figure 24 Clinker production by technology in cement sector (Japan)

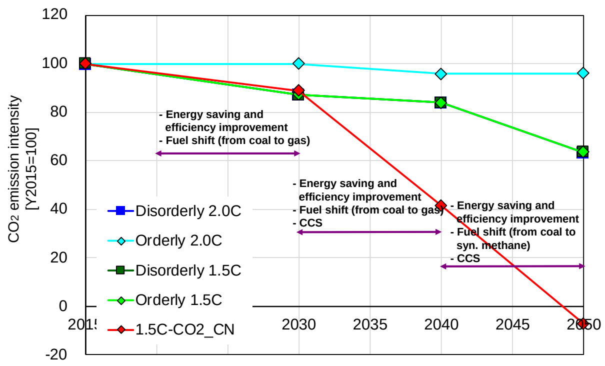

Figure 25 CO_2 intensity of cement sector (Japan)

The scenario analysis and roadmap development for the pulp and paper and the chemical sectors have been also conducted.

3.5. Transport sector

Figure 26 shows the final energy consumption in the transport sector. In the Orderly scenario and the 1.5C-CO_2_CN scenario, which assume significant reduction in the costs of renewable energy and EVs, electricity consumption particularly increases, and the use of e-fuels can be observed as well, from around 2040. In Orderly 1.5C and 1.5C-CO_2_CN, passenger cars are expected to be BEVs or FCEVs, and e-fuels is mainly used in trucks in the road transport sector.

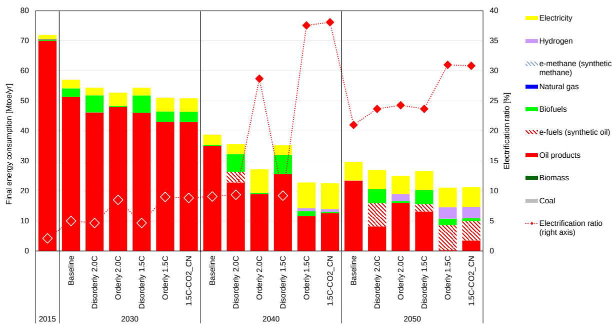

Figure 26 Final energy consumption in transport (Japan)

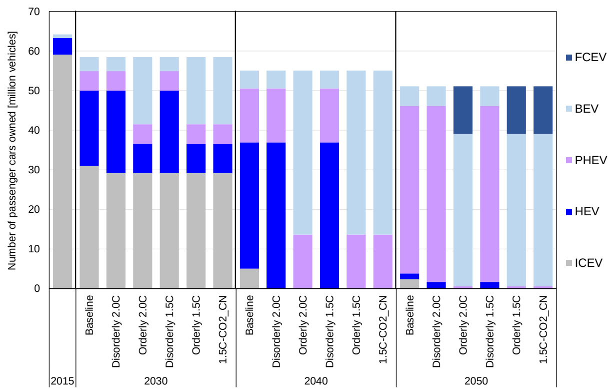

Figure 27 Number of passenger cars by technology (Japan)

Figure 27 shows the number of passenger cars by technology in Japan. In the Disorderly scenarios, which assume a medium level of EV technological progress, emission reduction measures for passenger cars focus on HEVs around 2030, expand to PHEVs afterward, and PHEVs become the main focus in 2050. On the other hand, in scenarios which assume high cost reduction in EVs, BEVs are expected to diffuse from an earlier stage and become dominant in 2040, and FCEVs are also expected to diffuse in 2050.

3.6. Residential and commercial sector

Figure 28 shows the final energy consumption in building. The improvement of electrification ratio is cost-effective as emissions reduction is stricter. In Orderly 2.0C, city gas is used as before, and in other scenarios, the gaseous fuels are e-methane or hydrogen.

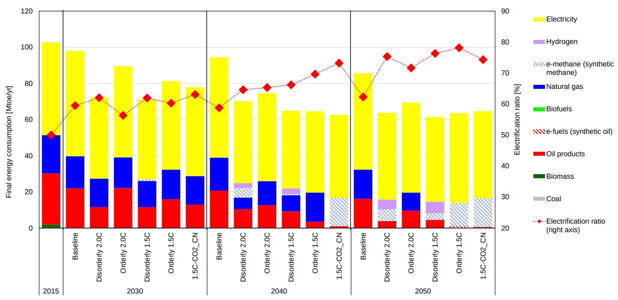

Figure 28 Final energy consumption in building (Japan)

4. Summary

Five scenarios that are consistent with the 2°C and 1.5°C targets and consistent with the NGFS and IEA scenarios were assumed and were analyzed including transition pathways, using the DNE21+ model, which enables quantitative and globally consistent analysis. Emission pathways varied significantly by sector and varied substantially by assumed scenarios of technology and other factors. In particular, there can be large differences depending on the projections of CDR. In addition, a comparison of emission pathways by sector shows that the power generation sector, which offers more emission reduction options, is required to improve its CO_2 emission intensity from a relatively early stage. This finding is consistent with IPCC and IEA scenarios. On the other hand, natural gas, which has a small CO_2 emission intensity, was assessed as a more economically efficient measure to be increased toward 2030 in Japan, even in the 2°C and 1.5°C scenarios. In addition, the steel sector was shown to have a scenario in which CO_2 reduction measures are difficult to implement and emissions will only be reduced by a maximum of 10% until around 2040. These analyses are generally consistent with the sectoral roadmaps developed by the Government of Japan for FY2021-22, and the government roadmap is consistent with not only the 2°C but also the 1.5°C emission reduction pathway.

In this analysis, we have presented only five scenarios. Even so, there is a large range, but in reality, there are uncertainties that cannot be fully taken into account in the five scenarios, and therefore, the interpretation of the scenarios needs to be carefully considered. Moreover, while the DNE21+ model is relatively detailed, the model still provides a highly simplified representation of real-world situations. The reality is that there are diverse agents and both re-tiring and new construction require a more complex transition process, including time-consuming coordination with the local community, however, the model is largely unable to account for these factors. To ensure transparency in the model analysis, non-transparent constraints are also intentionally not taken into account. Therefore, we believe that taking cost-effective measures from among the widest possible range of options, with a good understanding of these issues, will lead to the realization of CN at an earlier stage, and that this scenario analysis and roadmap will be useful in developing such a strategy.

It is an ongoing challenge to continue to follow technological trends and update the roadmap as appropriate, as well as to develop roadmaps for individual countries and regions other than Japan, to contribute to the promotion of its use in a wide range of countries.

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3) NGFS: NGFS Scenarios for central banks and supervisors (2022)

4) ICMA: Overview and Recommendations for Sustainable Finance Taxonomies (2021)

5) IEA: Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (2023)

6) METI: the Japan Public and Private Working Group on Financed Emissions to Promote Transition Finance (2021, 2022)

Molecular Microbiology and Biotechnology Group

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Satoshi Hasegawa, Senior Researcher
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Development of Bio-manufacturing Technologies that Contribute to Carbon Neutrality

1. Introduction

Since bioprocesses can be manufactured under ambient temperature and pressure, they are expected to reduce CO_2 emissions, unlike chemical processes, which are manufactured under high temperature and pressure. This also has an advantage over chemical processes in producing complex compounds with high carbon counts because they are generally synthesized by multistep reactions in the cell. Thus, biomanufacturing is attracting attention as an innovation that enables both economic growth and solutions to global-scale social issues such as resource autonomy and a breakaway from dependence on fossil resources. With the development of "bio x digital technology" through the fusion of biotechnology (e.g. synthetic biology and genome editing technology) with digital technology (e.g., the internet of things artificial intelligence) and the growing awareness of global environmental issues, such as the need to disengage from fossil resources for resource autonomy, the practical application of this technology is expected to accelerate and the market size to expand rapidly in the future. Major investments are being made in this field in the U.S. and China, and international competition is intensifying. In Japan, the Green Innovation (GI) Fund Project and the Biomanufacturing Revolution Promotion Project were launched this fiscal year as large-scale projects to develop and socially implement technologies for the design and development of new microorganisms and the advancement of manufacturing processes using microorganisms. These projects aim to be carbon neutral and carbon negative by switching from petroleum as a raw material to atmospheric CO_2 and unused resources.

Against this background, the Research Institute of Innovative Technology for the Earth (RITE) has been developing biorefinery technology to produce biofuels and green chemicals from non-food biomass at high efficiency through microbial bioprocesses. RITE discovered that coryneform bacteria, a typical industrial microorganism, maintain metabolic functions under reducing conditions despite growth inhibition and that they efficiently metabolize sugars and produce organic acids. Consequently, RITE developed the growth-independent bioprocess "RITE Bioprocess"[*1]. In addition, we established elemental technologies essential for industrialization, such as "complete simultaneous use of mixed sugars derived from non-food biomass" and "high tolerance to fermentation inhibitors" (see Chapter 2, Section 1). Using these technologies, we reported the world's highest efficiency production of ethanol, butanol, green jet fuel, and biohydrogen as biofuels, and lactic acid, succinic acid, alanine, valine, tryptophan, shikimic acid, protocatechuic acid, 4-aminobenzoic acid, and 4-hydroxybenzoic acid as green chemicals. Currently, RITE is focusing on developing production technologies for aromatic compounds that can be used as raw materials for high-value–added fragrances, cosmetics, pharmaceuticals, fibers, and polymers, as well as bio-manufacturing technologies that directly use CO_2 as a raw material.

So far, we have participated in the New Energy and Industrial Technology Development Organization (NEDO) "Smartcell" project and the "Data-driven Integrated Bioproduction Management System" project and have been developing "Smart Cell Creation Technology," a bio x digital technology (see Chapter 2, Section 2). We are also participating in the NEDO "Bio-Manufacturing Demonstration" project as a joint development with private companies using the same technology and are conducting research and development to commercialize bioproduction of carotenoids and flavors (see Chapter 3, Section 4 and Chapter 3, Section 5). In this fiscal year, the company began participating in the GI Fund Project and the Bio-manufacturing Revolution Promotion Project to develop bioproduction technology for high-performance adhesive raw materials from CO_2 and bio-upcycling technology to produce useful chemicals from unused resources (see Chapter 3, Section 1 and Chapter 3, Section 2). In addition, RITE is participating in the NEDO "Moonshot" project to research and develop ocean degradable multilock biopolymers made from non-food biomass (see Chapter 3, Section 6).

In this overview, we first explain our core technologies such as "RITE Bioprocess"[*1] and "Smart Cell Creation Technology." Next, we discuss a national project based on bio x digital technology innovation, which has been making remarkable progress in recent years as a basic technology development, and finally, we introduce our efforts for commercialization.

2. The Core Technologies of RITE

2.1. "RITE Bioprocess"[*1]

"RITE Bioprocess"[*1], developed by RITE, is a proprietary technology that enables highly efficient production of biofuels and green chemicals, such as amino acids and aromatic compounds (Fig. 1). The three features of "RITE Bioprocess"[*1] are described below (for details, see RITE Today 2022).

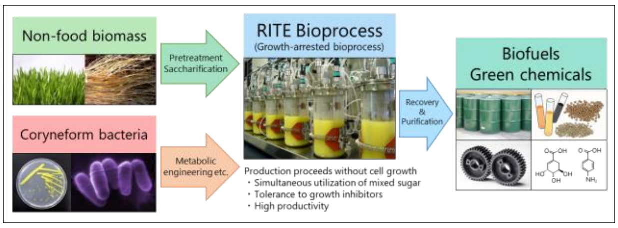

Fig. 1 Biorefinery concept using the "RITE Bioprocess"[*1]

Feature 1: Growth-arrested bioprocess

Anaerobic conditions and removing factors essential for proliferation allow the desired series of reactions to occur while cell division is arrested (Fig. 2). In other words, nutrients and energy previously used for multiplication are now used to produce the target substance. This has enabled microbial cells to be used extremely efficiently similar to a chemical catalyst, realizing a bioprocess with high productivity equal to or greater than that of ordinary chemical processes.

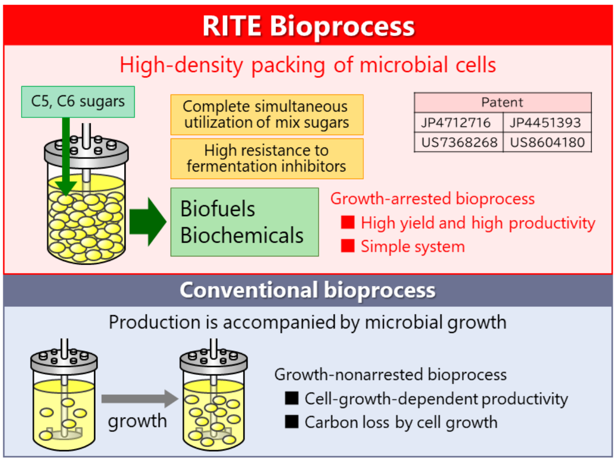

Fig. 2 Feature 1 of the "RITE Bioprocess"*1

(Growth-arrested bioprocess)

Feature 2: Complete simultaneous use of C5 and C6 mixed sugars

Most inedible biomass (cellulosic biomass) comprise a mixture of C5 sugars such as xylose and arabinose and C6 sugars such as glucose.

RITE has succeeded in increasing the utilization rate of C5 sugars to that of C6 sugars by introducing a C5 sugar transporter gene in addition to the C5 sugar metabolism gene (Fig. 3). This enables the full simultaneous use of C5 and C6 sugars and efficient use of cellulosic (non-food biomass) feedstock.

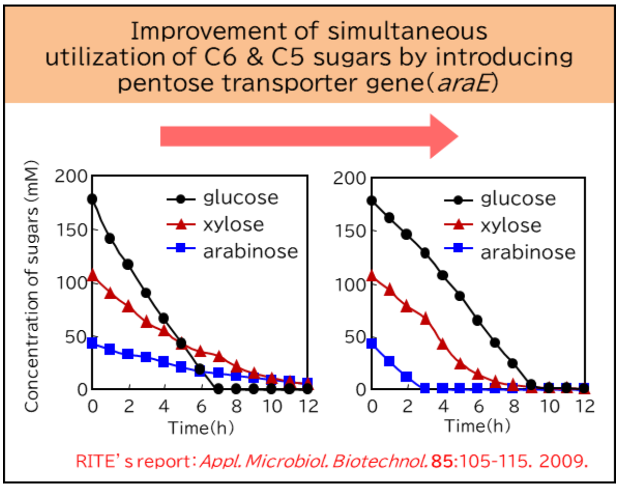

Fig. 3 Feature 2 of the "RITE Bioprocess"*1

(Simultaneous usage of mixed sugars)

Feature 3: High tolerance to fermentation inhibitors

"RITE Bioprocess"*1 has demonstrated high resistance to fermentation inhibitors because the microorganisms do not grow as described above (Fig. 4). Therefore, this can be applied to using saccharification liquids containing various fermentation inhibitors and even to producing fermentation inhibitors.

