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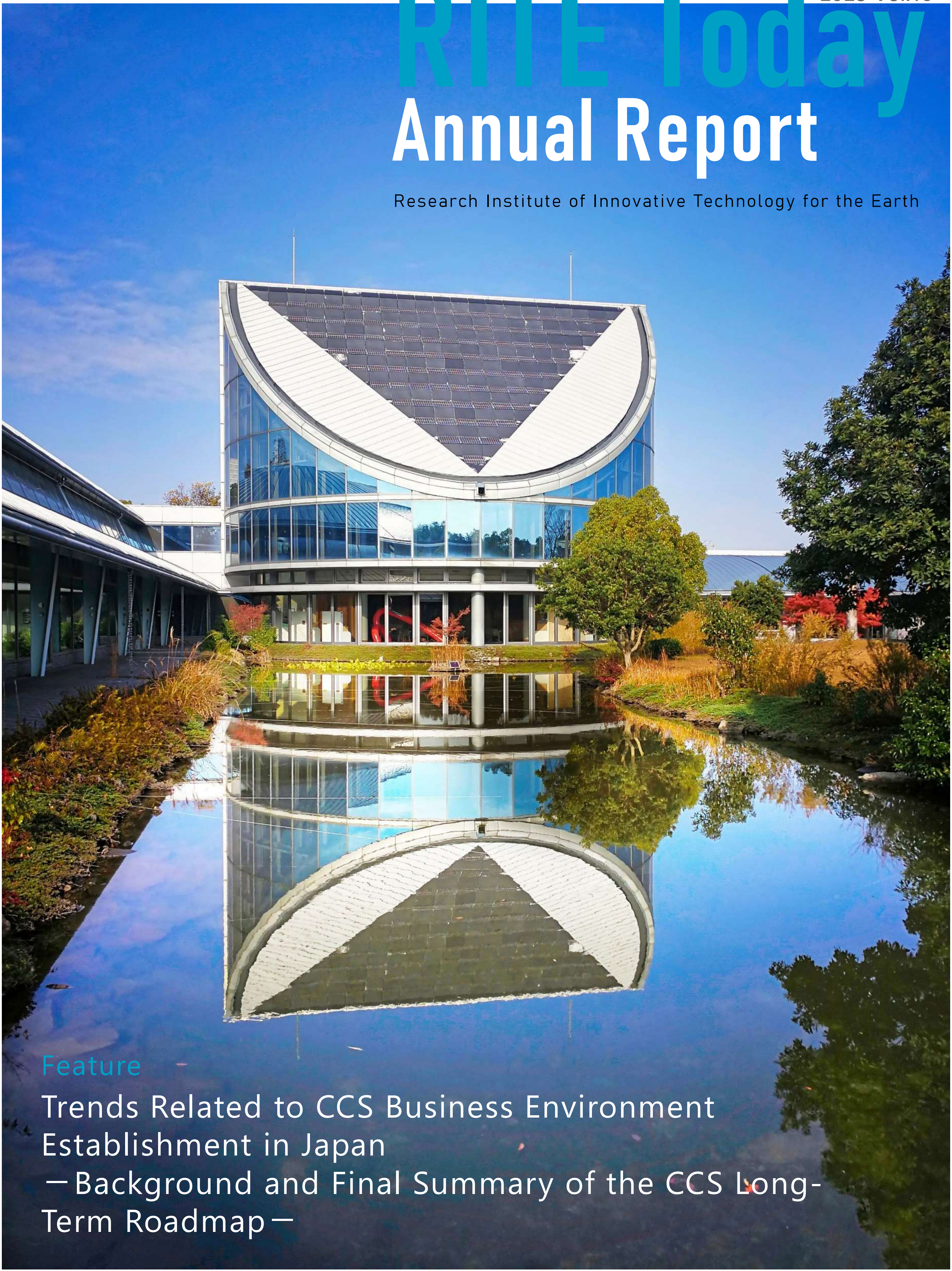

Feature

Trends Related to CCS Business Environment Establishment in Japan
－Background and Final Summary of the CCS Long-Term Roadmap－

RITE Today 2023 Vol.18

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RITE’s Contribution to Achieving Carbon Neutrality

Yoshiyuki Simoda
Director - General,
Research Institute of Innovative Technology for the Earth (RITE)

Over the past few years, the goals for mitigating global warming have changed significantly. The Paris Agreement adopted in 2015 proposed a previously unexplored goal of “pursuing effort to limit temperature increase to 1.5°C above preindustrial levels.” In response, the IPCC released a Special Report on 1.5°C in 2018, setting out pathways to carbon neutrality by 2050 as scenarios for achieving the 1.5°C goal. Following this, the EU and other countries announced the aim of becoming carbon neutral by 2050. Japan in 2020 also declared its goal of achieving carbon neutrality by 2050, and in 2021 established the “Sixth Strategic Energy Plan” and revised the “Plan for Global Warming Countermeasures” and the “Long-Term Strategy under the Paris Agreement.” In 2022, the IPCC published the Working Group III report of its Sixth Assessment Report.

Looking at these trends alone, it is tempting to assume that the 1.5°C target is easily achievable, but achieving it is not guaranteed, as suggested by the fact that there was intense debate in Japan before the carbon neutrality declaration about the feasibility of achieving a target of 80% reduction of greenhouse gases by 2050, which was largely in line with the 2°C target. Although there have been some positive developments in recent years, such as a decline in the price of renewable energy, there have not been major innovations leading to a significant reduction in greenhouse gas emissions. These moves to strengthen the mitigation targets have been driven by a strong sense of urgency in the international community about the increased risk of climate change due to the progression of global warming, and there is still a significant gap between the targets and viable solutions with current technology. To bridge this gap, there is an urgent need to create more innovation. In this regard, the situation is very different from that in the case of the Montreal Protocol, where the rapid spread of CFC substitutes was achieved to address the problem of ozone depletion.

I had seen the work of RITE for several years as a member of the Advisory Committee on Science and Technology, even before my appointment as director of the institute in June 2022. I found it remarkable the insight of those involved at the time of RITE's founding to devise innovative technology 30 years ago that would only be taken up later at such a significant turning point, and the steady efforts of RITE staff to develop that technology. The Working Group III report of the IPCC Sixth Assessment Report categorizes scenarios for significant reductions in greenhouse gas emissions. The distinctive ones are the IMP-Ren pathway, which heavily utilizes existing solar and wind power, the IMP-Neg pathway, which uses negative emission technology, and the IMP-LD pathway, which aims for a low demand for energy. In the IMP-Neg pathway, the CO_2 separation and capture technology nurtured by the Chemical Research Group and the Inorganic Membranes Research Center (integrated into the Chemical Research Group in April 2023) and the storage technology developed by the CO_2 Storage Research Group are important, while the LD pathway is a scenario addressed in the EDITS project conducted by the Systems Analysis Group. Research by the Molecular Microbiology and Biotechnology Group contributes Ren pathway as bioenergy, and also forms an important part of the LD pathway as a manufacturing alternative to fossil fuel resources. Outside of research, RITE staff have also made significant contributions to our nation's policy-making and IPCC operations over the past few years.

For the time being, I believe that the work of steadily implementing the technology we have cultivated over the years into society and preparation for the challenge of the next innovative anti-global warming technology will be important tasks for RITE. I ask for the continued support of all those involved.

Trends Related to CCS Business Environment Establishment in Japan －Background and Final Summary of the CCS Long-Term Roadmap－

Research & Coordination Group
Makoto Nomura, Deputy Group Leader, Chief Researcher
Jun-ichi Shimizu, Associate Chief Researcher

1. Introduction

Reduction of greenhouse gases (GHGs) is an important global challenge. Under the Paris Agreement (effective November 4, 2016), which is the international framework for tackling climate change issues in 2020 and later, efforts will be made to keep the average global temperature increase well below 2°C compared with the pre-industrial level, and limit it to 1.5°C as a common long-term goal for the world. It also stipulates that global GHG emissions should peak out as soon as possible, and we should ensure a balance between GHG emissions and absorption by forests, etc. in the second half of this century[1)].

Japan is working to reduce GHG emissions to achieve carbon neutrality (CN) by 2050 and a 46% reduction in GHG emissions (compared with the 2013 level) by FY2030, based on the "Plan for Global Warming Countermeasures," the "Strategic Energy Plan," etc. Under these circumstances, the CCS Long-Term Roadmap Study Group, which was established in January 2022, published the "Final Summary by the Long-Term CCS Roadmap Study Group" in March 2023 as a result of its year-long activities. This article reports on its overview. (Table 1 shows the main policies for carbon dioxide capture and storage (CCS)/carbon capture utilization (CCUS) in Japan for the immediate future.)

Table 1 Main policies for CCS/CCUS

Roadmap for Carbon Recycling Technologies (formulated June 7, 2019)[2)] • Carbon recycling technology, which treats CO_2 as a resource, separates and recovers it, and reuses it as diverse carbon compounds, and it is one of the promising options for the future, and we will accelerate innovation in this area.
Environment Innovation Strategy (formulated January 21, 2020)[3)] • We position carbon recycling and CCUS technologies, which are essential for a significant reduction in CO_2 emissions, as one of the priority areas. Therefore, we will promote the realization of decarbonized and inexpensive energy supply technologies, and make the greatest possible contribution to the reduction of GHG emissions domestically and globally. In particular, we aim to achieve a CO_2 separation and recovery cost of 1,000 yen/t-CO_2 by 2050 as a low-cost CO_2 separation and recovery technology that will be the foundation for CCUS/carbon recycling.
Policy speech by Prime Minister Suga (October 26, 2020)[4)] • He declared, "our country aims to achieve zero overall GHG emissions by 2050, or a carbon-neutral, and decarbonized society by 2050."
Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (formulated on June 18, 2021)[5)] • This is a further embodiment of the growth strategy (an industrial policy to tackle the challenging goal of achieving carbon neutrality by 2050) formulated on December 25, 2020. • The power sector will demonstrate the importance of pursuing all options, such as maximizing the introduction of renewable energy and the use of nuclear power, as well as promoting decarbonization through use of hydrogen, ammonia and CCUS.

Long-Term Strategy under the Paris Agreement as Growth Strategy (Cabinet decision on October 22, 2021)[6)]

- While the previous long-term strategy was approved by the Cabinet on June 11, 2019, this was the resulting strategy which later positioned the 2050 carbon neutrality declaration in October 2020 as the basic idea and was decided by the Cabinet.
- Measures against global warming are not a constraint on economic growth, but the key to transforming the economy and society in a major way, encouraging investment, increasing productivity, and creating a major shift in industrial structure and strong growth.
- It states that in order to achieve carbon neutrality by 2050, we will strive to introduce renewable energy to the maximum extent possible, promote the implementation of hydrogen and CCUS in society, and try to secure public trust in nuclear power, so that we can make sustained use on the necessary scale on the premise of ensuring safety.

Plan for Global Warming Countermeasures (Cabinet decision on October 22, 2021)[7)]

- It presents goals related to the amount of GHG emissions control and absorption, basic matters related to measures to be taken by businesses, citizens, etc., and measures to be taken by the national and local governments to achieve the goals.
- It specifies that Japan will aim to reduce GHG gas emissions by 46% by FY2030 compared with the FY2013 level, and that it will continue to take on the challenge to reach the 50% reduction level.

The 6th Strategic Energy Plan (Cabinet decision on October 22, 2021)[8)]

- It will lay out a path for energy policy to achieve new reduction targets of carbon neutrality by 2050, namely, a 46% reduction by FY2030, and aim for a further 50%.
- In order to achieve carbon neutrality by 2050, we will strive to introduce renewable energy to the maximum extent possible, promote the implementation of hydrogen and CCUS in society, and try to secure public trust in nuclear power, so that we can make sustained use on the necessary scale and on the premise of ensuring safety.
- In order to introduce CCS on the premise of commercialization by 2030, the roadmap for CCS implementation will be drawn up and shared, and efforts will be made to build a model base jointly between the government and private sector for technological development, suitable site development, transportation demonstration, business environment establishment, and network optimization.
- In addition to securing a stable supply of oil, natural gas, and mineral resources, we will develop a new "comprehensive resource diplomacy" to promote, in an integrated manner, the construction of hydrogen and ammonia supply chains and the securing of suitable sites for CCS using the networks we have cultivated with resource-rich countries through resource diplomacy.

1.1. Positioning of CCS Technologies in the 6th Strategic Energy Plan

The 6th Strategic Energy Plan[8)], which was approved by the Cabinet in October 2021, has two main objectives. One is addressing the issue of climate change. The plan lays out a path for an energy policy to realize the ambitious reduction targets of "carbon neutrality by 2050," announced by Prime Minister Suga in his policy speech in October 2020, and "reduction in GHG emissions by 46% by FY2030 (compared with FY2013) and aim for a higher 50% reduction" announced at the meeting of the Global Warming Prevention Headquarters in April 2021. The other objective concerns overcoming the challenges posed by Japan's energy supply and demand structure. The initiatives presented are based on the basic policy of "S + 3E (safety + stable energy supply, improved economic efficiency, environmental compliance)" while advancing measures to combat climate change.

In the 6th Strategic Energy Plan, CCS is positioned as a technology that should be fully utilized together with CCU to reduce CO_2 emissions from industries where decarbonization at thermal power plants as well as decarbonization using electrification and hydrogen are considered difficult. CCS is also positioned as an important technology for securing the necessary resources and fuel in a stable manner into the future. CCS is thus seen as one of the "key" options along with renewable energy, nuclear power, hydrogen and ammonia, and CCU to achieve both decarbonization and energy stability in our country. In addition, as a response to the utilization of CCS, it is clearly stated that a long-term road map will be prepared and shared with the relevant parties in order to establish the technology, reduce costs, develop an environment for suitable land development, and have commercialization.

2. CCS Long-Term Roadmap Study Group

As specified in the 6th Strategic Energy Plan, the CCS Long-Term Roadmap Study Group was established in January 2022 to examine the establishment and cost reduction of CCS technologies, development of suitable sites, and development of an environment for commercialization, and prepare a long-term CCS roadmap[9]. The CCS Long-Term Roadmap Study Group is comprised of members from academia, industry, research institutions, etc., and has held five discussions on a monthly basis after holding its first meeting in January 2022 to publish the Intermediate Summary in May 2022.

Furthermore, in September 2022, the "CCS business domestic law review working group" to discuss various issues for the establishment of domestic laws on CCS businesses, and the "CCS business cost and implementation scheme review working group" to discuss the current cost and future cost targets for the entire CCS value chain and how government support should be provided, were established to hold intensive discussions.

Based on the findings of these two working groups, the discussion to prepare the final summary was held at the 6th meeting of the CCS Long-Term Roadmap Study Group (joint meeting of CCS business cost and implementation scheme review working group and CCS business domestic law review working group) on January 26, 2023.

3. Overview of the "Final Summary by the CCS Long-Term Roadmap Study Group"[10]

This section provides an overview of the "final summary by the CCS Long-Term Roadmap Study Group," which was published in March 2023.

3.1. Global trends toward CCS commercialization

The global situation surrounding CCS has shifted from skepticism to policy adoption. In addition to the bipartisan Infrastructure Investment and Jobs Act (IIJA), the United States enacted a 10-year CCS program worth 50 trillion yen (the Inflation Reduction Act) in August 2022, which has been described as an "unprecedented CCS boom," and has had a major impact on international opinions. China specified the annual storage amount of 2 billion tons as its target for 2050, and is shifting to promoting CCS, including building relationships with other countries, in addition to domestic development. While Germany had been negative about the CCUS, it started at the end of last year to accept it and began to develop domestic policies. Other countries are also moving toward the introduction of CCS policies, ushering in the "era of great competition" for CO2 storage land. In addition, many ongoing projects are developing aquifer storage areas without enhanced oil recovery (EOR).

3.2. CCS Long-Term Roadmap

3.2.1. Basic philosophy

The basic philosophy of the CCS Long-Term Roadmap is stated as follows; "the purpose of this roadmap is to promote sound development of CCS businesses in our country while minimizing social costs by implementing CCS systematically and rationally, thereby contributing to economic and industrial development of our country, securing stable energy supply and achieving carbon neutrality."

3.2.2. Goals of the CCS Long-Term Roadmap

Based on the results of the IEA's estimate of CO_2 recovery amount under the global decarbonization scenario and Japan's share of CO_2 emissions, the estimated annual CCS storage amount as of 2050 is approximately 120 million to 240 million tons. If CCS is to be introduced in 2030, it will be necessary to launch CCS projects every year for 20 years until 2050 to increase the annual storage amount by approximately 6 million to 12 million tons, and postponing the implementation of CCS will make it difficult to secure the annual storage amount necessary to achieve carbon neutrality by 2050.

Therefore, with the aim of achieving an annual CO_2 storage amount of approximately 120 million to 240 million tons as of 2050, the goal is to establish the business environment (cost reduction, public understanding, promotion of overseas CCS, and legal development), and launch CCS businesses by 2030 with a view to commencing full-fledged operations in 2030 and onward.

3.2.3. Specific actions

The following specific actions will be taken as needed, with the period until the start of the CCS business in 2030 designated as the period of business model development and the period after that as the period of full-scale CCS development.

(1) Government support for CCS businesses
(2) Initiatives to reduce CCS costs
(3) Promotion of public understanding of CCS businesses
(4) Promotion of overseas CCS businesses
(5) Examination for the development of the CCS Business Act
(6) Development and review of the "CCS action plan"

(1) Government support for CCS businesses

① Support for advanced, model-oriented CCS businesses

In order to establish a business model that can be expanded laterally for the spread and expansion of the CCS businesses in the future, the government will select "advanced CCS businesses" led by business operators and provide more intensive support with the aim of starting the businesses by 2030.

Specifically, support will start for three to five projects with different combinations of CO_2 recovery sources, transportation methods, and CO_2 storage areas to establish diverse CCS business models, and they will aim to secure an annual storage amount of 6 million to 12 million tons by 2030.

As a model, the project will focus on large-scale operations and dramatic cost reduction through the clustering of CO_2 recovery sources and formation of hubs of CO_2 storage areas.

When selecting a project, matters will be confirmed with a focus on whether business is heading in a direction to gain people's understanding of CO_2 storage areas, and whether it will contribute to the development of CCS projects in the future, in addition to examining the early feasibility, scalability and economic efficiency of the project.

Table 2 Possible sources of CO_2 recovery, methods of transport, and patterns of CO_2 storage

Source of CO_2 recovery	Method of transportation	CO_2 storage area
Thermal power plants Steelworks Chemical plants Cement plants Paper mills Hydrogen production plants, etc.	Pipelines Ships	Underground in a land area Under the seabed (coastal areas) Under the seabed (offshore)

② Promotion of development of suitable sites for CCS/geological structure survey

While geological structure surveys have been conducted for the purpose of oil and natural gas development in the past, they will also be conducted for the purpose of CCS starting in FY2023. In the future, Japan Organization for Metals and Energy Security (JOGMEC) will examine plans for investigation of suitable sites for CCS and loan survey data to private companies.

Research to date has estimated that there are storage reservoirs amounting to a total of 16 billion tons at 11 sites. For the time being, analysis and evaluation of economic efficiency, etc. have been conducted by private companies and they are expected to lead to development activities such as exploratory drilling. However, data on coastal areas that are close to CO_2 emission sources and are expected to be lower in transportation costs, are scarce, making development difficult.

In addition, fault risk assessment is one of the important factors when considering suitable sites for CCS. The International Energy Agency (IEA) will urgently examine development of the method to assess the risks from geographic faults, although no previous demonstration project has recognized their relationship with earthquakes.

③ Examination of sustainability of CCS businesses

Although we will provide CAPEX support for the launch of the CCS businesses for the time being, we will examine the CCS business models for operational support, which will start in 2030, with reference to the latest findings from the UK and other countries that are ahead of us.

In addition, seamless support measures will be examined from the perspective of ensuring the sustainability of CCS for CSS businesses after the "advanced CCS businesses," based on the status of cost reduction and development of the business environment.

(2) Initiatives to reduce CCS costs

By setting the CCS cost targets for 2050 as one-fourth or lower for the separation and recovery costs, 70% or less for the transportation costs, and 80% or lower for storage costs, we expect to reduce the overall CCS costs in 2050 to approximately 60% or less compared with 2023. In addition, the target cost of separation and recovery by 2030 will be about half of the 2023 level.

To achieve these goals, the government will create research and development guidelines and promote research and development as well as demonstration of technologies that can significantly reduce costs.