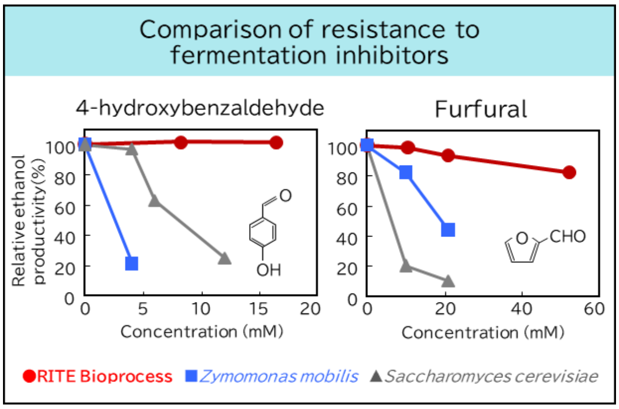

Fig. 4 Feature 3 of the "RITE Bioprocess"*1

(High tolerance to fermentation inhibitors)

2.2. Smart Cell Creation Technologies

With the fusion of cutting-edge biotechnology and digital technology, the potential of biological cells can be maximized to create "smart cells" that are optimized for biomanufacturing. This type of technology is called

Smart Cell Creation Technology and has made the development of smart cells dramatically more efficient. RITE is involved in developing these technologies by participating in the NEDO Smart Cell Project (2016–2020). During the project, we demonstrated the effectiveness of the Smart Cell Creation Technology by efficiently creating high-producing strains for the target chemical. By incorporating these technologies, RITE has succeeded in upgrading the production strain–breeding technology and fermentation-production technology (Fig. 5). Additionally, the Smart Cell Creation Technologies have been overtaken by the NEDO Bio-manufacturing project, and improvements are being made for the practical application of microbial production.

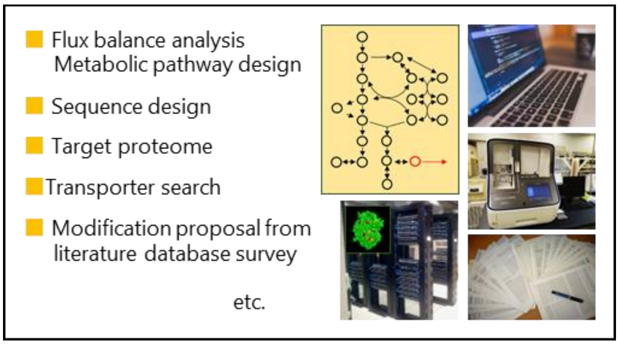

Fig. 5 Smart Cell Creation Technologies

2.3. Continuous Reaction System

RITE has developed biotechnological processes for producing various compounds. In this development activity, we have faced the problem that several target compounds have extremely strong cytotoxic effects, and production is halted because of the toxicity of the compounds that have accumulated during production. For example, catechol production, which is being developed in the NEDO Smart Cell Project and the NEDO Bio-manufacturing Project, plateaued after reaching a specific concentration in the conventional batch method. To avoid cytotoxicity and achieve high production, we constructed a continuous reaction system that selectively removes and recovers the target compound from the reaction system (e.g., by constructing a continuous reaction system that combines resin adsorption and membrane separation, Fig. 6). By applying this system to catechol production, a dramatically high production of catechol was achieved.

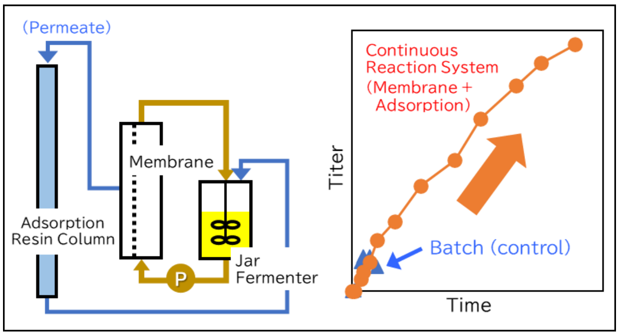

Fig. 6 A continuous reaction system using membrane separation and resin adsorption

2.4. Substances Produced by the "RITE Bioprocess"*1

Several materials currently in high production by RITE are shown in Figure 7. As mentioned above, the company has achieved world-class productivity in many substances. In biofuels, the company is expanding into production of butanol and high-performance biojet fuel materials in addition to that of ethanol and biohydrogen. Furthermore, in green chemicals, RITE is developing a wide range of high-performance chemicals such as aromatic compounds in addition to L-lactic acid, D-lactic acid, and amino acids.

Biofuels	Green chemicals
■ Gasoline additives ・Ethanol* ■ Bio-jet fuels ・Isobutanol* ・n-butanol* ・C9-C15 Saturated hydrocarbon + Aromatics ■ Biohydrogen *: Polymer raw materials Red character: World's highest productivity achieved	■ Aromatics ・Shikimic acid (Anti-influenza drug; Tamiflu raw materials) ・Phenol* (Phenolic resins, Polycarbonates) ・4-hydroxybenzoic acid* (Polymer raw materials) ・Aniline* (Natural resource tire (Age resistor)) ・4-aminobenzoic acid* (Pharmaceutical raw materials) ・Protocatechuic acid* (Cosmetic raw materials) ■ Organic acids ・D-lactate*, L-lactate* (Stereo-complex PLA) ・Succinate* ■ Amino acids ・Alanine (Chelators) ・Valine (Next-generation feed-use amino acids) ・Tryptophan (Next-generation feed-use amino acids) ■ Alcohols ・Isopropanol (Propylene raw materials) ・Xylitol (Sweetener)

Fig. 7 Substances produced using the "RITE Bioprocess"*1

3. Fundamental Technology Development (National Projects)

3.1. NEDO GI Fund Project[*2]

The GI fund project entitled "Promotion of carbon recycling using CO_2 as a direct raw material through biomanufacturing technology" aims to contribute to realizing carbon neutrality by developing new biomanufacturing products using CO_2 as a raw material and implementing them in society to transform the industrial structure by using CO_2 as a resource and to achieve "carbon neutrality by 2050."

In this context, RITE, in collaboration with Sekisui Chemical Co., Ltd, has started a project entitled "Commercialization of high-value–added chemicals using CO_2 as raw material through bioproduction technology" from FY2023 and is currently ongoing (project period: eight years from FY2023 to FY2030). (For details, see Special Feature)

3.2. Research and Development of Technologies to Promote Biomanufacturing[*2]

This project aims to solve both social issues such as environmental problems and economic growth by using unused resources such as discarded domestic biomass as raw materials and converting them into useful substances using biotechnology. (For details, see Special Feature).

3.3. NEDO Bio-manufacturing Project[*2]

The NEDO project "Development of bio-based product production technology to accelerate the realization of carbon recycling," also known as the Bio-manufacturing project, conducts research and development that combines biotechnology and digital technology to produce materials from biomass that does not depend on fossil resources (from 2020). The Smartcell Project is the predecessor of this project. This project aims to expand new bioresources, develop bioproduction processes including separation, purification, and recovery, and accelerate the creation of bioderived products by demonstrating industrial production systems. Specifically, teams in this project are conducting research and development in three areas: "Development of basic technology to promote the utilization of bioresources," "Development of basic technology for biofoundry production processes," and "Demonstration of industrial material production systems."

RITE has been involved in this project since the first year and is currently developing a new group of technologies (Industrial Smart Cell Creation Technology) to solve the problems associated with the practical application of biomanufacturing technology (Fig. 8). In FY2023, RITE mainly worked with partner research institutions to develop technology that eliminates productivity declines caused by uneven culture environments in large fermenters. RITE contributed to constructing and validating a fermentation-production simulation model by acquiring and providing detailed gene expression data and metabolite data in an environment that reproduces culture stress. By creating technologies to solve problems that may occur during large-scale production, we aim to eliminate rework in developing production strains and accelerate the social implementation of bio-based products.

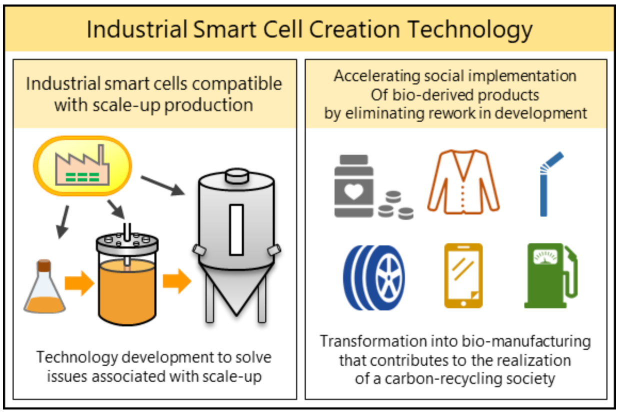

Fig. 8 Bio-manufacturing project: Development of Industrial Smart Cell Creation Technology

3.4. NEDO Bio-manufacturing Demonstration Project (Carotenoid)*2

Carotenoids are natural pigments produced by plants and some bacteria. They are popular as functional ingredients for lifestyle disease prevention and antiaging because of their high antioxidant activity, and their market size is growing. However, the carotenoid content in natural sources is low, and most of marketed carotenoids are produced by chemical synthesis from petroleum. Moreover, most carotenoids are characterized by low-absorption because of their chemical structure, and their bioavailability is also low. Several chemical processes that converting carotenoid structures from low- to high-adsorption types have been devised, but their conversion rates are unsatisfactory. Recently, as new sources of carotenoids, smart cells producing high amounts of carotenoids have been reported, but their carotenoids are also low-absorption types.

Since 2022, RITE has participated in the NEDO "Bio-manufacturing" project with Harima Chemicals, Inc. for social implementation of a bio-based mass production system for highly bioavailable carotenoids (Fig. 9). We have developed a smart cell that specifically produces high-adsorption types of carotenoids. We are currently improving the smart cell and developing other processes such as fermentation, carotenoid-extraction, and purification.

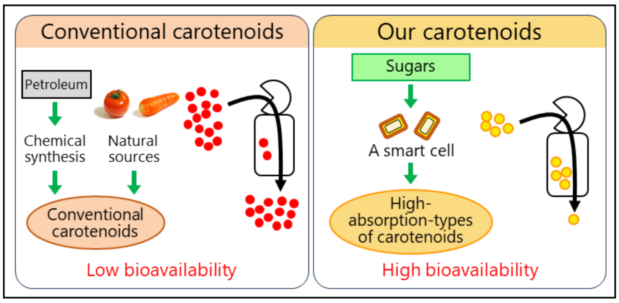

Fig. 9 Outline of our project for bio-based production of highly bioavailable carotenoids

3.5. NEDO Bio-manufacturing Demonstration Project (Rose Aroma Ingredient)*2

Since 2022, RITE has participated in the NEDO "Bio-manufacturing" project with Takasago International Corporation. We are driving the development of an "industrial smart cell" that can produce a rose aroma ingredient and a bioproduction system that can avoid microbial "product inhibition" derived from the fragrance materials (Fig. 10).

In FY2023, RITE succeeded in increasing the productivity by metabolic engineering and optimizing production conditions, by using the production system described above. We will continue with the improvement of the smart cells, testing of scale-up, and modification of the equipment. We aim to achieve Japan's first social implementation of production of a fragrance ingredient by precision fermentation.

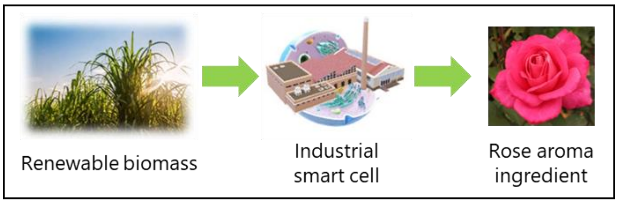

Fig. 10 Production of a rose aroma ingredient

3.6. NEDO Moonshot-type Research and Development Project*2

The project entitled "Development of Multilock Biopolymers Degradable in Ocean from Nonfood Biomasses" is performing research and development to introduce a "multilock mechanism" for plastic degradation (Fig. 11). Multiple stimuli such as light, heat, oxygen, water, enzymes, microorganisms, and catalysts can be used as triggers to start degradation of plastics, but avoid their degradation and maintain their durability and toughness while the plastics are in use. However, when accidentally dispersed into the marine environment, the multilock mechanism is unlocked to enable fast on-demand degradation.

Products targeted for practical application in this project include tires and textiles, which generate secondary fine debris when used, as well as plastic bottles, fishing nets and fishing tackle that contribute to ghost fishing, all of which negatively impact the environment due to runoff into the ocean.

In FY2023, we focused on developing a technology that enables the artificial control of the initiation timing of the degradation of multilocked plastics (Developments of new technologies using degradative enzymes). First, the thermostability of the enzyme was dramatically improved by electrostatic binding of the thermostable-plastic–degrading enzyme to a biodegradable carrier.

Next, we produced a film where the enzyme was mixed into plastic by thermal melting, exposed this to seawater, and succeeded in proving that rapid enzymatic degradation at the laboratory level (on-demand degradation) occurred.

We will aim to achieve faster on-demand degradation by improving the functionality of the plastic–degrading enzyme and optimizing the mixing conditions with the plastic. In addition to degradation tests in marine fields (e.g. Ainan Town, Ehime Prefecture), an international joint research with the U.S. Department of Energy's ARPA-E will be launched.
(The HP of the project can be found at:
http://www.moonshot.k.u-tokyo.ac.jp/en/index.html).