Table 3 Results of CCS cost reduction estimate under certain conditions (RITE)

Yen/tCO_2	Current	2030	2050 Rate of reduction from the current cost
Separation and recovery [1]	4,000	2,000-yen level (2,000)	1,000 yen or less (1,000)
Transportation [2] (PL 20 km)	2,600 (500,000 tCO_2/year)	2,600 (500,000 tCO_2/year)	1,600 (3 million tCO_2/year)
Transportation [3] (Ship 1,100 km)	9,300 (500,000 tCO_2/year)	9,300 (500,000 tCO_2/year)	6,000 (3 million tCO_2/year)
Storage (land) [4]	6,200 (200,000 tCO_2/year/well)	6,200 (200,000 tCO_2/year/well)	5,400 (500,000 tCO_2/year/well)
Storage (at sea) [5] *Grounding	6,900 (200,000 tCO_2/year/well)	6,900 (200,000 tCO_2/year/well)	5,400 (500,000 tCO_2/year/well)
Total			
PL + land: [1] + [2] + [4]	12,800	10,800	8,000 (38% reduction)
PL + at sea: [1] + [2] + [5]	13,500	11,500	8,000 (41% reduction)
Ship + land: [1] + [3] + [4]	19,500	17,500	12,400 (36% reduction)
Ship + at sea: [1] + [3] + [5]	20,200	18,200	12,400 (39% reduction)

(Source) The 3rd CCS business cost and implementation scheme review working group (October 31, 2022)

(3) Promotion of public understanding of CCS businesses

For the time being until 2030, CCUS briefings will be held in each region at the initiative of the national government to provide careful explanations to give people an understanding of the significance and burden of CCS, the safety of CCS, the investment effect in the region, the effect of job creation, and the effect of promoting consumption, etc., and dispel concerns about CCS. In areas where CO_2 storage sites will be located, a mechanism will be examined to support hubs and clusters centering on the CCS operated by local governments or private entities, related industries, and job creation activities.

(4) Promotion of overseas CCS businesses

Since utilization of the promising overseas storage potential would be one of the leading options, we will start concrete negotiations with several countries on the premise of CO_2 exports from Japan.

In addition, the government will support the acquisition of interests by Japanese companies through the "Asia CCUS Network" based on the Asia Energy Transition Initiative (AETI), which is led by Japan, through the provision of risk money by JOGMEC, etc. It will also support the launch of the Joint Crediting Mechanism (JCM) and an international credit system derived from CCS.

(5) Examination for the development of the CCS Business Act

The background to the need for measures in the legal system regarding CCS businesses is explained below.

- The application of laws and regulations to CCS businesses (Mining Act, Mine Safety Act, etc.) is not clear, and the rules to be followed on the business operator side and the system of national supervision are ambiguous.
- There are no rules for preparing, measuring, transporting and providing data on the composition of gases in the CCS value chain of CO_2 separation and recovery, transport and storage.
- There is no mechanism to eliminate or prevent interference from third parties in order to ensure long-term business stability.
- While the establishment of CCS needs to be carried out with the understanding of residents, there is no state of compliance with security regulations, no mechanism for compensation for damages, etc., and it is not clear what the business operator should explain to residents.
- The security and monitoring responsibilities of the storage operator are unclear, and the business viability cannot be ensured unless the responsibility is eliminated.

To this end, examination will be made with the following policies:

- Establish the CCS Business Act as a new law as soon as possible.
- In light of the CCS value chain, the scope of the Business Act should cover "separation and recovery," "transportation," and "storage," and the policy is to require notification in principle in order to lower the barriers to introduction, since "separation and collection" projects are likely to be carried out by CO_2 emitters in many cases, and "transportation" projects can be carried out by various means, such as pipelines and ship transportation.
- On the other hand, since the "storage" business has many things in common with the oil and natural gas business, the planned policy is to adopt a permit system and take measures to enable exclusive use of the CO_2 storage reservoirs. In addition, referring to mining legislation, the policy is to take measures such as the establishment of a "common

system for land and sea" and a "new storage business right," the development of a security system and clarification of liability for compensation (no-fault liability), and the limitation of monitoring responsibility.

- In addition to the measures to provide a legal framework for the export of CO_2 to promote overseas CCS, the policy is to make recovered CO_2 available for sale to promote CCU/carbon recycling.

(6) Development and review of the "CCS action plan"

A CCS action plan will be developed and reviewed in a timely manner after a more detailed review of CCS annual storage amount targets, cost targets, technology development guidelines and suitable site investigation plans. Therefore, a panel of experts will discuss the matter this fiscal year.

The "annual storage amount target" will be further refined based on the progress of other decarbonization initiatives, as well as the refinement of the annual storage amount target to be achieved by 2050 by gathering industry opinions.

With regard to "cost targets/technology development guidelines," technical development guidelines will be prepared to achieve the targets after reviewing the CCS cost targets as necessary. Further refinements will be made based on progress in reducing costs.

With regard to the "suitable site investigation plan," efforts will be made to estimate the location of suitable sites for CO_2 storage in areas where existing data are available, while also examining the possibilities of geological structure surveys in coastal areas. The methods for assessment of risks posed by geographic faults will also be examined.

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Research & Coordination Group

Members (As of Apr. 2023)

Isamu Yagyu, Group Leader, Chief Researcher
Makoto Nomura, Deputy Group Leader, Chief Researcher
Yuji Higuchi, Deputy Group Leader
Takayuki Higashii, Chief Researcher
Tetsuya Deguchi, Associate Chief Researcher
Yoshinori Aoki, Associate Chief Researcher
Jun-ichi Shimizu, Associate Chief Researcher
Kin-ichiro Kusunose, Associate Chief Researcher
Minehiro Takahashi, Manager
Noritaka Mochizuki, Planning Manager
Sou Kuranaka, Planning Manager
Masao Hoshino, Vice Manager, Researcher
Yuka Matsugu, Vice Manager
Yumi Kobayashi, Senior Researcher
Natsuko Yasumoto, Senior Researcher
Yuji Yamashita, Senior Researcher (concurrent)
Nami Tatsumi, Chief
Michiyo Kubo
Mizuki Nagata

Office for Expo 2025 Osaka Kansai

Members (As of Apr. 2023)

Isamu Yagyu, Director
Naoki Kikuchi, Deputy Director
Nobuo Umeda, Deputy Director
Tetsuya Deguchi
Yuji Higuchi
Noritaka Mochizuki
Minehiro Takahashi
Nami Tatsumi
Michiyo Kubo
Junichiro Kugai
Satoru Yokoi
Saeko Mito
Shoichiro Hozumi

Research Efforts to Realize a Carbon-neutral Society

The Research and Coordination Group aims to i) searching for new research topics that enhance the research potential of RITE, proposing and implementing new research themes, ii) government support for the relation with international organizations such as IPCC (Intergovernmental Panel on Climate Change), ISO (International Standard Organization), iii) dissemination of RITE's technologies and Human development of the future generation iv) practical application of technology through industrial collaborative R&D, together with the research groups. These efforts lead to a creation of new policy implementation, R&D and innovation aiming at the global environment and the economy[1).

The office for EXPO 2025 Osaka, Kansai is founded in April, 2023 in order to introduce the carbon neutral technologies such as DAC, CCS as the innovative environmental ones that RITE has been implementing the Research and Development for many years. The staffs comprise the Research and Coordination Group, Chemical research group and CO2 Storage Research Group to communicate with the Japan Association for the 2025 World Ex-position and so on.

In 2022, the Clean Energy Strategy[2)] was summarized in May, 2022 and showed the feasible paths to reduce greenhouse gas emissions by 46% in FY 2030 from its FY 2013 levels and realize a carbon-neutral, decarbonized society by 2050. Also, the Cabinet approved the

Basic Policy for the Realization of GX (Green Transformation)[3)], so it is outlined at first.

1.1. Clean energy strategy

In May 2022, Advisory Panel of Experts of the Clean Energy Strategy summarized the interim report of the Clean Energy Strategy. The Chapter 1, based on Ukraine Crisis and electric stringency of energy supply and demand, summarizes the policy to secure the energy security and also accelerate the decarburization. The chapter 2 summarizes ①the industrial GX connecting to the decarbonization with the economy growth and development, ② the concrete approach of energy transform of industry, ③the concrete approach of the decarbonization of the area and life, and ④the policy to realize the GX.

This transformation for the carbon-neutral society is to transform economy, society and industrial structure consisted of fossil fuel since the Industrial Revolution to the center of clean energy. The in-vestment for the carbon neutral of 2050 is estimated with about 17 trillion yen in 2030, and about 150 trillion yen in the next ten years under the constant supposition (Table 1, Table 2).

Table 1 Investment amount for decarbonization

Investment amount for decarbonization

● Calucalated under certain assumptions about the investment amounts in major areas, the investment amount required for CN in 2050 will be approximately 17 trillion yen in 2030 alone and approximately 150 trillion yen in the next 10 years

Decarbonization-related investment	About 17 trillion yen per year	→ About 150 trillion yen in 10 years	
"Power source decarbonization / fuel conversion"	About 5 trillion yen	✓Renewable Energy ✓Hydrogen/ammonia ✓Manufacture of storage batteries	About 2 trillion yen About 0.3 trillion yen About 0.6 trillion yen
Decarbonization of manufacturing processes, etc.	About 2 trillion yen	✓Energy saving and decarbonization of manufacturing processes ✓Introduction of industrial heat pumps, cogeneration equipment, etc.	About 1.4 trillion yen About 0.5 trillion yen
end- use	About 4 trillion yen	✓Introduction of houses and buildings with high energy-saving performance ✓Introduction of next-generation vehicles	About 1.8 trillion yen About 1.8 trillion yen
infrastructure development	About 4 trillion yen	✓System enhancement cost ✓ Infrastructure development for electric vehicles ✓ Response to digital society	About 0.5 trillion yen About 0.2 trillion yen About 3.5 trillion yen
Research and development, etc.	About 2 trillion yen	✓Carbon recycling ✓ Development of manufacturing processes that contribute to carbon neutrality ✓Nuclear ✓ Implementation of advanced CCS projects	About 0.5 trillion yen About 0.1 trillion yen About 0.1 trillion yen About 0.6 trillion yen

Table 2 Step-by-step development of the GX League

GX League plan

GX League (supported by 440 companies)	Carbon credit market
✓ **Efforts in the GX League** ① Discuss and create a carbon-neutral sustainable future image for 2050 ② Discuss market creation and rule-making in the carbon-neutral era (example: certification system for zero-CO2 products, etc.) ③ Conduct voluntary emissions trading to achieve the goals set for carbon neutrality	✓ **Corporate origin** Value Credits reduced by GX League Participating Companies ✓ **Derived from the project** J-Credit JCM High-quality overseas volunteers credit (international standard credit), etc.

Issues for the gradual development of the GX League (example)

- How to implement emissions trading
- Mechanisms to further expand the number of supporters, including businesses with high emissions
- Setting more ambitious reduction targets and mechanisms to attract more investment to reduce emissions
- Mechanisms for GC market creation (initial demand, etc.)
- Increase the depth of transactions, expand the creation of absorption/removal credits, and appropriately respond to discussions on international carbon pricing and carbon credit trends overseas.

1.2. The basic policy for the realization of GX

In May, 2023, " Basic Policy for the Realization of GX - the roadmap of the next ten years -" was approved by the Cabinet. Advisory Panel of Experts of GX summarized the policy of the approach in the next ten year through GX implementation, to realize the achievement of greenhouse gas 46% reduction in FY 2030 and the international promise of the carbon neutral in 2050, to implement the trans-formation of the energy supply and demand structure to be connected for stable, cheap energy supply, to revolutionize industry and social structure of our country, and to realize the society which all nations including the generation can live with hope in the future.

Specifically, it is summarized as follows.

(1) Approach of GX to secure the energy steady supply

① Thorough Energy Efficiency Promotion

・ The foundation of the Energy Efficiency subsidy which can support investment project of plural years

・ For 5 main types of industry, the government shows the indication of the non-fossil energy transformation

② Main Power Supply of the renewable Energy

③ Nuclear Energy utilization

・ Implementing the next-generation innovation nuclear furnace in the site to decommission the nuclear power plant

④ Other important matters

・ Toward production and supply network construction of hydrogen / ammonia, the introduction of the support system based on the price differences of existing fuel

(2) Realization and implementation of such as "a growth-oriented carbon pricing"

① The forward investment support utilizing GX economy shift bonds

・GX economy shift bonds were founded and the forward investment of the 20 trillion yen scale for the next ten years was supported.

② GX investment incentive by the growth-oriented carbon pricing (CP)

③ Application of new finance technique

・the risk supplement plan (debt guarantees, etc.) in the social implementation stage of the GX technology.

④ International strategy, fair transformation, GX of small and medium Enterprises

・Realizing the implementation of "Asian Zero-Emission Community"

(3) A progress evaluation and necessary review

2. Research activities

In FY2021 and FY2022 (continuing project), the research project commissioned by the Ministry of Economy, Trade and Industry "Survey project on measures for stable fuel supply (Survey project on improving the CCS business environment and implementation roadmap toward carbon neutrality in 2050)" [4], and conducted a survey report at the "CCS Long-term Roadmap Review Committee" in FY2022, so the outline will be introduced in the below.

2.1. Hydrogen/Ammonia and trial calculation of thermal power plant cost with CCS[5]

In order to understand the positioning of CCS, we calculated the power plant cost when using decarbonized fuels (hydrogen (H_2), ammonia (NH_3)) produced by introducing CCS and the power plant cost when CCS is introduced into thermal power plant. The cost of power plant using H_2 and NH_3 was calculated by the Central Research Institute of Electric Power Industry based mainly on the results of literature research. The cost of thermal power plant with CCS was calculated by RITE based on the specifications of the Power Plant Cost WG[6] published in September 2021, in the case of transportation costs using a liquefied CO_2 transport ship. The Central Research Institute of Electric Power Industry is in charge of summarizing the results of these trial calculations. It should be noted that the prospects for technological progress and preconditions required for the cost estimation are arbitrarily set based on existing literature, etc., so it should be noted that the results of the estimation may change depending on future technological progress.

2.1.1. Trial calculation

Figures 1 and 2 show the images of the 10 cases calculated. The case of importing raw materials as fossil fuels such as natural gas and coal and using them in thermal power plants with CCS, the case where H_2 and NH_3 are produced overseas from natural gas and coal respectively, imported, and used in thermal power plants, and the case where H_2 is produced from domestically produced natural gas and used in a thermal power plant are calculated.

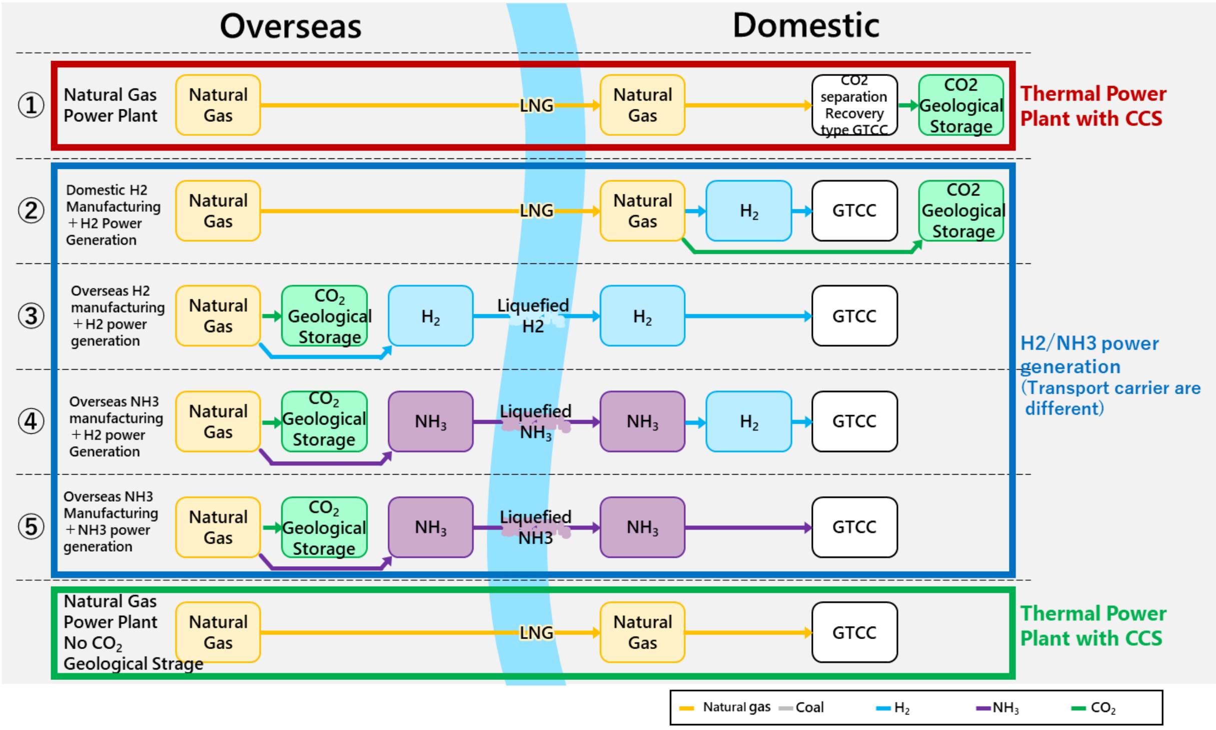

Fig.1 Trial calculation case of overseas natural gas + CO_2 underground storage[5)]

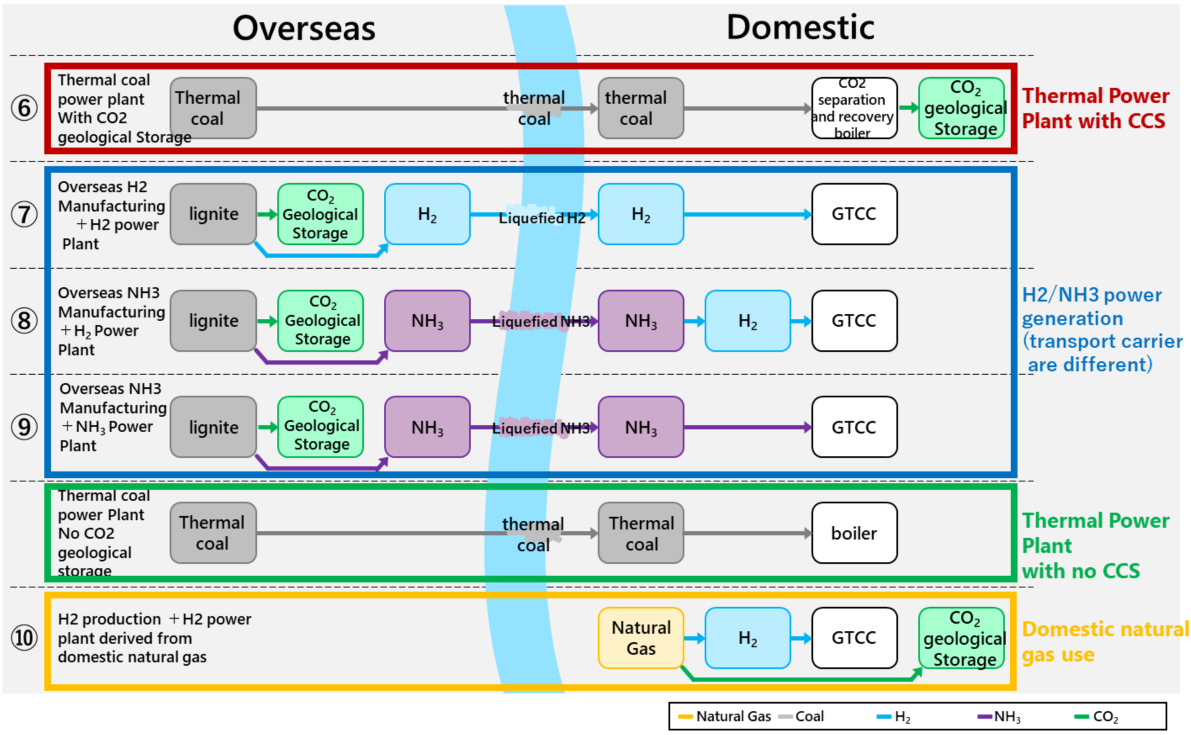

Fig.2 Trial calculation case of overseas coal, domestic natural gas + CO_2 underground storage[5)]

2.1.2. Trial calculation result

The trial calculation results are sorted by capital cost, operation and maintenance cost, fuel cost, social cost and policy cost. Social costs are CO_2 transportation and underground storage costs in Japan and overseas, including CO_2 transportation and underground storage costs during H_2/NH_3 production. Policy costs are costs covered by taxes, etc. required for each type of power source, such as the budget for technology development.