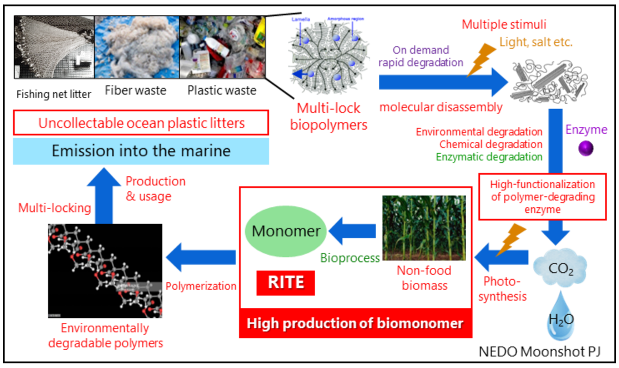

Fig. 11 Marine-degradable multilock biopolymers from nonfood biomass and their circulation

3.7. Japan Science and Technology Agency COI-NEXT

RITE has participated in the program on open innovation platform (COI-NEXT) commissioned by the Japan Science and Technology Agency. In the platform "Carbon Cultivation Hub Challenging the Limits of Carbon Negativity" started in 2023, we are working on developing biohydrogen production and liquid biofuel production technologies for establishing carbon-cultivation–based fuel-production technology. In this project, we will develop biological conversion technologies to efficiently produce fuels (hydrogen/ liquid fuel) from various biomass feedstocks in collaboration with the participant organizations working on developing biomass cultivation technologies, enabling an increase in CO_2 fixation by photosynthesis (Fig. 12). Hydrogen is expected to be the ultimate clean energy and is key in realizing carbon neutrality/negativity. In this context, a medium- to long-term theme is to develop CO_2-free hydrogen production processes. A short- to medium-term theme is to develop liquid fuel-production processes that use the same fundamental technologies as the other long-term theme. One of the key challenges for the social implementation of biomass fuel-production technology is reducing production costs. In addition, the components of biomass feedstock are diverse, and their composition considerably varies depending on the type of feedstock, making it difficult to meet a wide range of demands with uniform technology. To solve these issues, this project will promote the development of technologies in different fields, including various thermochemical and biological conversion technologies in an integrated manner for enabling the construction and expansion of a flexible biomass fuel supply system tailored to regional and feedstock needs.

RITE has developed a biohydrogen production process with high production rate. Building on this achievement, we are developing a microbial catalyst for improving the hydrogen yield from biomass-derived sugars to a large extent. We constructed a genetically engineered microorganism with a novel hydrogen production pathway enhanced by metabolic engineering. In addition, RITE has established a bioprocess that efficiently converts mixed C6 and C5 sugars to ethanol. Using this technology, we will develop an alcohol to jet process to produce a sustainable aviation fuel using various biomass feedstocks, such as energy crops, rice with high CO_2 fixation capability, and microalgae with high carbohydrate productivity.

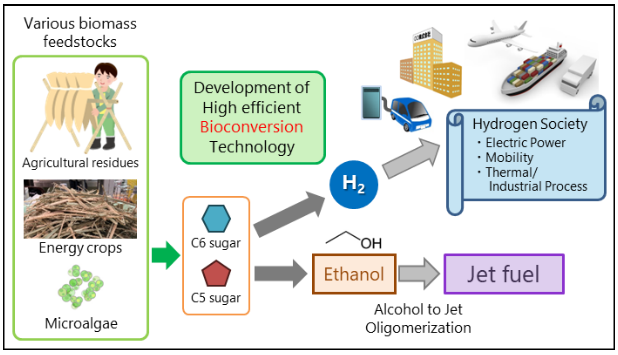

Fig. 12 Development of biohydrogen/bioethanol production technologies

4. Future Industrialization of Our Technologies

4.1. Green Chemicals Co., Ltd. (GCC)

(Head Office･Laboratory: in Kyoto headquarters, RITE; Shizuoka Laboratory: in Shizuoka plant, Sumitomo Bakelite Co., Ltd.) (Click here for GCC)

In February 2010, RITE established the "Green Phenol and High-Performance Phenolic Resin Production Technology Research Association" (GP Association) with and Sumitomo Bakelite Co., Ltd. to develop fundamental technologies related to phenol production and phenolic resin production through the application of bioprocesses that use cellulosic raw materials (non-food biomass).

In May 2014, the GP Association was reorganized as "Green Phenol Development Co., Ltd." (GPD). This was the first example of demutualization of a technology research association.

In April 2018, given that GPD technology can produce useful compounds in parallel with phenol production, the trade name of Green Phenol Development Corporation was changed to Green Chemicals Co., Ltd., (GCC).

Since the phenol-producing technology and knowledge of Green Chemicals Co., Ltd can be applied to producing other aromatic compounds (Fig. 13), we are developing a bioprocess for other high-value–added chemicals and commercializing products that meet customer needs.

In FY2023, approval for industrial use of the two production strains of GCC's products (4-HBA, PCA) was obtained by the Ministry of Economy, Trade and Industry.

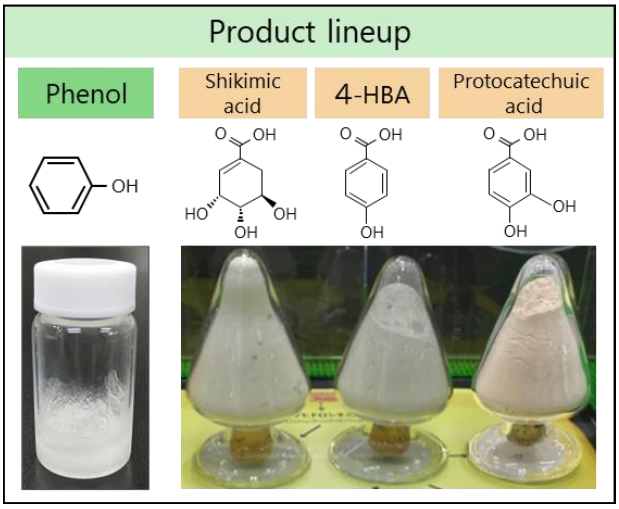

Fig. 13 Major product lineup of Green Chemicals Co., Ltd.

4.2. Green Earth Institute Co., Ltd.

(Head office: 6F Q Plaza Shinjuku 3-chome, 3-5-6 Shinjuku, Shinjuku-ku, Tokyo, Laboratory: 2-5-9 Kazusa-kamatari, Kisarazu-shi Chiba)

(Click here for the Green Earth Institute Inc. web site)

In September 2011, RITE established the Green Earth Institute Inc. to commercialize "RITE Bioprocess"[*1]. In December 2021, due to successful business results, the company was listed on the Tokyo Stock Exchange (Mothers), and in April 2022, moved to the Tokyo Growth Market due to market reorganization.

Currently, the company is promoting research and development with domestic and overseas partner companies, including "Biofoundry Base" (based on the government's "Biostrategy 2020), NEDO's "Green Innovation Fund Project," and NEDO's "Bio-manufacturing Revolution Promotion Project."

4.3. Joint Research with Companies

In addition to the main substances produced (see Chapter 2, Section 4) introduced in this overview, we are conducting joint research on many other substances in response to requests from companies.

In addition to Harima Chemicals, Inc. and Takasago International Corporation, in the NEDO Bio-manufacturing Demonstration Project, we are also conducting joint research with many other companies. These include research and development to convert a company's product (fossil resource-derived material) to bioderived materials at an early stage, as well as research and development to convert company's main products or main raw materials (fossil resource-derived materials) to bioderived materials in the medium to long term.

5. Closing remarks

In recent years, technological innovations and new knowledge and methods in the aforementioned "bio x digital technology" have dramatically improved the efficiency of smart cell development, especially in the national projects described in Chapter 3. And production demonstration efforts are vigorously underway for social implementation of the smart cells created by these results. These are expected to create a new industry (smart cell industry) and have a significant ripple effect on the industrial sector (manufacturing) in addition to the energy sector (Fig. 14).

RITE will continue to promote the development of bio-manufacturing technologies that contribute to carbon neutrality by utilizing the "Smart Cell Creation Technology" and "RITE Bioprocess"[*1] to focus on research and development using unused resources and CO_2 in the atmosphere as raw materials, as well as the development of practical production technologies for green chemicals.

Since the declaration of "carbon neutrality by 2050" in October 2020, inquiries from companies have been increasing, and the number of joint research projects with companies has also been increasing. RITE is still looking for companies to collaborate with. Compounds that have generally been considered difficult to produce by microorganisms may be produced at high levels by using the latest elemental technology development results. If you have a compound you would like to biologize, we would like to hear from you.

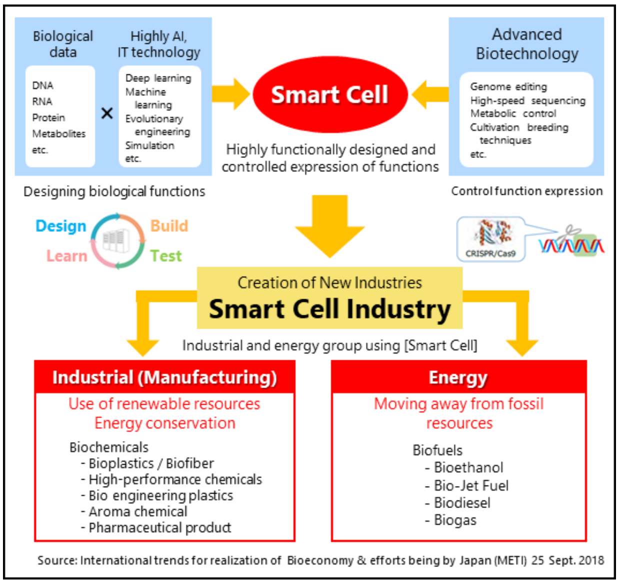

Fig. 14 Fusion of industrial / energy fields impacted by new bio and digital technologies

[*1] "RITE Bioprocess" is a registered trademark of RITE.

[*2] This article is based on results obtained from a project commissioned or subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

Chemical Research Group

Members (as of April 2024)

Katsunori Yogo	Group Leader, Chief Researcher
Masahiko Mizuno	Deputy Group Leader, Chief Researcher
Hidetoshi Kita	Chief Researcher
Naoki Kikuchi	Deputy Group Leader, Associate Chief Researcher
Masahiro Yamada	Deputy Group Leader, Associate Chief Researcher
Narutoshi Hayashi	Associate Chief Researcher
Firoz Alam Chowdhury	Associate Chief Researcher
Teruhiko Kai	Senior Researcher
Tomohiro Kinoshita	Senior Researcher
Junichiro Kugai	Senior Researcher
Kazuya Goto	Senior Researcher
Masahiro Seshimo	Senior Researcher
Toshinori Muraoka	Senior Researcher
Makoto Ryoji	Senior Researcher
Fuminori Ito	Researcher
Yusuke Ohata	Researcher
Takayasu Kiyokawa	Researcher
Shuhong Duan	Researcher
Vu Thi Quyen	Researcher
Lie Meng	Researcher
Soji Yamaguchi	Researcher
Yoshiyuki Kubota	Researcher
Aoi Torigoe	Researcher
Hiroaki Maeda	Researcher
Hanako Araki	Research Assistant
Hiromi Urai	Research Assistant
Noriko Onishi	Research Assistant
Hidenori Ogata	Research Assistant
Kumiko Ogura	Research Assistant
Mai Kashima	Research Assistant
Kozue Kataoka	Research Assistant
Keiko Komono	Research Assistant
Rie Sugimoto	Research Assistant
Takashi Teshima	Research Assistant
Yuko Nara	Research Assistant
Yozo Narutaki	Research Assistant
Akiyoshi Fujii	Research Assistant
Yoichi Fujiwara	Research Assistant
Yuko Miyaji	Research Assistant
Keiko Mori	Research Assistant
Misato Mori	Research Assistant
Atsushi Yasuno	Research Assistant
Takahiro Yoshii	Research Assistant
Naomi Yoshino	Research Assistant
Junko Yonezawa	Research Assistant

Challenges Associated with the Advanced Industrialization of CO_2 Capture and Utilization Technologies

1. Introduction

The Chemical Research Group, including the R&D division and industry collaboration division, has carried out activities to achieve the technical breakthroughs needed to realize solutions for early-stage practical application and industrialization of various technologies related to CO_2 capture and utilization (CCU). The current research topics of the Chemical Research Group are described as follows.

2. Technologies for CO_2 capture and utilization

The Paris Agreement was adopted at COP 21 in December 2015, and in order to minimize the adverse effects of climate change, such as abnormal weather, the rise in global average temperature before the Industrial Revolution was kept well below 2°C. Pursuing efforts to keep the temperature down to 1.5°C was the goal. After that, in response to the heightened sense of crisis, such as further temperature rises and the enormous natural disasters occurring on a global scale, the Glasgow Climate Agreement at COP 26 in November 2021 demonstrated the determination to pursue efforts to limit the temperature rise to 1.5°C with the world's first numerical target of 1.5°C. According to the IPCC, the 1.5°C target requires a 45% reduction in CO_2 by 2030 compared to 2010 and net zero by 2050.

In May 2022, the Clean Energy Strategy was formulated by the Ministry of Energy, Trade and Industry

(METI), and under the strategy, a practical roadmap for *carbon capture and storage* (CCS) was developed. The long-term plan set a goal of storing approximately 120 to 240 million tons of CO_2 by 2050, and seven CCS projects within Japan have been selected to accomplish the storage of CO_2 goal. *Carbon dioxide capture, utilization, and storage* (CCUS) and carbon recycling is an important innovative technology that enables carbon neutrality. In CCUS/carbon recycling, the combination of captured CO_2 is recycled as a carbon resource for fuels and materials (CCU), and the captured CO_2 storage under the ground (CCS) is expected to have a significant CO_2 reduction effect. Furthermore, it has been shown that CO_2 separation and capture technologies are the basis for CCUS, and the targets for the technologies are to reduce the cost of CO_2 separation and capture to 1,000 yen/t-CO_2 by 2050 and to establish CO_2 separation and capture technologies for various CO_2 emission sources. Negative emission technology, which contributes to the reduction in the concentration of CO_2 in the atmosphere, is required to achieve carbon neutrality. In particular, direct air capture (DAC) of CO_2 from the atmosphere has been attracting attention recently. In the Carbon Recycling Technology Roadmap (Ministry of Economy, Trade and Industry) revised in July 2021, DAC was added as a new technology field in progress. Carbon management, which involves the utilization, reduction, and storage of CO_2 in Carbon Dioxide Removal (CDR) and Carbon Capture, Utilization, and Storage (CCUS) initiatives, is gaining momentum.

Against this background, it is necessary to promote the practical application of CCUS by proposing optimal separation and capture technologies for the various CO_2 emission sources and CO_2 utilization technologies. In particular, in order to introduce and put into practical use CCS, which is expected to reduce CO_2 on a large scale as a measure to address global warming, it is important to reduce the cost of CO_2 capture from large-scale sources. In parallel, promotion of the standardization of CO_2 capture technologies is also important. It is necessary to establish a common evaluation standard for the various CO_2 capture materials, while keeping pace with the international trends in this field. CCU (utilization) implementation into society as soon as possible is also highly needed. It is important to develop innovative CO_2 utilization and carbon recycle technologies to effectively convert CO_2 into chemicals and fuels.

The Chemical Research Group is dedicated to developing innovative CO_2 capture and utilization technologies and to providing world-leading R&D and innovation results with a special focus on chemical absorption, adsorption, and the membrane separation process. Our research topic covers the development of new materials and their innovative manufacturing processes and high-efficiency carbon capture systems and membrane reactors. As for chemical absorption, the solvent developed in COURSE50 (Development of Environmental Technology for Steelmaking Process as commissioned by the New Energy and Industrial Technology Development Organization [NEDO]) has been put into practical use in a commercial CO_2 capture plant owned by a private Japanese company.