Regarding the results of this trial calculation, the power plant cost of thermal power plant with CCS (natural gas; ①, coal; ⑥) is cheaper than that of H_2/NH_3 power plant (natural gas; ②～⑤, ⑩, coal; ⑦～⑨). The reason is that under the conditions set this time, the transportation cost of natural gas and coal is cheaper than the transportation cost of liquefied H_2 and liquefied NH_3, and the cost of producing H_2 and NH_3 from natural gas/coal (energy loss, etc.) is higher than the CCS cost added to thermal power plant.

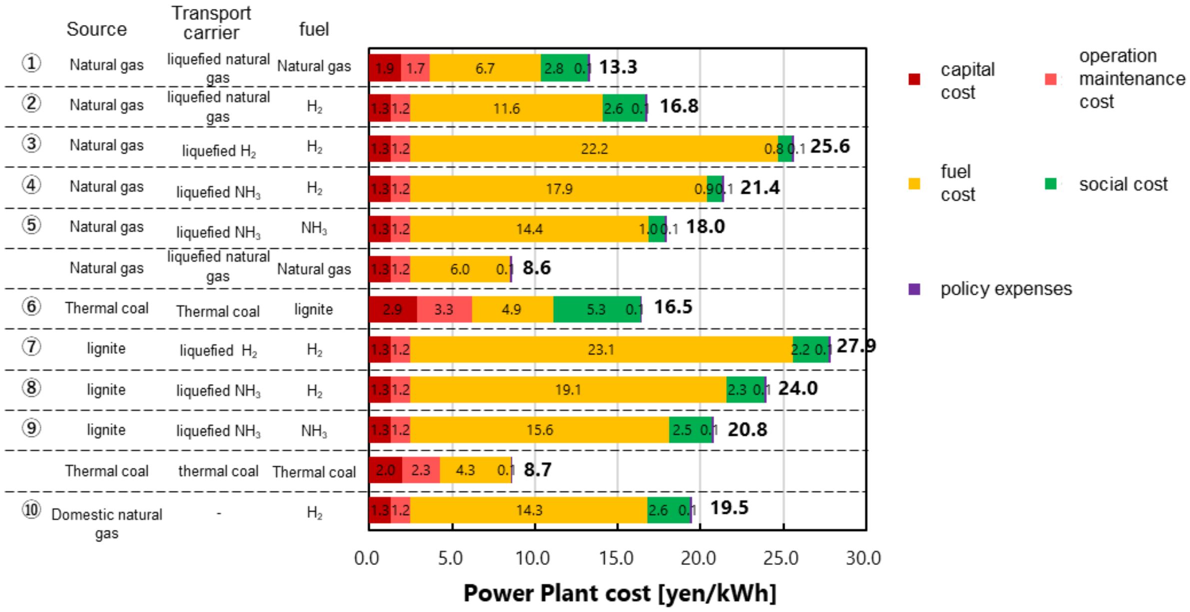

Fig.3 Trial calculation case of Power Plant Cost[5)]

2.2. Overseas examples of frameworks for the spread of CCS[7)]

We investigated overseas cases to consider the introduction of CCS in Japan.

In many cases, the spread of CCS requires incentive measures that can ensure the predictability of the business. In particular, when CO_2 storage is aquifer storage, unlike enhanced oil recovery (EOR), business profits cannot be expected, so sufficient incentive measures are essential.

2.2.1. Overseas examples of incentive measures and regulations

Regarding incentive policies and regulations for overseas commercial CCS projects, as a result of re-searching projects in Norway, Alberta, Canada, Saskatchewan, the United States, Australia, the United Kingdom, and the Netherlands, direct subsidies to CAPEX and OPEX mainly consist on combine support. Regarding OPEX support, except for the United States, which has introduced tax credits, many nations have introduced that emission credits are exempted or granted, and carbon taxes are exempted, but not direct subsidy. Since all of these aids are intended for pre-ceding projects, they are generous subsidies, and the subsidy rate is estimated to be around 100%.

Table 3 Overseas cases of regulations and incentives[7)]

	CAPEX Support	Operational Support	Subsidy Rate
Norway Longship	・Direct Subsidy	・10-years Direct Subsidy ・Emission credit exemption or provision	Direct Subsidy 67% ＋ Emission credit exemption・grant20%
Canada Alberta Quest	・Direct Subsidy	・10-years Direct Subsidy ・Carbon Tax Exemption ・Double Offset Credit of CO2 Storage	100%
USA	・Direct Subsidy (under consideration) ・Low-interest loans for pipelines (under consideration) ・Investment tax credit for clean coal ・Obligation guarantee for fossil fuel CCS	・Tax credit according to storage amount (or use amount)	unknown
Australia Moomba	・Direct Subsidy (small amount)	・Carbon credit exemption ・Granting carbon credits for 25 years	>100% (25 years)
England Hub&Cluster	・ Direct Subsidy for transport/storage and industrial CCS, and thermal power CCS	・Various subsidies. 15 years for industry ・Emission credit exemption ・Transportation/storage: Collection of usage fees	100% ＋ α (15 years)
Netherland Porthos	・Direct Subsidy in EC (Equivalent amount reduced from SDE++)	・Fixed-price purchase for 15 years ・Emission credit exemption ・Transportation/storage: Collection of usage fees	100% ＋ α (15 years)
Canada Saskatchewan BD3	・Federal Direct Subsidy ・Public funding by state governments	・Transfer to electricity charges	100%

Table 4 Features of Overseas regulations and incentives[7)]

Scheme	Analysis	Remarks
CAPEX Support	Direct subsidies are basically for advanced projects.	Invest in businesses with high ripple effects.
	The government faces the risk of non-operation. Early recovery of investment for businesses.	In Quest, Alberta, to avoid non-operating riskImplement CAPEX payment in 8 stages.
	For investment tax reduction, the amount of tax paid must be greater than or equal to the amount of tax reduction. Investment tax cuts are unfavorable to start-up companies.	
Operational Support	High compatibility with existing schemes.	
	Direct subsidies are basically for advanced projects.	Invest in businesses with high ripple effects.
	Retained tax credit must be taxable amount ≥ tax reduction amount.	In the 45th quarter of the United States, there was a movement to subsidize unspent credits.
	Tax credits reduce revenue.Emission credit exemption and carbon tax exemption do not increase or decrease revenue.	US EOR is $70/bbl due to royalty and corporate tax increases Excess revenue.
	Price drop risk for emission credits.	If carbon prices fall below a certain level in the UK and the Netherlands,Introduce a carbon tax.
Financing assistance	Only advantages for business operators. Large operational burden on the administrative side.	The U.S. DOE has a department specializing in debt guarantees.

2.2.2. Toward the introduction of CCS in Japan

Many of the commercial CCS in operation overseas are injected into oil fields (locations with a lot of underground information) for the purpose of EOR from emission sources that separate high concentrations of CO_2 in existing processes[8)]. Based on this situation, it is thought that the total investment amount will be reduced by combining CCS implemented in Japan with less additional cost for separation and recovery and storage site development, making CCS more acceptable. CCS with such a combination can be a powerful candidate, especially in the early days of its spread.

However, the emission source that separates CO_2 at high concentration in the existing process is considered to be relatively small (scale of tens of thousands of tons per year), which is assumed to be higher than CCS from a large emission source (scale of several million tons per year). CCS is an external diseconomy and cost reduction is essential. Therefore, in order to aim for the wide-spread spread of CCS in the future, it is necessary to con-sider a hub and cluster that accumulates CO_2 emitted from multiple emission sources, transports and injects it as a shared infrastructure. By adopting a hub and cluster, we can expect cost reductions through economies of scale, and we can also expect to reduce cross-chain risk*[1] because multiple businesses participate.

Whether introducing small-scale emission sources or introducing large-scale emission sources, in any case, for the spread of CCS, it is necessary to develop incentive measures for business operators working on CCS to be able to decide investment.

*[1] Cross-chain risk: The risk that the suspension of operation of any of the collection, transportation, or storage chains will force the suspension of all chains.

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) (Fig. 4). The IPCC released the WG1 contribution to the Sixth Assessment Report in August 2021, followed by the release of the WG2 and WG3 Report in February and April 2022 respectively, and the Synthesis Report was released in March 2023. The Seventh Assessment cycle will start, beginning with the IPCC session scheduled to be held in July. RITE has also been supporting METI through information gathering, analysis, report, advise, etc.

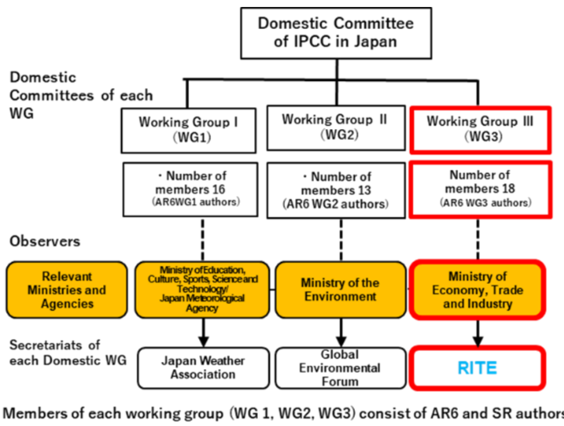

Fig.4 Committee structure and RITE

3.2. ISO

ISO (International Standard Organization) is an organization composed of 168 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 international 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 (capture, transportation, and geo-logical storage of CO_2) 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 (Fig. 5).

As of the end of March, 2023, twelve standards related to the CCS have been published from ISO / TC265. Currently TC265 as a whole are becoming more active as seven documents are under development including three new projects started in 2022 and two systematic review projects. In particular, CO_2 ship transportation is attracting attention as a powerful means of transportation from emission sources to CO_2 storage site. WG7 has been newly established to deal with issues specific to CO_2 ship transportation, and the development of standards has been started.

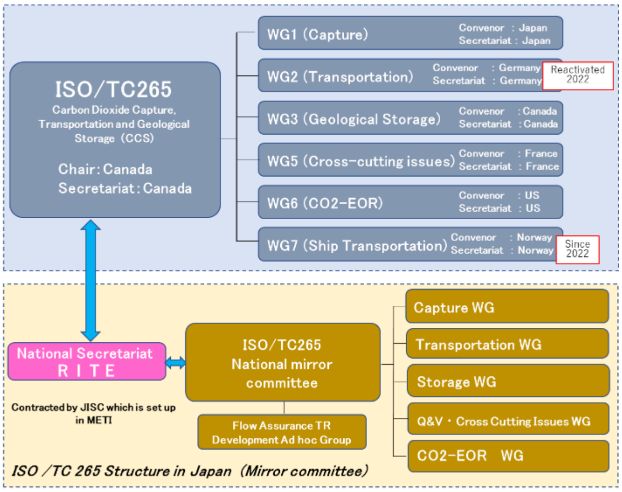

Fig.5 ISO/TC265 structure

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 university/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 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 (Fig. 6).

However, in 2022, as in 2021, the number of students remained at 58 due to the impact of the new coronavirus (54 in 2021), but classes and workshops have resumed, and we plan to actively respond in the future.

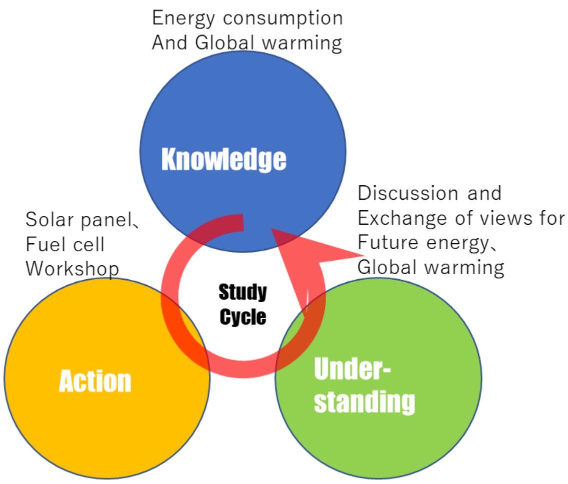

Fig.6 Human resource development by RITE
(Elementary, Junior and high school students)

<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 (Fig. 7). For example, Nara Institute of Science and Technology (Nara Institute of Science and Technology) 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, and are promoting research and education on CO_2 separation and recovery technology.

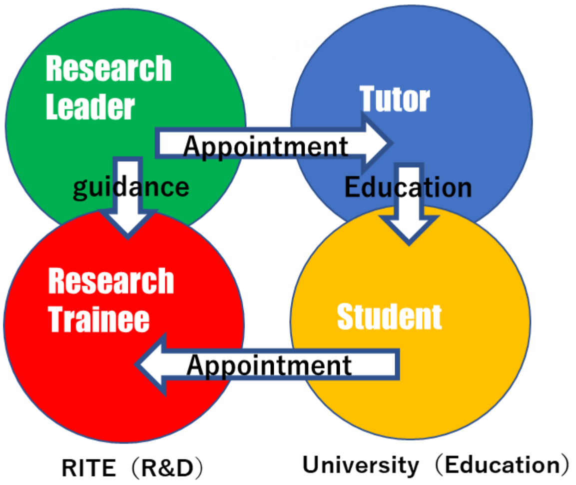

Fig.7 Human resource development by RITE （University ＆ Post graduate students）

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 diverse 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 2022, of the patents for which RITE is the sole or joint applicant, 17 domestic applications and 16 foreign applications are pending patent applications, and the registered rights are maintained. It holds 72 domestic patents (including 8 under license to companies) and 52 foreign patents (12 of which are licensed to companies).

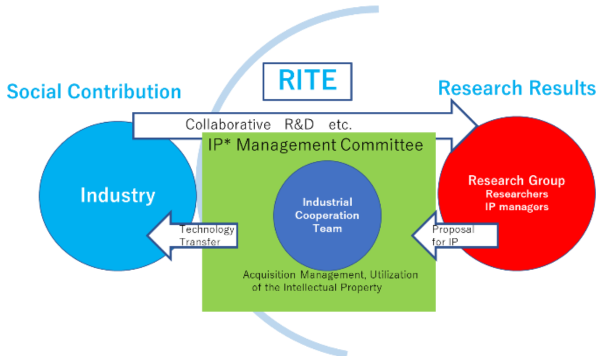

Fig.8 Strategic IP management and industrial collaboration

5. Conclusion

In April 2023, RITE established the office for Expo 2025 Osaka Kansai, and is considering exhibiting negative emission technology (Direct Air Carbon Capture and Storage: DACCS) at EXPO 2025 Osaka Kansai.

To realize 2050 Carbon neutrality is almost im-possible with ordinary efforts, and RITE needs to make maximum efforts to spread carbon neutral technologies. In December 2021, RITE conducted the recognition survey of DACCS, and found that nearly 70% said they did not know anything about DACCS. RITE would like to make maximum efforts to increase the public recognition of DACCS technologies at EXPO 2025 Osaka Kansai.

The Research and Coordination Group not only collects domestic & foreign policy and technology information, but promotes the technology development in order to aim the social implementation in 2050 with Research Group. Thereby, RITE can contribute to the achievement of "a balance be-tween the global environmental protection and economic growth".

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Systems Analysis Group

Members (As of Apr. 2023)

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
Hironobu Yamakawa, 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
Jubair Sieed, Researcher
Dahyun Kang, Researcher
Kiyomi Yamamoto, Assistant Researcher
Misako Saito, Assistant Researcher
Sachiko Kudo, Assistant Researcher
Ryoko Minamimura, Assistant Researcher

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.

This article reports research status for the international collaborative model comparison project, commonly called "EDITS" (Energy Demand changes Induced by Technological and Social innovation, commissioned project entrusted by the Ministry of Economy, Trade and Industry), which has been developing scenarios to support achieving of a society with low energy demand through technological and social innovation. For further EDITS project information, refer to RITE Today vol. 17 (2022).

1. Introduction

Inducing social changes toward the low energy demand society to achieve the 2°C and 1.5°C goals not only on the energy supply side but also on the energy demand side is crucial. Moreover, it is not just a reduction in demand but a society that brings about a "virtuous cycle between the economy and the environment," in other words, the actualization of a society that increases wellbeing along with lowering demand is consequential. Separately, while developing models under the ALPS (Alternative Pathways toward Sustainable Development and Climate Stabilization) project, we developed quantitative scenarios that are consistent globally, across energy supply and demand sides, and between demand side sectors by following the scenario protocol in the EDITS project and harmonizing with other research institutes.

1.1. Importance of energy demand side measures and scenario trends

The Intergovernmental Panel on Climate Change (IPCC) released its 1.5°C Special Report (SR15)[1] in 2018. In the report, various emission pathways to achieve 1.5°C were presented, and in particular, the Low Energy Demand (LED) scenario[2] was the focus of attention. This shows a much smaller picture of energy consumption than the final energy demand, as would normally be shown in model analysis. Also, this could contribute not only to combating climate change, but also to the simultaneous achievement of the Sustainable Development Goals (SDGs). The study in Ref. 3) also points out the fast technological progress of small-scale technologies, which are often found on the demand side. It points out that the distributed small-scale technologies have been increasingly utilized in recent years due to the energy liberalization market, technological innovation and digitalization. The IPCC Sixth Assessment Report (AR6)[4] includes a new chapter dedicated to demand-side measures, with a survey of current papers and other information, and states that "Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors by 40-70% by 2050 compared to baseline scenarios.", and "Demand-side mitigation response options are consistent with improving basic well-being for all." (Summary for Policymakers: SPM, C.10).

Figure 1 shows the overall picture of global warming measures. Traditionally, social structural and lifestyle changes have been mostly analyzed as exogenous scenarios. In such cases, however, it was unclear what measures would achieve low energy demand. Lifestyle change is mostly discussed in the context of education, and while the importance of education is understandable, there has not been enough analytical research on the subject due to the long-time scale and uncertainty of the effects to be shown as a major global effect. This study is novel in that it attempts to quantitatively analyze the possibility that technological changes, such as digitalization, will trigger changes in social structure and lifestyles. Unless there is a change in the baseline emissions themselves to a lower level due to advances in energy demand side technologies, it will be very difficult to achieve carbon neutrality in 2050 or significant emission reductions.

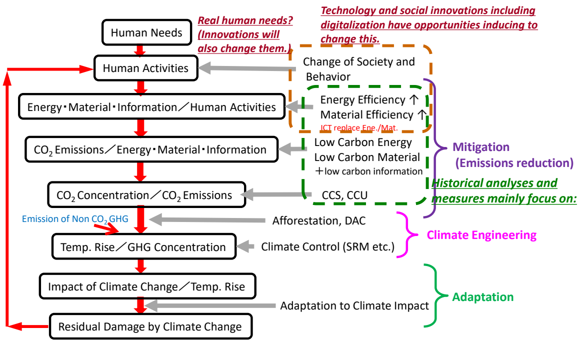


Figure 1 Basic structure of global warming countermeasures and changes in social structure and lifestyles

1.1. Example of evaluation of the feasibility of low energy demand by DX

Digital transformation (DX) and other innovations have created potentials to reduce implicit costs and induce the circular and sharing economy through relatively low costs (e.g., Ref. 5)). The IPCC Sixth Assessment Report (AR6)[4] also presents Figures 2 and 3 as a result of reports on the effects of each measure on reducing energy demand and CO_2 emissions from various studies, including the Ref. 5). Although there is a large range of estimates, it has been shown that fairly large reductions in energy demand and CO_2 emissions can also be expected. On the other hand, these analyses evaluate reduction rates for each measure and do not show consistent and quantitative energy reductions or CO_2 emission reductions across sectors. Also, as noted above, the IPCC AR6 states that "Demand-side measures and new ways of delivering end-use services could reduce global GHG emissions in the end-use sector by 40 to 70 percent by 2050 compared to the baseline scenario." However, each measure is evaluated by cumulating each of the measures and is not necessarily estimated across sectors using a consistent and quantitative model, including the cost of the measures.