For adsorption, pilot-scale tests of solid sorbents with good CO_2 desorption performance at low temperatures and adsorption systems are being conducted in collaboration with private companies in a project commissioned by NEDO using flue gas from coal-fired power plants. The solid sorbents technology is also applied to the low CO_2 concentration carbon capture from the gas at natural gas-fired power plants that featured not only low temperature regeneration but also high residence to oxidation degradation. Furthermore, Direct Air Capture (DAC), which captures CO_2 from the atmosphere, is proceeding as the NEDO Moonshot Research and Development Project.

The membrane-separation-based carbon capture technology is developed for potential high-pressure CO_2/H_2 separation in the Integrated Coal Gasification Combined Cycle (IGCC) and hydrogen production plants. Starting from 2024, sponsored by NEDO, a compact medium-pressure hydrogen production system (CO_2 captured hydrogen production system) will be developed and will be demonstrated in field tests.

Efforts have also been devoted to the standardization for CO_2 capture.

Awarded by the NEDO project to establish a common base for evaluating CO_2 separation materials, Japan's first Real-Gas Test Center will be built at RITE (construction to be completed in 2024), and the standard methods with the use of real gas will be established. As the only organization in Japan that is a member of the International Test Center Network (abbreviated ITCN, a global association of facilities around the world that promote research and development of CO_2 capture technology), RITE regularly exchanges information with overseas ITCN members. Through ITCN, our efforts towards standardization of CO_2 capture will be disseminated throughout the world.

As for effective CO_2 utilization technology, we have been developing carbonate fixation utilization amine technology and methanol synthesis utilization dehydration membrane technology. In carbonate fixation, calcium and magnesium from industrial waste are fixed by reacting with CO_2 from the flue gas. By using amines, liquid calcium and magnesium are extracted and after reacting with CO_2, high-purity calcium or magnesium carbonate are produced. In methanol synthesis, CO_2 emitted from power plants, steel mills, cement plants, and chemical facilities reacts with hydrogen in a membrane reactor to synthesize methanol at high efficiency. We were awarded a NEDO project for optimal system development for methanol synthesis from CO_2 jointly with a private company in FY 2021.

3. Chemical absorption method for CO_2 capture

In the absorption method, CO_2 is separated by using the selective dissolution of CO_2 from a mixed gas into a solvent. In particular, the chemical absorption method based on the chemical reaction between amine and CO_2 in a solvent can be applied to gases with a relatively low CO_2 concentration, such as combustion exhaust gas, and the method is one of the most mature CO_2 capture technologies developed. In the COCS project (METI's Subsidy Project) and the COURSE50 project (NEDO consignment project), RITE has been working to develop a high-performance amine solvent that reduces the cost of CO_2 capture.

The chemical absorbent and process created by the COURSE50 project were adopted by the energy-saving CO_2 capture facility ESCAP® of Nippon Steel Engineering Co., Ltd. (Fig. 1)

Fig. 1. Equipment of energy-saving CO_2 absorption process ESCAP® at Niihama Nishi power station, Sumitomo Joint Electric Power Co., Ltd.
(This is the second commercial plant and produces CO_2 for chemical production.)

Although the chemical absorption method for CO_2 capture is mature, in order to accelerate CCUS, we still have to overcome technological issues of cost reduction and practical implementation. In particular, R&D to decrease energy consumption in a solvent regeneration process and enhancement of amine durability for a stable long-term operation are required.

In COURSE50, we also demonstrated the new technological concept with the possibility of further reducing energy consumption by using the absorption solvent with an organic compound instead of water (Fig. 2). We call the new technology *mixed solvent*, which can control the reaction mechanism of CO_2 absorption and the effect of polarization.

Since 2022, we have been working to develop novel compounds and optimal formulations of the mixed solvents for practical use under the NEDO Green Innovation Fund Project for the development of hydrogen reduction technology using blast furnaces. In January 2024, bench-scale plant tests started at the Kimitsu Steelworks of Nippon Steel Corporation. The new high-performance mixed solvents developed by RITE are evaluated using actual blast furnace gas.

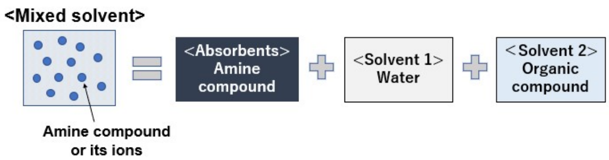

Fig. 2. Concept of mixed solvent

4. Solid sorbent method for CO_2 capture

Unlike a chemical absorbent where amines are dissolved in a solvent, such as water, a solid sorbent is one where the amines are supported on a porous material, such as silica or activated carbon. In the process of using a solid sorbent, reduction of CO_2 capture energy can be expected because the heat of vaporization and sensible heat caused by the solvent can be suppressed.

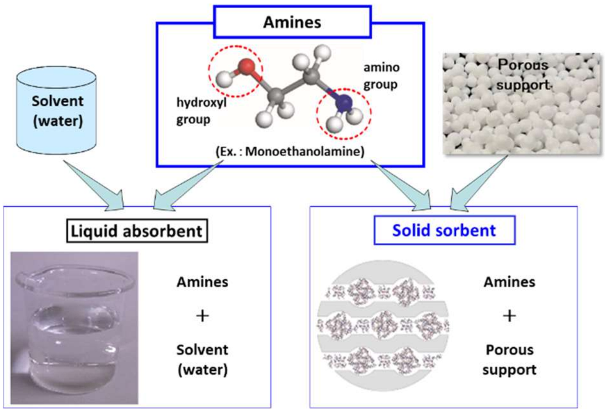

Fig. 3. Liquid absorbent and solid sorbent

1) For coal-fired power plants

In 2010, RITE started the work to develop solid sorbent materials for CO_2 capture from the combustion exhaust gas of coal-fired power plants (METI consignment project). In the fundamental research phase (FY 2010–2014), we created a new amine suitable for solid sorbents, and in a laboratory scale test with the new amine, we obtained the prospect of capture energy of 1.5 GJ/t-CO_2 or less. This solid sorbent system is an innovative material that enables not only low energy capture but also a low temperature process at 60°C. Compared to other technologies that use amine-based solid absorbents, this technology is at the top level globally in terms of low-temperature regeneration.

In the practical application research phase (METI/NEDO consignment project) from FY 2015 to 2019 with Kawasaki Heavy Industries, Ltd., (KHI) as a partner, we conducted scale-up synthesis of solid absorbent (>10 m^3), bench scale tests (>5 t-CO_2/day), and real-gas exposure tests at a coal-fired power plant.

In 2020, RITE was chosen for the NEDO commissioned project with KHI. In this project, with the cooperation of Kansai Electric Power Co., Inc., KHI completed trial operation of the pilot scale test facility (40 t-CO_2/day scale) constructed at the Maizuru power plant. In the second half of 2023, CO_2 capture tests have started using the solid sorbent supplied by RITE against flue gas from the combustion exhaust gas emitted from the coal-fired power plant. (Fig. 4)

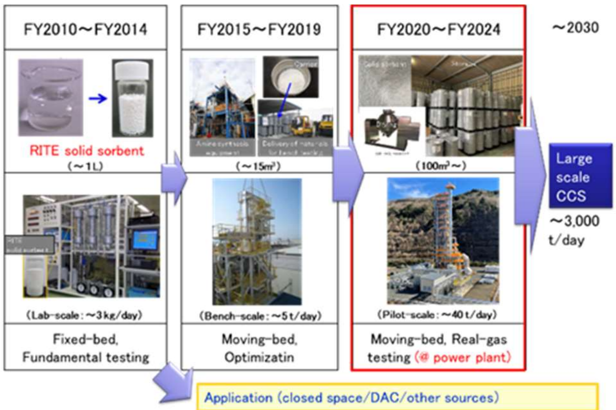

Fig. 4. Development roadmap of solid sorbent method for CO_2 capture

We are now working on elucidating the material deterioration mechanism to develop deterioration prevention technology, studying reuse technology for used solid sorbent, and studying efficient operating conditions using process simulation technology.

For process simulation technology, we are developing a simulator that can predict the amount of CO_2 captured and the energy used for separation and capture with high accuracy in KHI's moving bed system. (Fig. 5)

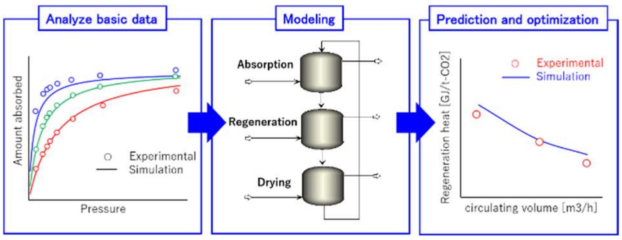

Fig. 5. RITE's simulation technology

In the pilot test, we plan to optimize the operating conditions using this simulation technology.

In addition, the simulation is useful for understanding the adsorption and desorption behavior inside the facility, which is difficult to observe in practice, and the calculation results are also used in material development.

2) For natural gas-fired power plants

In 2022, the Technology Development Project of CO_2 Separation and Capture in the Green Innovation Fund project started jointly with Chiyoda Corporation (organizer company) and JERA in order to commercialize low-cost CO_2 separation and capture processes from natural gas combustion exhaust gas.

The CO_2 concentration contained in natural gas combustion exhaust gas is around 4%, which is lower than the CO_2 concentration in coal combustion exhaust gas (13%), and the oxygen concentration is as high as about 10%. Therefore, solid sorbent materials with high CO_2 absorption performance even at low CO_2 concentrations and high durability against oxidation are required. RITE is in charge of the development of amines based on the knowledge and technology accumulated during the R&D histories in this field, in addition to the development of solid sorbent materials composed of developed amines and optimal support.

The stage gate for this project is set for FY 2024, and we have succeeded in developing a solid sorbent that will achieve the target this year. The developed solid sorbent is characterized not only by the fact that it can be regenerated at low temperatures but also by its excellent resistance to oxidative degradation (Fig. 6). Therefore, the sorbent can be applied to natural gas-fired power plant exhaust gases with relatively high oxygen concentrations.

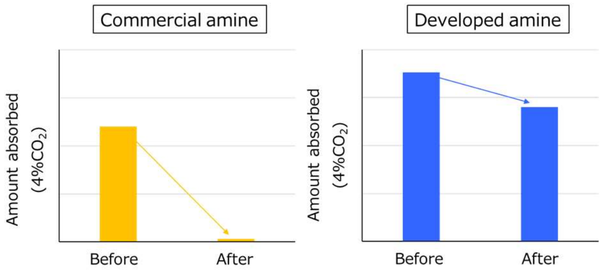

Fig. 6. Comparison of commercial and developed amines by oxidative degradation test. Both y-axials show the same values.

5. Membrane separation

CO_2 separation by membranes involves the selective permeation of CO_2 from the pressure difference between the feed side and the permeate side of the membrane. So, CO_2 capture at low cost and low energy is expected by applying the membrane processes to pre-combustion (Fig. 7). For this reason, we are currently developing novel CO_2 selective membrane modules that effectively separate CO_2 for precombustion.

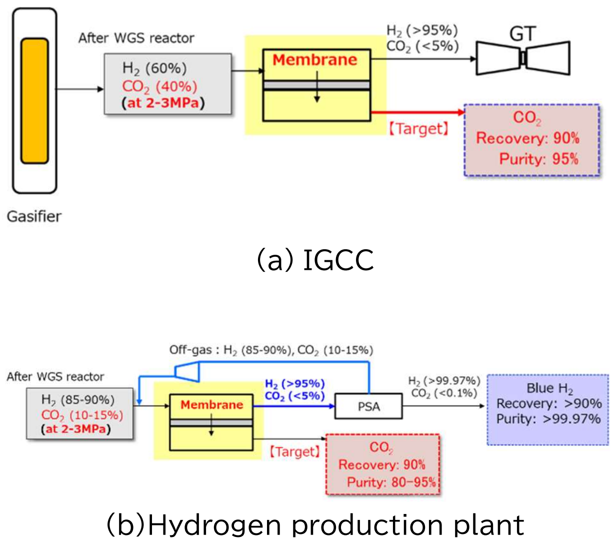

Fig. 7. Schematic of the IGCC and hydrogen production plant with CO_2 capture by CO_2 selective membrane modules

We found that novel polymeric membranes composed of dendrimer/polymer hybrid materials (termed molecular gate membranes) exhibited excellent CO_2/H_2 separation performance. Fig. 8 presents a schematic that summarizes the working principles of a molecular gate membrane.

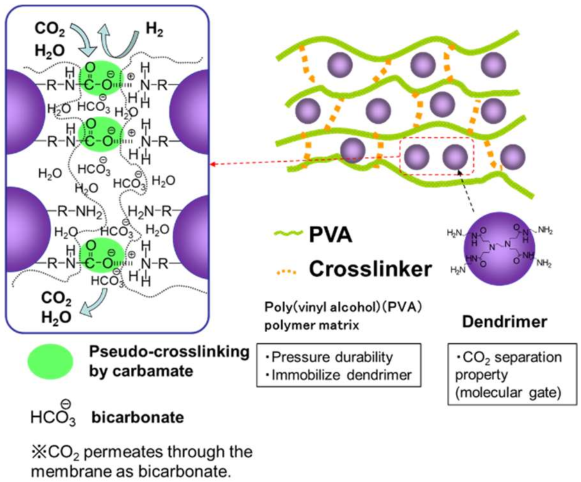

Fig. 8. Schematic illustration of the working principles of the molecular gate membrane

Under humidified conditions, CO_2 reacts with the amino groups in the membrane to form either carbamate or bicarbonate, which then blocks the passage of H_2. Consequently, the amount of H_2 diffusing to the other side of the membrane is greatly reduced, and high concentrations of CO_2 can be obtained. A poly (vinyl alcohol) (PVA) polymer matrix is used for pressure durability and to immobilize the dendrimers.

We developed new types of molecular gate membranes that provide superior separation of the CO_2/H_2 gas mixtures. Based on this work, the Molecular Gate Membrane module Technology Research Association (MGMTRA consists of the Research Institute of Innovative Technology for the Earth [RITE] and Sumitomo Chemical Co., Ltd.) is conducting research in new membranes, membrane elements, and membrane separation systems.