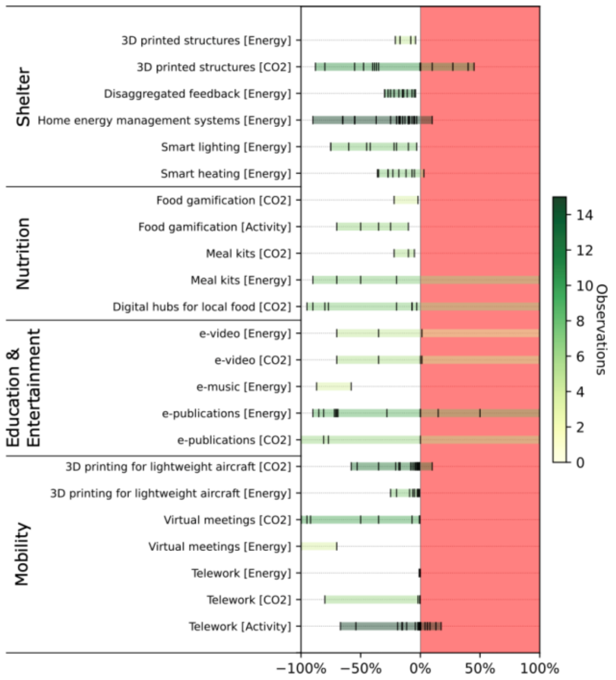


Figure 2 Impact of digitalization on energy consumption and CO_2 emissions (Source: Ref. 4))

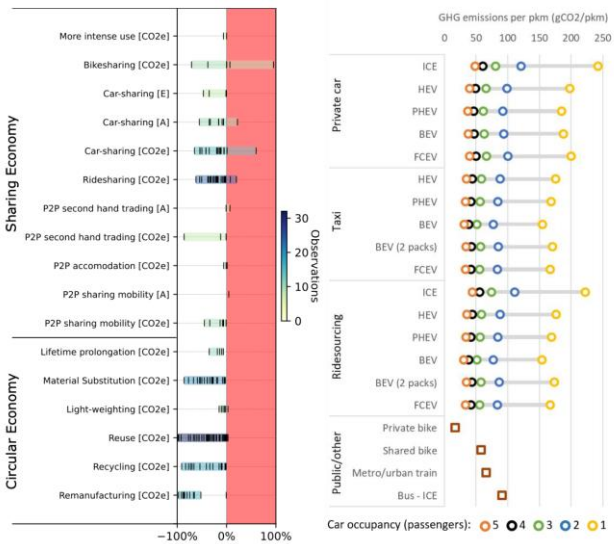


Figure 3 Impact of the sharing and circular economy on energy consumption and CO_2 emissions (Source: Ref. 4))

2. Assumptions on analysis scenarios

Comprehensive and quantitative analysis of complex systems and clarification of their usefulness and challenges will be a powerful driving force for society as a whole to promote a society with low energy demand, such as a circular and sharing economy, induced by DX. What the EDITS project will explore and attempt to present as a quantitative scenario is not simply a demand reduction, but a scenario that will bring about "the Virtuous Cycle of Environment and Economy," i.e., a society in which demand is reduced while wellbeing is improved.

2.1. Narrative scenario

In the EDITS project, the Narrative WG presented a qualitative “high wellbeing with low resource use (High-with-Low)” scenario that considers the drivers shown in Figure 4[6].

This scenario is a worldview that combines the advancement of digitalization, innovation through new combinations, and decent living standards (DLS), and assumes that low demand (in energy and various materials and products, etc.) can be achieved while increasing wellbeing. The relationship between the elements is shown in Figure 5.

In previous Integrated Assessment Model (IAM) analyses, final energy consumption is often given exogenously based on population and GDP scenarios, and elasticities are used to estimate final energy consumption under climate change measures. However, industrial and other demands are only a result of consumption behavior that enhances wellbeing. Energy demand is only a derived demand to obtain products and services. The method is highly novel in that it focuses on changes in consumption behavior to obtain products and services, estimates the resulting reduction in demand for material products and energy, and then estimates the overall energy supply and demand, as well as the resulting CO_2 emissions. Through this, the effects of demand-side measures will be visualized and used as an incentive for social change toward the realization of “the Virtuous Cycle of Environment and Economy”.

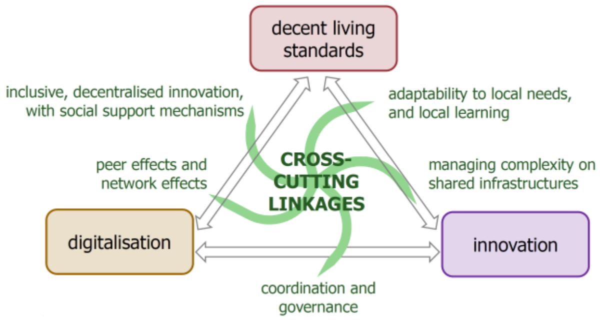


Figure 4 Assumed drivers for qualitative scenario 'High-with-Low' (Source: Ref. 6))

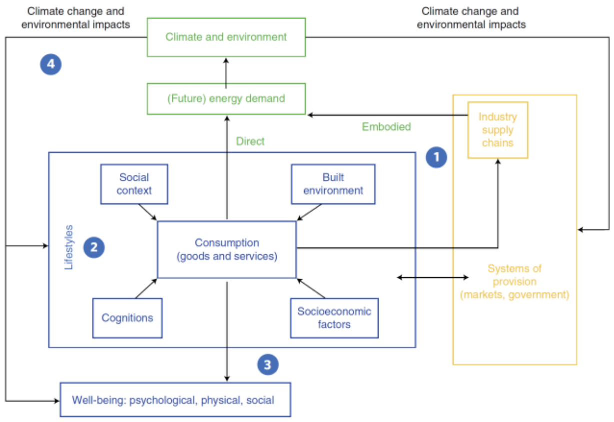


Figure 5 Relationship among the elements in qualitative scenario 'High-with-Low' (Source: Ref. 6))

2.2 Assumptions in quantitative scenario analysis

The potential for achieving a low-energy demand society as well as the impact on emission reduction of GHG realized by the circular and sharing economy mainly induced by DX, are quantitatively estimated using the global energy assessment model DNE21+. It is noted that currently only a fraction of spillover effects is considered for estimates due to the limited availability of quantitative data. In addition to that, large uncertainties exist in the assumed precondition for the model, leaving us with issues of acquiring and reflecting better data. DNE21+ conducts a bottom-up assessment of carbon-intensive products such as iron and steel, cement, or chemical products, enabling us to consistently analyze the effects of the circular and sharing economy such as a decrease in basic material production or accompanying reduction in energy consumption.

Quantitative assumptions of scenarios based on qualitative scenario drivers shown in Figure 4 are conducted. Table 1 shows scenario assumptions of circular economy (CE) induced by DX (hereafter in this report, sharing economies shall be included in circular economy and thus described as "CE" as a whole). Table 2 presents the titles of the scenarios analyzed and their assumptions. For emissions scenarios, the Baseline scenario without any specific emissions scenario, and the B2DS scenario that assumes 2°C with >66% probability, are assumed. For B2DS, GHG neutrality by 2050 is assumed to be achieved within each major developed country including Japan.

As a potential impact of advanced digitalization and innovation on the demand side, in addition to the CE, the provision of flexibilities on the electricity demand side which contribute to increased consumption of variable renewable energies (VRE) is considered. More specifically, technologies such as BEV, PHEV, heat-pump water heaters, and cogeneration systems are assumed to be able to provide a capability of more flexible demand adjustment towards VRE (especially PV) supply within the electricity load curve of DNE21+, than the standard scenario ("FL" scenario). Grid integration costs are assumed to be able to reduce, considering the possibility of reducing battery storage size in the grid due to the reverse power flow from BEV and PHEV.

In many cases, the demand-side technologies are in smaller sizes, called granular technologies. The learning rates of these technologies tend to be observed as being higher in general, due to their quicker development cycles. Although DNE21+ has already assumed larger cost reductions for PV, wind power, or EV batteries, even in the standard scenario, we have assumed a scenario in which the learning rates of these relatively smaller-scale technologies are further higher ("GR" scenario) However, it is noted that this scenario is an exogenous assumption, and should be treated as a reference scenario to be compared with the results of other scenarios.

Table 1 Scenario assumptions of circular economy (CE) induced by DX

Changes due to digitalization	Direct impacts	Indirect impacts	Model assumptions (tentative)
1) Ride and car-sharing associated with fully autonomous cars	- Energy consumption reductions due to ride-sharing	- Reductions in consumption of basic materials, e.g., iron and steel, plastics, tire, glass, and concrete, due to reductions in number of cars associated with car-sharing - Reductions in freight shipping => 8)	- Iron and steel production: -4% (for cars and multi-story car park) - Plastic production: -1% - Tire production (for cars): -28% - Glass production (for cars): -28% (corresponding reductions in energy consumption is assumed.) - Cement production: -1% (only for multistory car park)
2) Virtual meeting and teleworking	- Reductions in travel service demand and the associated reductions in energy consumptions in transport sector	- Potential reductions in numbers of commercial building, and the resulting reductions in iron and steel, concrete, and others *[Not yet considered]*	- Reductions in person-km travel by passenger cars, buses, and aircraft by 10%
3) E-publication etc.	- Reductions in paper consumptions due to large deployment e-publications etc.	- Potential reductions in freight services for papers *[Not yet considered]*	- Reductions in paper/pulp by 20%
4) Recycling and reductions in apparels due to e-commerce and other digitalization	- Reductions in energy consumptions for apparel productions	- Potential reductions in energy consumption at shopping centers, and the reductions in iron and steel, concrete due to less building construction, etc. *[Not yet considered]*	- Reduction in new productions of apparels by 20% (No explicit modeling for apparels in DNE21+, and corresponding reductions in energy consumption is assumed.)
5) Loger life time of buildings due to improv. In city planning	- Potential reductions in cement and steel due to longer life time of buildings		- Longer lifetime of building: +40%; the related reductions in cement (-3%) and steel (-3%) productions
6) Reductions in food losses due to better demand projection	- Reductions in nitrogen fertilizer, plastics, etc. and the resulting energy consumption reductions - Potential reductions in energy consumption at supermarkets etc. - Red. In CH_4 and N_2O	- Reductions in freight shipping services => 8) - Potential reductions in construction for supermarkets etc., and the resulting reductions in iron and steel, concrete, and others. *[Not yet considered]* - Potential increases in afforestation due to increase in rooms of land area. *[Not yet considered]*	- Reduction in petrochemical products including ammonia by 1% - Reduction in plastics by 1% - Reduction in paper and pulp by 0.5% - Reduction in transport services by 1% and others (according to I/O analysis results) - Reduction in CH_4 and N_2O emissions: 493 $MtCO_2eq$/yr in 2050
7) AM (3D-printing) for applying aircraft	- Reduction in aluminum and steel production - Reduction in electricity for productions	- Energy efficiency improvements of aircraft and the energy consumption reductions - Energy efficiency improvements of cars and the energy consumption reductions *[Not yet considered]*	- Reduction in aluminum and steel productions by 1% and 0.02%, respectively - Reduction in electricity consumption by 1% - Increase in energy efficiency of aircraft by about 10%
8) Reductions in freight shipping services due to reductions in basic materials and products	- Energy consumption reductions in freight shipping		- Reduction in freight shipping demand by 1%

Red: residential sector, **Green**: commercial sector, **Blue**: transport sector, **Purple**: industry sector, **Brown**: Non-CO_2 GHGs etc.