In the NEDO project, CO_2 Separation Membrane System Practical Research and Development/Development of CO_2-H_2 Membrane Separation Systems using High-

Performance CO_2 Separation Membrane Modules, we conducted practical research and development to improve the separation performance and durability of the membrane elements, scale up the membrane modules, and design membrane systems suitable for the CO_2 utilization process based on previous results.

As for the development of membrane materials, we modified the membrane materials for a new application (small-scale, medium pressure hydrogen production equipment). As a result, separation performance under the medium pressure was improved as shown in Fig. 9.

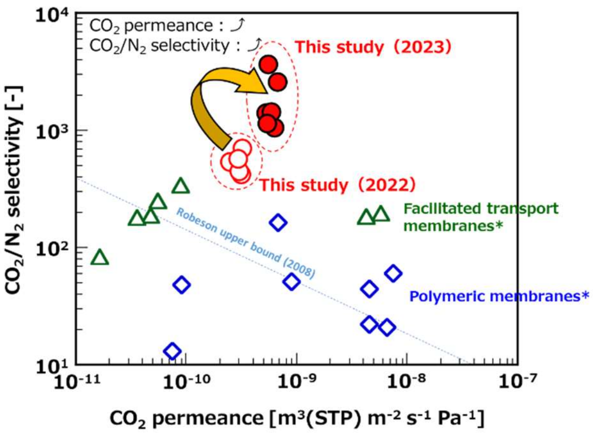

Fig. 9. CO_2/N_2 Separation performances of MGM membranes.

Operating conditions of molecular gate membranes: temperature 85°C, total pressure 0.85 MPa, feed gas composition CO_2/N_2=20/80.

*Reference: Kamio et al., *J Chem Eng Jpn* 56 (2023) 2222000.

By modification of membrane materials, both CO_2 permeance and CO_2/N_2 selectivity increased compared with our previous modified membranes (in 2022). The separation performance required to apply the membranes for use with hydrogen production equipment was obtained.

As for the development of the membrane elements, we succeeded in developing commercial-size membrane elements (ϕ = 20 cm, L = 60 cm) (Fig. 10). As of FY 2024, we set the new application (small-scale, medium pressure hydrogen production system [hydrogen production equipment with CO_2 capture]), and we will develop membrane module systems and conduct field tests.

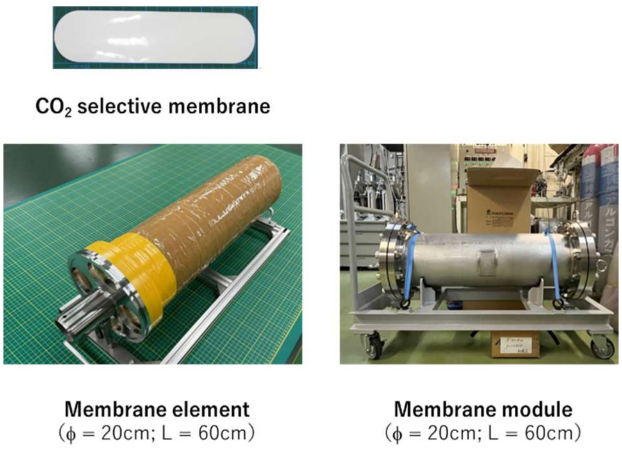

Fig. 10. CO_2 selective membrane, membrane element, and membrane module.

Membrane element: The structure with a large membrane area composed of the membrane, support, and spacer.

Membrane module: The structure in which the membrane element is placed.

6. CO_2 capture technology from the atmosphere

NEDO's Moonshot R&D Program was launched in FY 2020 as one of the systems to support the action plan of the Environment Innovation Strategy, which aims to establish technologies that enable Beyond Zero by 2050.

RITE is working to develop technologies for high-efficiency CO_2 capture from the atmosphere and carbon circulation in cooperation with Kanazawa University and Mitsubishi Heavy Industries, Ltd., in the (1) Development of technologies to capture, convert, and detoxify greenhouse gases of Goal 4 "Realization of sustainable resource circulation to recover the global environment by 2050."

The technology for capturing CO_2 directly from the atmosphere called Direct Air Capture (DAC) is expected to be one of the negative emission technologies. Seven research themes on DAC, including the RITE's theme, have been adopted in the Moonshot R&D Project, and six of them are still ongoing in 2023. Fig. 11 shows our R&D items and a carbon cycle society as our goal.

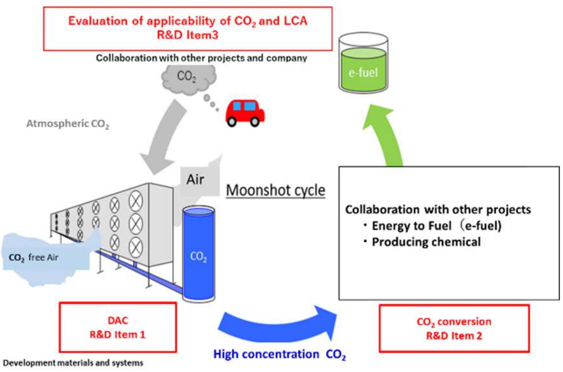

Fig. 11. Development of highly efficient DAC and carbon recycling technologies

RITE is developing new amines suitable for DAC and structured solid sorbents that show low-pressure drops at a high flow rate and low energy consumption in CO_2 desorption. The fundamental properties of both amines and structured sorbents are collected using lab testing equipment (Fig. 12), CO_2 capture performances of real-sized sorbents are evaluated using DAC system evaluation equipment (Fig. 13, designed by Mitsubishi Heavy Industry Co., Ltd., and built on the RITE premises), and improved sorbent structure and optimized operation conditions are predicted by process simulation. Pilot-scale testing (0.5 t-CO_2/day at the maximum) is scheduled for 2025 at Expo 2025 Osaka, Kansai, Japan. Manufacturing of solid sorbents and the pilot-scale DAC system is underway.

Fig. 12. Lab test equipment for DAC

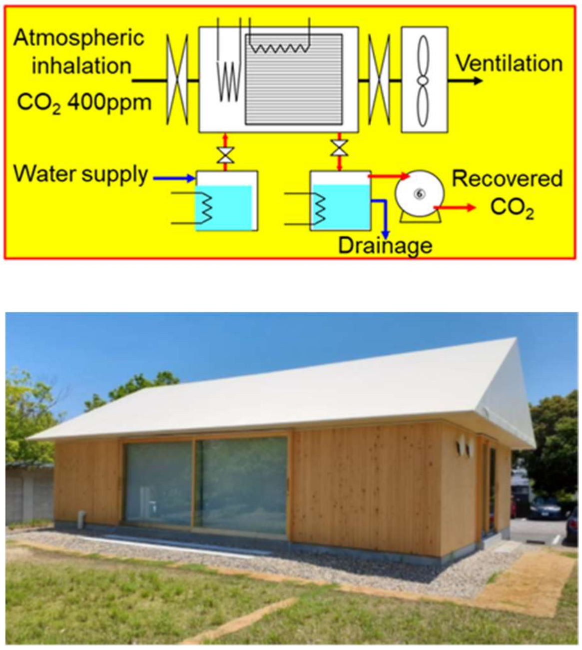

Fig. 13. Schematic image of DAC system evaluation equipment (upper) and DAC experimental laboratory in RITE premise (below)

7. Common evaluation standard for CO_2 capture materials

In order to move toward decarbonization, fuel and energy sources in both the power and industrial sectors are shifting to renewable energy sources, but a certain amount of fossil-fuel-based thermal power generation remains to meet electricity demand, and CO_2 emissions are inevitable. Therefore, it is necessary to develop low-energy-consumption and low-cost technologies for CO_2 capture from low-pressure and low-concentration mixed gas, for example, a natural gas combustion gas of 10% or less with relatively low CO_2 concentrations.

Since 2022, RITE has been conducting the NEDO Green Innovation Fund Project for the establishment of a common evaluation standard for CO_2 capture materials in collaboration with the National Institute of Advanced Industrial Science and Technology (AIST). Along with the vision of the realization of a carbon neutral society, a common base for CO_2 capture materials will be established, and it will support the enhancement of domestic companies' global share of the expanded CO_2 capture market.

The project is scheduled for the nine years from 2022 to 2030 (the first stage: 2022–2024) and will carry out the following R&D objectives: (a) formulation of standard evaluation methods using actual gas (installation and operation of the test center), (b) establishment of standard evaluation methods for development of innovative capture materials, (c) development of durability evaluation methods, and (d) database construction and the spread of the standard evaluation methods.

RITE will formulate standard performance evaluation methods using actual gas and develop a test center in the first stage up to FY 2024 in order to evaluate CO_2 capture materials at the flue gas conditions of power plants and boilers. The test center will be constructed at the RITE headquarter site in Kyoto. Three different test facilities for absorption, adsorption, and membrane processes will be installed there, and a natural gas combustion boiler will be the source of actual flue gas (Fig. 14). The basic engineering of the test center was completed in FY 2023.

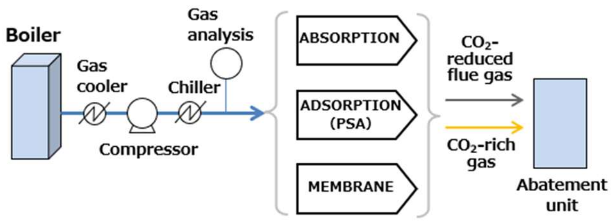

Fig. 14. Schematic of the test units for absorption, adsorption and membrane.
(Each unit capacity: –100 kg-CO_2/day)

In recent years, in the development of CO_2 capture materials for carbon neutrality, test centers for CO_2 capture technologies have been established throughout the world, but such a test center has not been organized in Japan. We exchange opinions on a CO_2 capture test center with domestic companies in the project and built cooperative relationships with overseas organizations, especially with ITCN (International Test Center Network) members. RITE will provide the first real gas test center in Japan, which is used by companies and institutions involved in the development of CO_2 capture materials. It will contribute to the promotion of domestic CO_2 capture materials development so that Japan will continue to be the world's top operator of CO_2 capture technologies.

8. Effective methanol synthesis from CO_2 hydrogenation

Carbon dioxide (CO_2) is one of the causes of global warming; therefore, a significant reduction is a critical global challenge and attaches special important to Carbon Capture and Utilization (CCU) technologies. On the other hand, CO_2 hydrogenation as a one of the utilization technologies that produces water and that causes deactivation of the catalyst and decreases the reaction rate. In order to solve these problems, we shed light on methanol synthesis using CO_2 as the raw material using a membrane reactor that combines the membrane and the catalyst.

At RITE, we successfully developed a novel hydrophilic zeolite membrane, which has higher hydrothermal stability and water/methanol permselective performance compared to conventional LTA-type zeolite membranes. This membrane was applied to the membrane reactor for methanol synthesis, and CO_2 conversion was achieved at a rate three times higher compared to the conventional packed-bed reactor. Currently, we are studying the possibility of extending the length of the developed dehydration membrane under the NEDO project Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation / Development, and Demonstration of Technologies for CO_2 Utilization, and have succeeded in synthesizing a practical length of dehydration membrane with comparatively high permeation and separation performance. We also succeeded in synthesizing a dehydration membrane with a practical length that has relatively high permeation separation performance. In addition, target values (H_2O permeability: 1 x 10^{-6} mol m^{-2} s^{-1} Pa^{-1}, H_2O/MeOH selectivity: >1,050) were achieved in the reaction temperature range for methanol synthesis. Notably, the long dehydration membrane exhibited high permeability at approximately twice the target value, an achievement that can be expected to improve methanol synthesis efficiency when applied to a membrane reactor (Fig. 15).

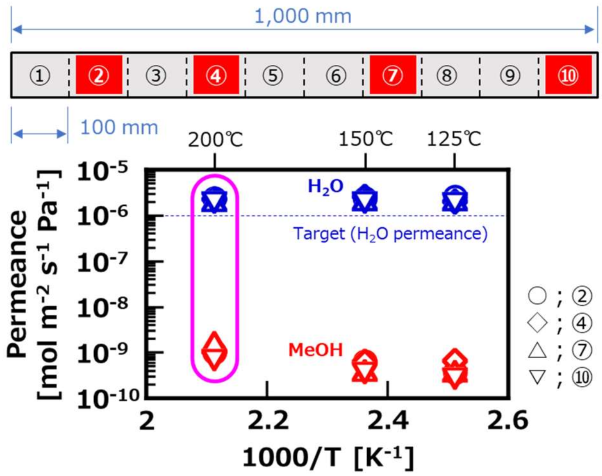

Fig. 15. Temperature dependence of H_2O/MeOH permselective performance though long-scale dehydration membrane (100 mm-cut sample).

Bench-scale membrane reactor tests equipped with multiple dehydration membranes of practical length with this performance are underway at JFE Steel (Fukuyama). We are also examining ways to improve the reproducibility of practical-length dehydration membranes, and have successfully synthesized a membrane as long as that of the lab-scale test (champion data in the figure) by carefully examining the synthesized membranes and as shown in Fig. 16. This performance was higher or comparable to that of dehydration membranes already commercially available (+ plot in the figure). In addition, compared to LTA-type zeolite membranes, which are commonly used dehydration membranes, the Si-rich LTA membranes are expected to have higher hydrothermal stability, which will enable their application in separation systems that have had difficulty applying LTA-type zeolite membranes.

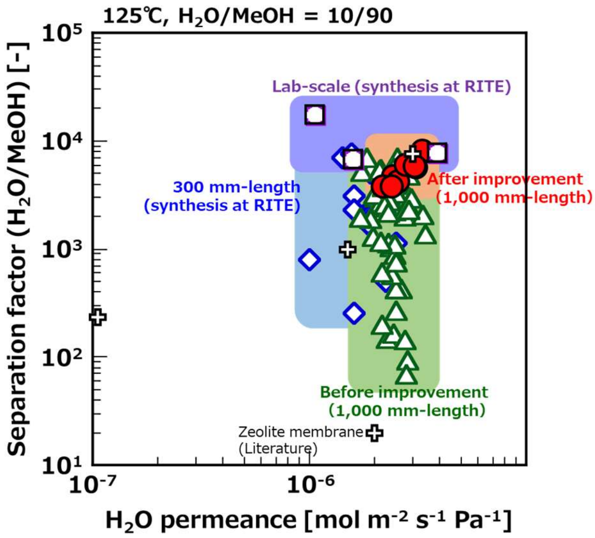

Fig. 16. H_2O/MeOH permselective performance though long-scale dehydration membrane

9. He recovery membrane

RITE has been developing silica membranes for hydrogen separation and has succeeded in producing various silica membranes that can permeate hydrogen produced from a variety of different reactions, including dehydrogenation of methylcyclohexane (MCH), one of the hydrogen carriers. The silica membrane was formed using the counter diffusion chemical vapor deposition (CVD) method (Fig. 17). Oxygen was supplied from inside of the porous support, and a silica source was fed to outside of that. When the pores are filled with silica, the reaction occurs preferentially in the unfilled areas, allowing for the reproducible formation of silica membrane with relatively high performance.

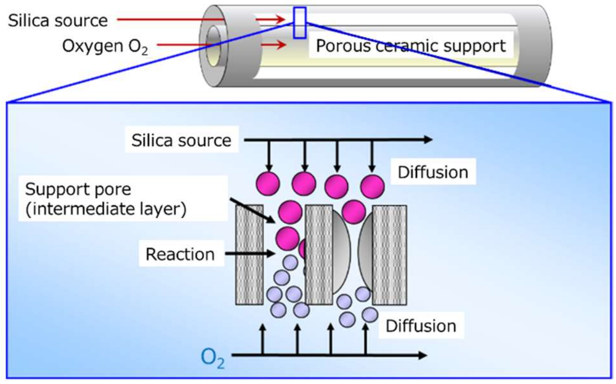

Fig. 17. Schematic diagram of counter-diffusion CVD method.

Recently, the global helium crisis has become an issue, and it is important to find a way to secure helium. Considering energy conservation, a method to recover helium using a membrane separation method that does not involve a phase change is considered the best option. The smallest molecular size of helium is 0.26 nm, and other small molecules are H_2: 0.29 nm, CO_2: 0. 33 nm, N_2: 0.36 nm, and CH_4: 0.38 nm. The silica membranes for hydrogen separation developed at RITE are considered to be sufficiently applicable to helium separation. Currently, we are studying the development of longer silica membranes for helium separation under the NEDO Leading Research Program / Leading Research Program for the Creation of New Industry and Innovative Technology / Development of Highly Efficient Helium Membrane Separation and Recovery Technology in Nonflammable Gas Fields entrusted by the Japan Fine Ceramics Center (JFCC).

10. CO_2 fixation

CO_2 fixation (CO_2 mineralization) has the same basic concept as enhanced weathering, which is one of the negative emission technologies. It is a technology that reacts CO_2 with alkaline earth metals and immobilizes it as a chemically stable carbonate, which is attracting attention as a CO_2 fixation technology that does not affect the ecosystem. In recent years, early implementation of

CO_2 fixation using byproducts and waste containing alkaline earth metals is expected to contribute to the building of a sustainable society.

RITE has a proprietary process that has been developed over many years for the fixation of CO_2 as carbonate, and since 2020, in collaboration with private companies, has been developing technology to extract alkaline earth metals from steel slag, waste concrete, and other materials in a wet process and recover CO_2 emitted from factories as a stable compound, as well as developing effective technology for the production of carbonate (Fig. 18).

With this process, energy savings have been achieved by lowering the reaction temperature and shortening the reaction time, and a process in which the liquid used once can be used again (application of regenerated liquid) has been established. It has also been shown that the process can be scaled up. In addition, by improving the solution used during extraction, a reduction in material costs can be expected. Based on the knowledge and information that has been acquired so far, studies are currently being conducted with the aim of industrialization.

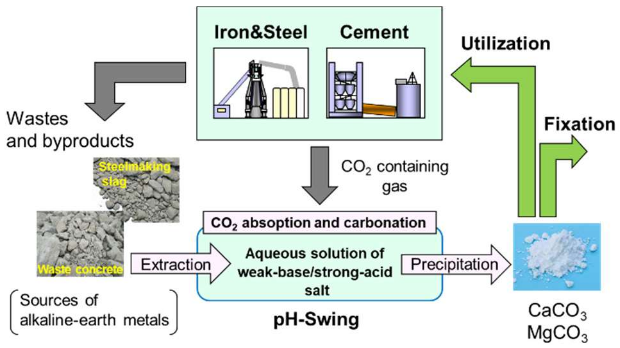

Fig. 18. CO_2 fixation as carbonates

11. Activities and efforts toward commercialization and industrialization

The core of the Industrial Collaboration Division is the Industrialization Strategy Council, which includes a total of 33 private companies (as of March 2024) and the Fine Ceramics Center, Inc., as a special member.

From FY 2023, activities were expanded to promote the following projects with the aim of establishing technologies for CO_2 separation and effective utilization that will contribute to innovative environmental and energy technologies. We are promoting a variety of activities, which include the following:

【General Activities】

(1) Sponsorship of research meetings
(2) Free seminars for members only
(3) Dissemination of information on needs and seeds and hot topics to members
(4) Sponsorship of symposiums

【Individual Activities】

(1) Plans for joint implementation projects funded by the government and NEDO
(2) Acceptance of researchers from council members to the Research Section of the IMeRC and the implementation of training workshops
(3) Offers for technical guidance from the IMeRC Advisory Board and Research Section
(4) Hosting exclusive technology seminars for council members

In FY 2023, two research group activities were launched: the CO_2 Separation and Recovery Research Group and the Membrane Reactor Research Group.

In the CO_2 Separation Study Group, the Chemical Research Group presented an overview of the DAC technology and topics of each DAC company.

In the Membrane Reactor Group, the Chemistry Research Group provided information on membrane reactors in general and CO_2-free hydrogen production in particular.

The members-only free seminars were held three times at the venue and online. Researchers from universities and private companies gave lectures on the latest

R&D trends and case studies on CO_2 capture and effective utilization, and active Q&A sessions took place.

In addition, we conducted patent and literature searches related to the information presented at the lectures and sent out *needs and seeds information* twice with comments from Chemical Research Group researchers, and *hot topics* once with the latest information from academic society topics, METI, and NEDO, contributing to the promotion of technological development and improvement of knowledge of the members.

Two member companies participated in poster presentations at the Symposium on Innovative CO_2 Capture and Effective Utilization held in February 2024.

12. Conclusion

The Chemical Research Group will continue to actively participate in the development of technology for CO_2 separation and capture from a variety of CO_2 emission sources. In future, the Chemical Research Group will be fully committed to the above-mentioned research topics. For carbon capture technologies in a stage very close to practical applications, we will conduct scale-up studies and tests under real-gas conditions with the aim of establishing the technology at an early stage for early implementation into society. It is necessary to develop technology that can handle low-concentration CO_2 emission sources. The negative emissions technologies, such as DACCS making a significant contribution to sustainable development scenarios for decarbonization, will be the focus. As the CO_2 concentration decreases, the amount of gas to be treated increases, and the oxygen concentration increases. The development of materials at low cost with higher deterioration resistance and its corresponding system is highly Important. We will accelerate the development of these technologies so that we can implement energy-saving and low-cost CO_2 capture technologies into our societies as soon as possible.

Specially, the chemical absorption process will be enhanced by the development of practical high-performance chemical solvents. For solid sorbents, we will steadily conduct a pilot test planned to start FY 2023 on a scale of 40 t-CO_2/day captured from flue gas at a coal-fired power plant and steadily develop new sorbents for natural gas-fired flue gas. Regarding the DAC technology, we will accelerate the system development and sorbent manufacturing for a bench-scale on-site demonstration at Expo 2025 Osaka, Kansai. As for membrane separation, the project of a compact medium-pressure hydrogen production system started from 2024. About the establishment of a common base for evaluating CO_2 separation materials, the construction of the Real-Gas Test Center will be completed in 2024, and the test using real gas will be initiated.

Also, efforts will be continuously devoted for the effective utilization of the captured CO_2 and hydrogen production technologies for that purpose. We will develop technology for CO_2 fixation into carbonates using steel slag and waste concrete and then explore technology for recycling CO_2 into fuel and chemical feedstocks. Furthermore, we will further strengthen the cooperation with the carbon capture industry through the establishment of the Real-Gas Test Center and the activities of the Industrialization Strategy Council. We will continue to contribute to the development of domestic carbon capture technology.

CO_2 Storage Research Group

Member (As of Apr. 2024)

Ziqiu Xue, Group Leader, Chief Researcher
Nobuo Umeda, Deputy Leader, Chief Researcher
Satoru Yokoi, Chief Researcher
Makoto Nomura, Chief Researcher
Nobuo Takasu, Associate Chief Researcher
Takahiro Nakajima, Associate Chief Researcher
Takeshi Myoi, Associate Chief Researcher
Tsutomu Hashimoto, Associate Chief Researcher
Saeko Mito, Senior Researcher
Tetsuma Toshioka, Senior Researcher
Osamu Takano, Senior Researcher
Keisuke Uchimoto, Senior Researcher
Hironobu Komaki, Senior Researcher
Atsushi Ibusuki, Senior Researcher
Yuji Watanabe, Senior Researcher
Yi Zhang, Senior Researcher
Hyuck Park, Senior Researcher
Jiro Suekuni, Senior Researcher
Yuji Yamashita, Senior Researcher
Ken Asajima, Senior Researcher
Tetsumi Imamura, Senior Researcher
Satoko Fuchikami, Vice Manager
Kimiko Nakanishi, Chief
Takayuki Miyoshi, Researcher
Takeya Nagata, Researcher
Rasha Amer, Researcher
Jinrong Cao, Researcher
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Hiraku Miyasaka, Researcher
Masafumi Kotani, Researcher
Junko Hirai, Research Assistant
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Megumi Okumichi, Research Assistant
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Nae Hidaka, Research Assistant
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Technology Demonstration, Knowledge Sharing and Non-technical Support for Large Scale Deployment of Geological CO_2 Storage

1. Introduction

The final summary of the CCS Long-term Roadmap Study Group, published by the Ministry of Economy, Trade and Industry in March 2023, clearly states the indispensable role of CCS in achieving a stable energy supply and carbon neutrality in Japan. The business environment must be developed to enable operations by 2030. The government is presenting concrete plans for commercialization in this context. In June 2023, seven "Japanese Advanced CCS projects" were selected as part of the "Japanese Support for CCS projects." In February 2024, the Cabinet approved a draft law on CCS projects which was submitted to the Diet.

In the 213th ordinary session of the Diet, the Bill for the Act on Carbon Dioxide Storage Businesses (CCS Business Act) was passed into law. The CCS business Act establishes a licensing system for storage, exploratory drilling rights, as well as business and security regulations CO_2 transport projects, and other business environment.

In technological development, the law the group will set concrete cost reduction targets and promote technological development and demonstration. RITE, as a member of the Geological Carbon Dioxide Storage Technology Research Association, is promoting technological development with application to domestic CCS projects under a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The group is developing technologies to ensure safety and reduce costs by monitoring geological formations and pipelines with fiber optic sensor technology, supporting the commercialization of CCS and producing technical manuals that will serve as a guide for CCS operators. In developing monitoring technology, we are conducting demonstration tests at domestic and overseas sites, including a commercial

CCS project site in the US. We are conducting a technical demonstration of a method to monitor the integrity of geological storage facilities, such as CO_2 pipelines and wells, and the stability of geological formations by measuring temperature, strain and acoustics using optical fibers.

In addition, we are working on technologies to support the various steps leading to commercialisation of CCS, such as the development of communication methods with local communities, the development of information on the location of emission sources, which is essential for the design of project plans, and the development of cost estimation tools to assess commercial feasibility.

Furthermore, we are also compiling a collection of technical case studies from national and international case studies to share knowledge on each stage of the CCS project, from planning to operation and post-closure. A total of seven editions have been prepared by the end of 2023 and will be made available successively.

2. Main research topics and results

2.1. Development of a fiber optic based formation integrity monitoring system

Subsurface monitoring is one of the essential elemental technologies for CO_2 geological storage projects that are being pursued in earnest in Japan and abroad. To confirm that the injected CO_2 is safely stored in the formation, in addition to monitoring the extent of CO_2 spread, monitoring of formation deformation and the extent of pressure propagation due to increased formation pressure, and monitoring of well integrity to detect any leakage are carried through. As this monitoring is carried out over a long period of time, it is necessary to use economical technology. In addition, real-time monitoring systems are expected to provide information that contributes to immediate decision making, such as changes in injection conditions. Fiber-optic sensing is a promising monitoring technology that meets these requirements.

Fiber optic sensing is a technology that measures environmental changes around an optical fiber by measuring the backscattered light generated when an optical pulse is transmitted through the fiber. Raman scattering is used to measure temperature (DTS: Distributed Temperature Sensing), and Brillouin scattering is used to measure temperature and strain (DSS: Distributed Strain Sensing). Rayleigh scattering light is mainly used for damage detection and acoustic (vibration) measurement (DAS: Distributed Acoustic Sensing) by utilizing the change in scattered light intensity due to bending, etc. Recently, Rayleigh scattering light is also used for high-precision temperature and strain measurement by utilizing its spectral change. Fiber optic sensing technology is characterized by the fact that the entire optical fiber acts as a receiver, making it possible to acquire spatially continuous records. In addition, a single fiber optic cable bundled with multiple fibers can be installed as a multi-sensor to measure temperature, strain and acoustics, significantly reducing the cost of installing a large number of sensors. In particular, the fiber optic cable is thin, with a diameter of only a few millimeters to a few centimeters, and can be easily installed in confined spaces, allowing the cable to be installed in a small gap between the formation and the outside of the steel pipe, known as the casing, that holds the well.

RITE has been conducting research and development of optical fiber sensing technology through laboratory and field tests, and is currently conducting verification tests at several domestic and overseas sites. At domestic sites, in addition to evaluating the performance of the developed fiber-optic cable and improving the installation method, the effectiveness of the technology is being verified in a CO_2 injection environment, such as injection in multiple wells, assuming a real project. Furthermore, at the CCS site in North Dakota, USA, simultaneous temperature, strain, and acoustic measurements using a single optical fiber cable are being conducted as a technical demonstration of a multi-sensing CO_2 geological storage monitoring system. In Australia, field tests are progressing at the Otway site in Victoria and the South Perth site in Western Australia to monitor leakage from shallow faults and the stability of deep faults.

The following is an overview of the field testing underway at each site.

2.1.1 Domestic test sites

At a test site in the Mobara area of Chiba Prefecture, Japan, we are conducting field tests to verify the technology of the CO_2 geological storage monitoring system using fiber-optic sensors. Various optical fibers have been installed in shallow wells at depths of around 300m, water injection and pumping tests have been carried out using wells to measure and evaluate the optical fibers. Various optical fibers were installed in shallow wells at depths of around 300m, water injection and pumping tests were carried out in the wells to evaluate the measurement ability of the optical fibers. In FY2022, a new well was drilled to a depth of over 900m, and optical fiber cables were installed to measure temperature, strain, and sound simultaneously. Through these tests, we were able to develop the technology for installing optical fiber cables, equipment, also installation method (Figure 1). In parallel, we are in the process of developing fiber optic technology for the evaluation of the cement integrity of the wellbore. The technology is expected to be a real-time monitoring technology that can be used during construction to assess cementing integrity which affects the potential leakage from an injection well at underground CO_2 storage sites.

Long-term continuous monitoring using DSS (strain measurement) has been ongoing at the site since the fiber was installed in FY2022. Strain changes caused by water injection and pumping around the site are measured and used as a technology to evaluate hydraulic properties around the site through geomechanical analysis based on optical fiber strain measurement data. This technology should lead to the efficient placement of multi-well sites, essential for future underground CO_2 storage in Japan.

Figure 1 Fiber optic installation work at a site in Japan

2.1.2 North Dakota CCS Site, USA

The North Dakota CCS project is a commercial project stores approximately 180,000 tons per year of CO_2 collected from the ethanol refining process in a saline aquifer approximately 2,000m deep underground. Injection began in mid-June 2022, and as of March 31, 2024, approximately 250,000 t of CO_2 had been stored.

In this project, fiber optic cables have been installed in four wells (one injection well, one observation well and two shallow groundwater observation wells) and along the CO_2 pipeline (Figure 2), with simultaneous measurements of DAS, DTS and DSS This project is a technical demonstration of multi-sensor technology in a single fiber-optic cable in a commercial project, and we will continue measurements until the injection of 1Mt , which is one of the guidelines for the scale of commercialization in Japan, in order to accumulate knowledge of problems and countermeasures in the operation of monitoring systems for domestic CCS projects.

Imaging techniques using repeated seismic surveys are used to map the CO_2 plume. Vertical seismic profiling (VSP), in which the receivers are placed downhole, is one of the techniques used for seismic profiling because it brings the receivers closer to the target and thus enables high-quality data acquisition. In furthermore, the use of a fiber optic cable equipped with numerous receivers as a downhole receiver reduces the noise caused by the misalignment of the receiver points and also speeds up the data acquisition.

Repeated 3D seismic surveys aimed at understanding how the CO_2 plume spreads are typically conducted every one to several years. To fill this time gap, a fixed Surface Orbital Vibrator (SOV) was introduced to allow frequent data collection.

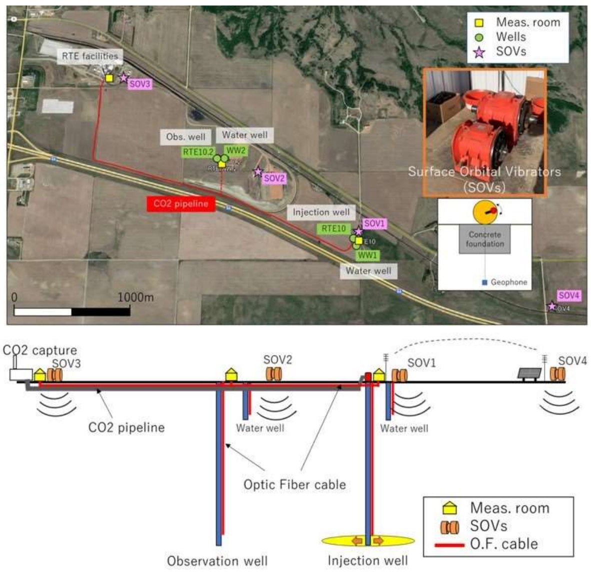


Figure 2 Overview of the fiber optic monitoring system at the North Dakota site

The SOV is a permanent vibration device that transmits vibration into the formation by means of an inclined weight mounted on a concrete block rotating at high speed. They can be remotely and automatically controlled, eliminating the need for an on-site operator to vibrate. At the North Dakota site, SOVs are installed at four locations on the site and vibrate as required. Of the recordings made, the (zero) offset recordings are used to detect the CO_2 plume immediately after injection begins, while the offset VSP recordings are used to determine the spread of the CO_2 plume. Time-lapse analysis of repeated VSP recordings is currently underway to ascertain the CO_2 spread.

In addition, DTS and DSS (temperature and strain measurement) in all sections of CO_2 pipelines and injection wells are conducted to detect any possible leakage. In the past, point measurements were taken by flow meters and temperature/pressure gauges installed at the entrance and exit of the pipeline and at the bottom of the well. Fiber optic sensing technology, on the other hand, continues real-time monitoring of the entire route section, exploiting the fact that the entire fiber is the measuring point.

2.1.3 Australia Site

The risks associated with the deployment of CO_2 geological storage projects in Japan, where there are many faults, include the effects of injection on faults and leakage from faults. To address these risks, fault zone characterization, fault stability monitoring, fault leakage detection and monitoring technology are essential. The fiber optic sensing technology developed by RITE will be an effective tool, but various tests at actual sites are essential to establish these technologies. For this reason, since fiscal 2021, we have been conducting a Japan-Australia joint research project with an Australian research institute that has a test site where known faults are distributed. A CO_2 leak detection field test from a shallow fault using fiber optic sensing technology is underway at the Otway site in southwest Victoria, Australia. The site is a demonstration test site where tens of thousands of t of CO_2 have been injected by the Australian research institute CO2CRC. Two new wells have been drilled at the site, a new fiber-optic cable capable of high performance DSS (strain measurement) has been installed and water injection tests have been conducted. Hydraulic characterization of the site and the fault is now underway using the measured data. We plan to evaluate the performance of small-scale CO_2 injection for leak detection in the future.

Figure 3 Fiber optic installation work at Otway site

At the South Perth site in south-west Western Australia, field tests are underway to assess fault stability, particularly for deep faults. At the test site, a well has been drilled through the deep fault zone and fiber-optic cables have been installed to evaluate the hydraulic and mechanical properties of the fault and fracture zone based on DSS (strain measurement) results and to assess fault reactivity. In FY2023, a new inclined well was drilled. The successful installation of the optical fiber cable in the back of the casing of the inclined well has improved the optical fiber installation technique for CO_2 geological storage monitoring. We plan to conduct fluid injection tests in the future and evaluate the hydraulic and mechanical properties of the fault using the results of the same measurements.

Figure 4 Fiber optic installation at the southern Perth site, Australia

2.2 CCS Commercialization Support

With the start of the Japanese advanced CCS support projects by JOGMEC in FY2023, the large-scale deployment and commercialization of CCS in now started.

RITE is also undertaking research and development to support large-scale deployment of CCS. Specifically, RITE has been conducting research and development on methods to promote understanding of CCS deployment areas, support for setting up appropriate CCS commercialization forms, and economic evaluation of CCS. The progress of the projects are reported below.

2.2.1 Communication with Local Communities in CCS Projects

Once the project candidate sites have been chosen, the project developers need to communicate with stakeholders and local residents to gain their understanding and support for the project. Communication activities should be conducted as early as possible with a wide range of stakeholders. The basic idea is that the communication activity should be a two-way process, with close communication with the local community at an early stage and local ideas and wishes being incorporated into the project plan, rather than a one-way communication from the project proponent to the local community, with the project proponent asking the local community to accept the project after all the project plans have been decided. RITE has conducted research on communication with local communities in the deployment of CCS projects. This paper discusses the importance of raising awareness of CCS in the early stages of communication. There have been cases overseas where local residents and stakeholders were unfamiliar with CCS and the project plan proceeded without their knowledge of CCS, leading to opposition to the project from the local community. Therefore, it is important to have local residents and stakeholders understand CCS.

In Japan, awareness of CCS is low, with about half of the general public having never even heard of the term. Therefore, it is necessary to familiarize people with the term "CCS. After all, even if there is a communication event about "CCS" that they have never heard of at all, they are unlikely to want to participate. The government considers CCS as an important option toward carbon neutrality, and advanced CCS projects started last year. We expect to see and hear the term "CCS" more often in the future, and for the time being, CCS providers also need to promote the term "CCS" as a first step in their communication activities.

As more people see and hear the term "CCS," more people are likely to search for and look up CCS. The first information a person decides to look up "CCS" is important. This information may lead them to have positive or negative opinions about CCS. Misinformation about CCS can prevail. For example, information about CCS that was spread by a celebrity social networking site immediately after the Hokkaido Eastern Iburi earth quake was considered "fake news," Initial exposure to misinformation can lead to misconceptions about CCS. It is said that once people believe information and base their ideas on that information, those ideas are not easily changed In addition, people tend to selectively accept only the information that matches their own ideas, and nowadays, through social networking services, people tend to connect only with others who share their ideas, thus reinforcing their ideas. It is therefore important that information based on scientific and academic knowledge about CCS is easy to find in searches.

However, even if it is easy to find in a search, it is meaningless if it is not read. We, RITE, have prepared *FAQs* to answer questions that the general public may have about CCS. This *FAQs* is to help people who are searching or investigating "CCS" to solve their questions. A (Answers) are designed to be readable without prior knowledge for the purpose. We plan to develop the *FAQs* to make it even more approachable and easy to read with inserting diagrams and illustrations.

2.2.2 Analysis of Local Economic impacts by deployment of CCS

When applying CCS projects, it is important to explain not only the technical and scientific aspects of CCS, but also the socio-economic benefits that the project will bring to the local community. RITE has developed methodology for analyzing the local economic impacts of CCS deployment and has applied it to actual areas to appeal the socio-economic benefits. The following outlines how to examine the benefits

① Estimation of CCS Investments

First of all, it is necessary to figure out the CCS scheme and determine the total investment amount. These are specified using the emission source data base (DB) and CCS cost estimation tool described below.

② Analysis of Economic impact by CCS investments

After determining the total amount of the CCS investments, we estimate direct, indirect and induced economic effects and the employment opportunity gains by the CCS investment.

To estimate the CCS investment impacts on the local economy, we could use the input-output table and economic effect analysis tool provided by each local government. However, "CCS" is a new industry and the existing tables and tools do not include such items. Therefore, the components of the CCS industries have examined and arranged by combining existing industry items. Finally, we produce the analysis tool fit on the CCS type and the targeted local economy. As the components of CCS projects are diverse, definition of the details of the CCS industrial structure and its procedures is a future work in progress.

③ Economic impacts of site visits

In addition to the industrial economic impacts of attracting the CCS, the host area will also benefit from the economic impact of the site visits by bringing visitors to understand what is CCS. In fact, many domestic and international visitors came to Tomakomai, Hokkaido, where the large-scale CCS demonstration was tested. It is also important to estimate the number of CCS visitors and analyze the induced impacts of their visits by referring to such previous examples. Some local governments provide tools to assess the economic impact of tourism, which should be applied.

④ Approach to improve economic benefits

The main components of the CCS industry are 'construction' and the procurement of materials and equipment such as 'general-purpose machinery'. Construction can largely be carried out locally, contributing to the expansion of economic impacts. Many materials and equipment, however, cannot be sourced in the CCS deployment area, and this is a factor in the absence of local economic stimulation.

The input-output table shows the self-sufficiency of relevant industries, and improving this value can boost the economic benefits. It provides quantitative guidance on which industries and human resources should be developed locally.

Thus, the consultation of the economic impacts of CCS will also contribute to the design of industrial development policies in the region where it is located.

⑤ CCS/CCU Coordination Effectiveness Analysis

As well as the geological storage of CO_2, the use of CO_2 (CCU) is also attracting attention. In the case of CCU, matching CO_2 supply and demand is critical. In some cases, however, the supply of CO_2 far exceeds demand, forcing the captured CO_2 to be vented. If CCS is used in conjunction with CCU, the excess CO_2 for CCU can be stored underground and create carbon reduction credits.

In other words, the use of CCS helps to reduce the uncertainty of CCU businesses and increase their predictability; this perspective is also important when discussing the economic benefits of CCS.

⑥ Application and adaptation of the analysis method

The above is an introduction to the methodology for analyzing the local economic impacts of CCS. We have already applied the method in some areas, but we would like to increase the number of practical examples of the analysis and improve its accuracy and usability in the near future. If you are considering the local economic impact of CCS, we would like to hear from you.

2.2.3 Development of CO_2 emission source database

Appropriate matching of CO_2 emission sources and reservoirs is crucial for the commercialization of CCS. Therefore, RITE is working on the development of a CO_2 emission source database (hereinafter referred to as "emission source DB") to support this matching.

Below is an overview of its data structure, functional overview, and future development.

① Data structure of the emission source DB

The Ministry of the Environment's public data based on the "Greenhouse Gas Emissions Calculation, Reporting, and Publication System" (hereafter referred to as "Greenhouse Gas Public Data") contains over 10,000 CO_2 emission source information. The Emission Sources DB is based on this information, and addresses the following a), b), and c) to fit the characteristics of decarbonization through CCS.

a) Estimation of direct CO_2 emissions and DB

The CO_2 emissions of each site in the Greenhouse Gas Public Data include the CO_2 equivalent of electricity and heat supplied by others as a numeric value. CCS collects and stores the direct CO_2 emissions actually emitted by the business site concerned, and it is needs to exclude CO_2 emissions equivalent to electricity and heat. Therefore, a "direct emission factor" is calculated for each business type using a specific statistical method, multiplied by the CO_2 in Greenhouse Gas public Data, and the direct CO_2 emissions from each business site are determined for the database.

b) Inclusion of biomass fuel CO_2 emission source information

The data of the Greenhouse Gas public Data covers CO_2 emissions from fossil fuels, while CO_2 emissions from biomass fuels are not covered because they are carbon neutral. On the other hand, biomass power plants also emit CO_2, which can be captured and stored for BECCS and negative emissions, which are important factors in promoting decarbonization. Therefore, we are also investigating CO_2 emission source information from biomass fuels with reference to information from the Agency for Natural Resources and Energy's Electricity Survey Statistics, etc., to estimate CO_2 emissions and incorporate them into the emission source DB.

c) Reflection of storage potential information

Mapping information on storage potentials from the National Reservoir Availability Survey conducted by RITE is also reflected in the emission source DB.

② Information mapping and screening capabilities

a)Mapping of emission sources with potential reservoirs

In order to properly match emission sources and reservoirs, it is important to visually grasp their location. Therefore, we realized a function to map the data shown in ①. Figure 5 is an example of such a mapping, where emission sources are concentrated on the Pacific Ocean side and reservoirs are mostly located on the Sea of Japan, and their geological characteristics can be easily captured.

Figure 5 Example of integrated display of CO_2 emission source and storage potential

b) Information screening function

The visualized map can be moved freely, and specific areas can be zoomed in on. In addition, information on emission sources can be extracted by circling an area, which can be used to cluster emission sources. It is also possible to display emission sources by type, such as coal-fired power plants and factories. For example, if the display is limited to CO_2 emission sources from biomass fuels, it can contribute to the development of CO_2 offsetting strategies through BECCS.

③ Work towards the Platform to Help Commercialization of CCS

In anticipation of the large-scale and full deployment of CCS, the ability to map existing gas pipelines, the screening of inland emission sources at a certain distance based on the concentration of CO_2 emissions will be added over time to the features already described. The commercialization of CCS requires the cooperation of a wide range of stakeholders, including policy makers, engineers, investors and business managers, to steer the direction of the project.

This database will facilitate quick access to required information and the sharing of information between stakeholders using the visualization function. In addition, we plan to link it with other support functions, such as the CCS cost estimation tool to be introduced next, to create a platform that accurately supports the commercialization of CCS. If you have any comments or requests regarding this DB, please let us know.

2.2.4 Development of CCS cost estimation tool

This tool has been developed to enable industrial companies to compare the costs of several possible project types. In addition to estimating a range of costs from capture to storage for stand-alone CCS, the tool also includes cost estimates for hubs and clusters where multiple emitters are aggregated in coastal areas.

The latter multiple emitter cost estimation tool is also useful to specifically assess the extent to which the proposed configuration of aggregation groups using the source database (2.2.3) is expected to reduce costs, or whether such a configuration is the best one. Furthermore, because this tool can perform calculations at high speed, results can be checked in real time as parameters are changed. We therefore believe that the tool will be used to support the trial and error process of finding the optimal deployment of a CCS project.

① The cost that the tool can estimate

Assuming CCS in Japan, the tool includes options for each of the capture, transport and storage processes. For example, coal-fired and LNG-fired power plants are among the options for capture while onshore, offshore pipelines and maritime transport are among the options for transport.

In addition to these process-related options, the project period annual CO_2 throughput, discount rate, and exchange rate can be set as options related to the entire CCS project. By selecting and combining these options, users can build the CCS they envision in the tool.

② An example of estimation

Here we present an example of estimation in the storage process. As most storage in Japan is considered subsea, this tool targets subsea storage. The sea area setting is determined by the offshore distance water depth of the storage location, and the system automatically selects one of the following three methods: A. Injection from land (Tomakomai method), B. Injection from a fixed base (jack-up method), or C. Injection from a floating base (semi-submersible method).

Figure 6 shows the three storage methods compared in this study. The left side of the figure shows an image of the storage system, and the right side shows the assumptions used in the estimation.

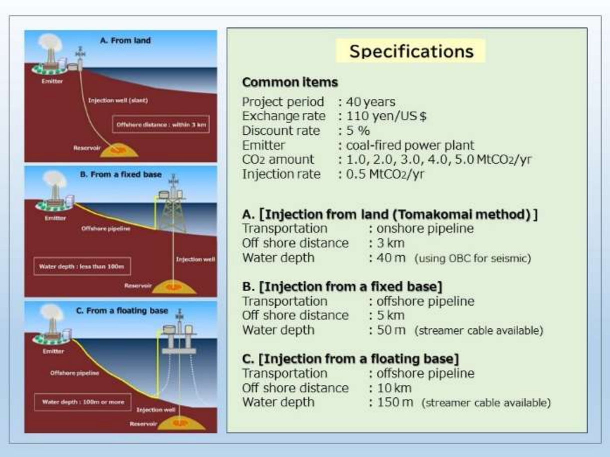


Figure 6 Illustration of storage methods

In addition, the injection of CO_2 into the subsurface requires associated monitoring, so the monitoring costs are also included in the estimation of the storage process.

Figure 7 shows the difference of the costs storage methods.

During the test calculation, we varied the amount of CO_2 (injection volume) in five steps from 1 Mt/yr to 5Mt/yr, and examined how much economies of scale would occur.

The figure shows that the lowest storage cost was achieved by injecting from land, followed by a fixed base type and the floating type. Regarding economies of scale, the floating type was effective up to 3Mt /yr, but not at higher CO_2 throughputs. For the other storage methods, economies of scale were small or almost nonexistent.

In terms of monitoring, on the other hand, economies of scale were found to significant in all three storage methods. In terms of cost, injecting from land was more expensive than the others. This may be because the water depth setting was 45 m, which did not allow for seismic exploration using streamers, therefore seismic exploration using an ocean bottom receiving cable (OBC) was employed.

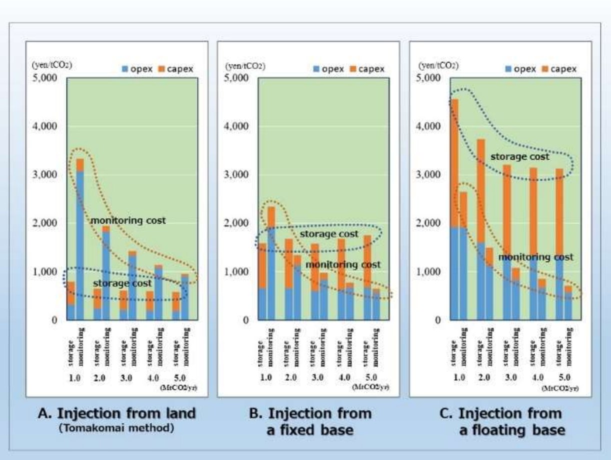


Figure 7 Difference in the cost of storage method

③ Considerations for networking of emitters

In terms of reducing the cost of CCS, the networking of emitters in hubs, clusters and the processing of large quantities of CO_2 can have a significant cost-reducing effect. As networking is a cost-reducing measure that can be implemented with existing technologies, the idea of clustering emitters for joint implementation is a natural concept. In this section, we will explore which of the two networking groups forming in a given coastal area would be more advantageous for intermediate emitters to join.

Figure 8 shows an image of the consolidation group formation process. The figure shows that there are two groups under consideration, Group A and Group B. The setting is that there is a difference in the total amount of CO_2 already contracted between Groups A and B. It is assumed that Group A and Group B have 3Mt/yr and 1.5M t/yr of CO2 secured, respectively. It is also assumed that emitter X bears the cost of the onshore pipeline from emitter X (1 Mt/yr) to the hub of each group, and that the ship transportation distance and storage method are the same for both groups. The distance between Port A and Port B was assumed to be 100 km (with a hub at each port).

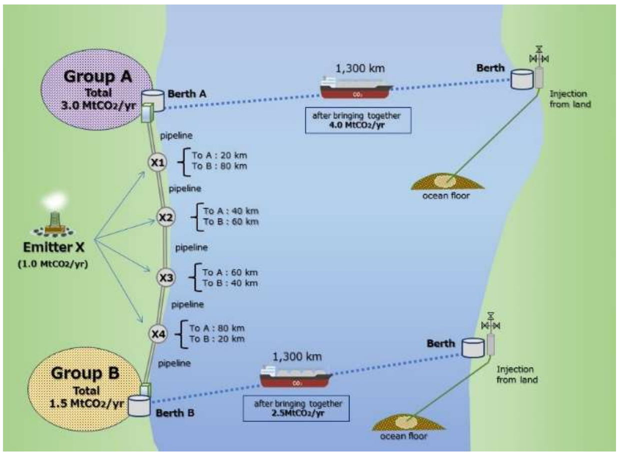


Figure 8 Image of CCS facilities grouping formation

Figure 9 shows the relationship between distance from emitter X to port A and CCS costs. The purple line shows the cost of using Port A and the orange line shows the cost of using Port B. The top figure in Figure 9 is for the case where emitter X implemented CCS alone and was not affected by the networking group, so both costs simply meet at the midpoint between the two ports (50 km).

On the other hand, in the lower panel of Figure 9, emitter X is affected by the networking group, and Group A, which originally had a larger CO_2 processing scale, has a larger cost reduction than Group B. As a result, the purple line has moved more downward, and thus the intersection of the lines has moved to the right. This shows that for emitter X, it is less expensive to participate in group A when the distance from port A is within 80 km, and beyond that, i.e., when the distance from port B is within 20 km, it is less expensive to participate in group B.

Note that in the above discussion, we considered only the CO_2 throughput and distance from source X for Groups A and B. In reality, there are many variations. For example, Groups A and B could have different shipping distances, different storage methods, different injection rates, different project periods, and even one of the groups could bear the cost of laying the pipeline.

④ Working towards the release of the tool

At this point, we have completed the installation of the planned costing engine, which allows us to perform the trial calculations shown above. On the other hand, in order to make the tool publicly available, it is necessary to provide an interface that is easy for anyone to understand, and at the same time, it is important to provide easy-to-understand output in the form of charts and diagrams. Furthermore, since this tool will be released as a web system, measures against cyber-terrorism are also considered essential.

After completing these various tasks, we plan to conduct tests (field tests) before releasing the system to the public on the Internet, and release it to the public once its reliability and stability are confirmed.

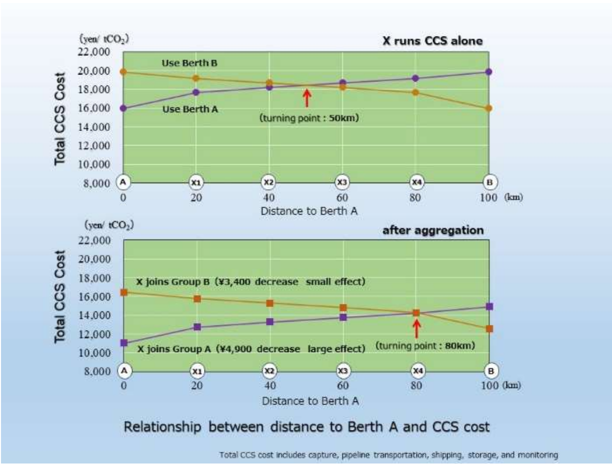
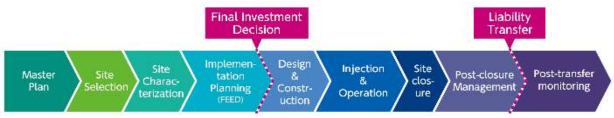


Figure 9 Distance from emission source X to port A and CCS Cost Relationship

2.3. Practical Guidance

RITE has been working on the development of various technologies and methodologies, including monitoring technologies, for the practical application of CO_2 geological storage technology. Based on the results of these efforts, RITE has been is preparing a *Practical Guidance for Geological CO_2 Storage* (hereinafter referred to as this *Practical Guidance*) as part of the development of conditions and standards for the widespread use of CCS.

Designed as a reference for future CCS operators, this collection of case studies summarizes national and international technical information and case studies on geological storage of CO_2. For example, the main findings of "Development of Carbon Dioxide Geological Storage Technology" (FY2000-2007; Nagaoka CO_2 Injection Demonstration Test), "On Safe Implementation of CCS Demonstration Project" (2009, METI), "Large-scale CCS demonstration test project in Tomakomai" (2022, METI, et al.), etc. Manuals and guidelines summarizing the results of large-scale geological CO_2 storage projects by overseas organizations are also referenced. Figure 10 shows the overall CO_2 geological storage project described in this *Practical Guidance*.



- Master Planning ------------Development of a master plan for a CCS
- Site selection --------- -Extraction of multiple candidate storage sites
- Decision on the site ---- Evaluation of the characteristics of candidate sites, selection of the optimal site, and conceptual designs
- Implementation planning----Development of implementation plans, basic designs, and economic evaluations
- Design and construction------ Detailed design and construction, such as project equipment and the development of a management plan
- Operation and management -- Operation and management of sequestration and execution of the monitoring plan
- Site closure --------------------------------Plugging the injection well
- Post-closure care----- Site care until project responsibility is transferred

Figure 10 Overall structure of the CO_2 geological storage project

(1)Master Planning

The overall picture/basic concept of the project (including economic feasibility study), work policy and content in each phase, timetable, etc. are presented.

(2) Site selection (screening)

Based on the overall plan presented in the master plan, candidate site(s) that meet the requirements as CO_2 storage site(s) will be selected using existing geological data.

(3) Decision on the site

CO_2 Geological data will be gathered for candidate storage sites as necessary and evaluated in detail. A geological model will be developed and the CO_2 storage capacity will be evaluated by injection simulation, and an economic and risk assessment will be performed based on the conceptual design of transport and injection facilities. As a result, the injection site will be finalized.

(4) Implementation planning

Based on the results of the site characterization, develop a specific project deployment, work plan for CO_2 injection operations and monitoring. Make a final investment decision including total project cost/economics study, risk assessment, etc., and submit the deployment plan for project application to the regulatory authority.

(5) Design and construction

Once the project is approved by the regulatory authority, the detailed design of the injection and transportation facilities, etc. is carried out on the basis of the conceptual and basic designs made up to that point, as well as the construction and commissioning.

(6) Operation and management

Injection operations will be carried out according to the deployment plan. The spread of the CO_2 plume injected underground and pressure changes in the reservoir will be monitored, and if there are deviations from the CO_2 behavior simulation, the geological model will be improved to develop the accuracy of the long-term behavior prediction. Monitoring of CO_2 leakage will also be conducted.

(7) Site closure

Upon completion of CO_2 injection, the injection well will be closed, all facilities will be removed except those required for post-closure monitoring. Following site closure, confirmation of CO_2 behavior and leak monitoring will continue. After some time, when the regulatory authority determines that the site is safe, the site management and other operations will be transferred to a public organization.

Figure 11 *Practical Guidance for Geological CO_2 Storage, Series 1-7*

Series 1-7 of *Practical Guidance*, has been written and will be uploaded successively on websites of METI and NEDO to share the knowledge with the Southeast Asia and the rest of the world.

Click the link to open the RITE website

Press Releases

Events

Paper, Presentation and Publication

- Systems Analysis Group
- Molecular Microbiology and Biotechnology Group
- Chemical Research Group
- CO_2 Storage Research Group

Other Activities

◆Environmental Education (Facility Visit Program)

Date	Participants	Number of participants
13 Jul. 2023	Tezukayama Junior High School	27
27 Jul. 2023	Kyoto Prefectural Nishimaizuru High School	8
4 Oct. 2023	Izumo Senior High School	42
31 Oct. 2023	Nara Prefectural Narakita Senior High School	21
6 Nov. 2023	Ritsumeikan High School　Japan Super Science Fair	28
2 Feb. 2024	Seikanishi Junior High School	7

◆Environmental Education (Workshop)

Date	Title	Number of participants
3 Aug. 2023	Craft and Science Experiment to Learn about Global Warming and Energy	97

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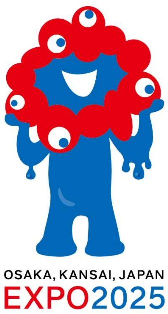

RITE is a silver partner of "Green Expo" - one of the Future Society Showcase Projects – at Expo 2025 Osaka, Kansai, Japan.
We are constructing the RITE Negative Emission Pilot Plant at the venue and will conduct pilot-scale testing on DAC (Direct Air Capture) technology.