Table 2 Assumed scenarios for circular economy (CE) induced by DX

	Emissions reduction	Energy demand reductions due to mainly digitalization						Demand flexibilities in electricity (EV, HP, CGS)	Rapid cost red. in granular tech's, e.g., PV, Wind, EV
		Transport 1)	Residential 2, 3, 4)	Building 5)	Food 6)	Industry 7)	Spill over 8)		
BL-Std	Baseline (non specific climate policies)	—	—	—	—	—	—	—	—
BL-Mobil		X							
BL-Resid			X						
BL-Build				X					
BL-Food					X				
BL-Ind						X			
BL-All_CE		X	X	X	X	X	X		
BL-All_CE+FL		X	X	X	X	X	X	X	
BL-All_CE+FL+GR		X	X	X	X	X	X	X	X
B2DS-Std	B2DS (well below 2C; NDCs in 2030; CN by 2050 in G7 countries)	—	—	—	—	—	—	—	—
B2DS-Mobil		X							
B2DS-Resid			X						
B2DS-Build				X					
B2DS-Food					X				
B2DS-Ind						X			
B2DS-All_CE		X	X	X	X	X	X		
B2DS-All_CE+FL		X	X	X	X	X	X	X	
B2DS-All_CE+FL+GR		X	X	X	X	X	X	X	X

Note) For Shared Socioeconomic Pathways (SSPs), this study employed the SSP2, middle of the road scenario.
The rebound effects other than the ones associated with the reductions in carbon prices are not considered.

3. Results

Firstly, the results of the Baseline scenarios are presented. Figure 6 and 7 show the reductions in global final energy consumption and in global GHG emissions, respectively, from the standard scenario (Std) where CE progress is not assumed. Although it is in the analysis stage considering only limited spillover effects, it is indicated that considerable cross-sectoral energy-saving effects can be expected by realizing the assumed CE. The contribution of car sharing and ride sharing, induced by the realization of fully automated cars, to low energy demand is significant as the effects of DX assumed in this analysis, including the spillover effects on the industrial sector. Besides, large impacts can be expected by other changes such as virtual meetings. It is shown that reducing food loss has the potential to greatly promote the reduction of non-CO_2 GHGs in particular.

Similarly, for the B2DS scenarios, Figure 8 and 9 show the reductions in global final energy consumption and in global GHG emissions, respectively, from the standard scenario (Std) that does not assume CE progress. Even considering only the limited number of CE cases and spillover effects, it is indicated that about 6% of the world's current total final energy consumption and around half of the energy saving estimated to be economically efficient under the 2°C target could be additionally saved by CE in 2050. Under the condition where the emission reduction targets are defined, the assumed CE measures are relatively inexpensive, and the dependence on the technologies recognized as the measures with marginal costs, such as carbon dioxide removal (CDR) including bioenergy with CCS (BECCS) and CO_2 direct capture and storage (DACCS) can be reduced. Although the final energy consumption reduction effect is significant, the CO_2 reduction effect is not estimated as large as the energy consumption, because it includes a reduction in CO_2 intensity on the energy supply side. However, the cost reduction effect is huge.

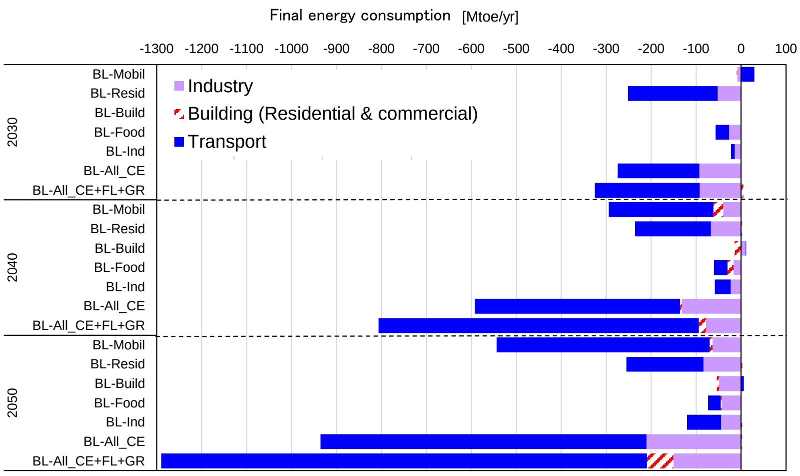


Figure 6 Changes in global final energy consumption under CE scenarios (Baseline)

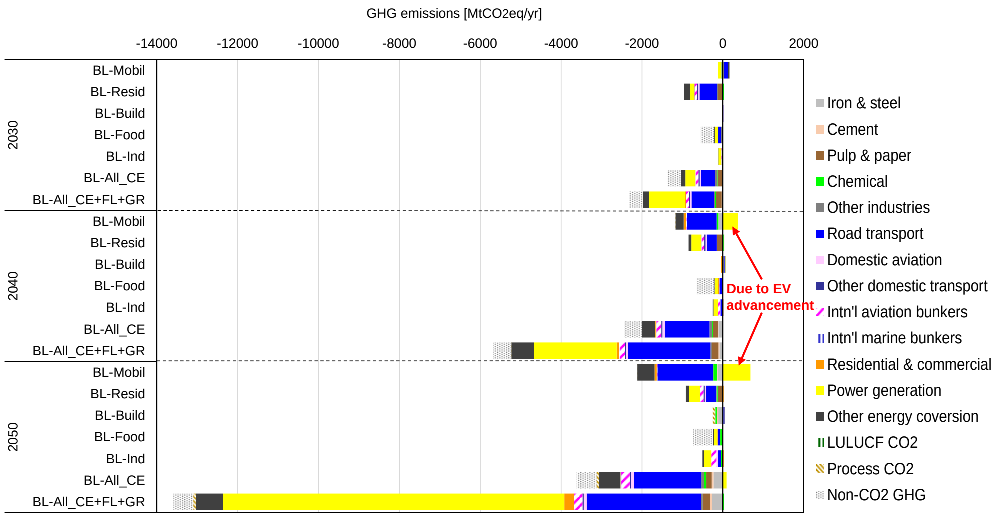


Figure 7 Changes in global GHG emissions under CE scenarios (Baseline)

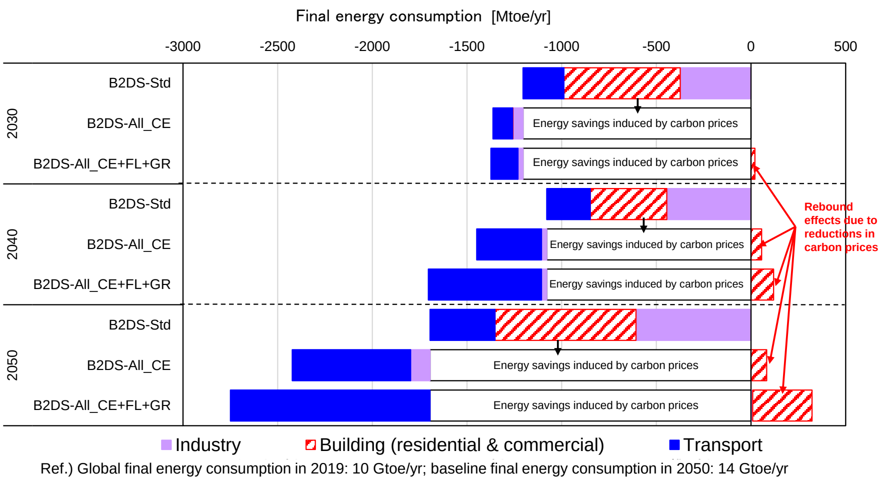
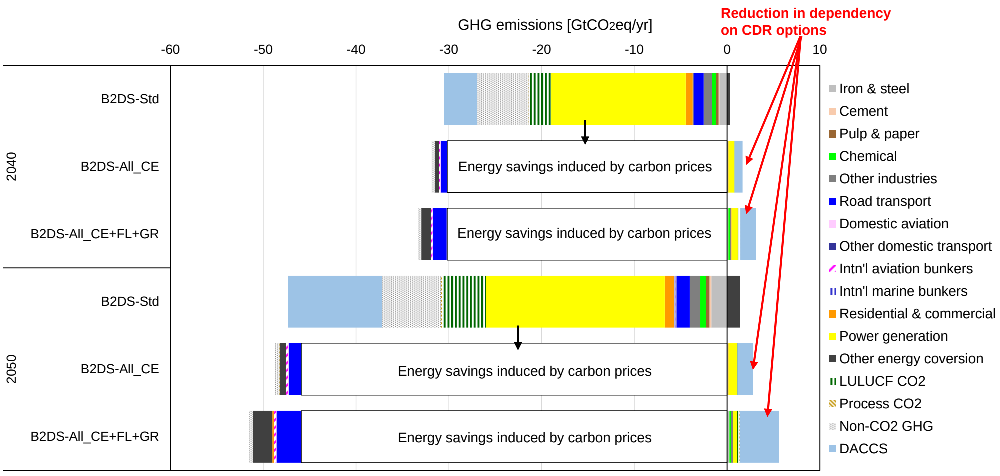


Figure 8 Changes in global final energy consumption under CE scenarios (B2DS)



Ref.) Global GHG emissions in 2019: 59 $GtCO_2eq./yr$; baseline GHG emissions in 2050: 73 $GtCO_2eq./yr$

Figure 9 Changes in global GHG emissions under CE scenarios (B2DS)

Figure 10 shows global final energy consumption per capita by region. Developed countries are consuming more energy than needed especially on the demand side, and the realization of low energy demand is induced and the international disparities of energy consumption per capita is reduced in 'High-with-Low' scenario.

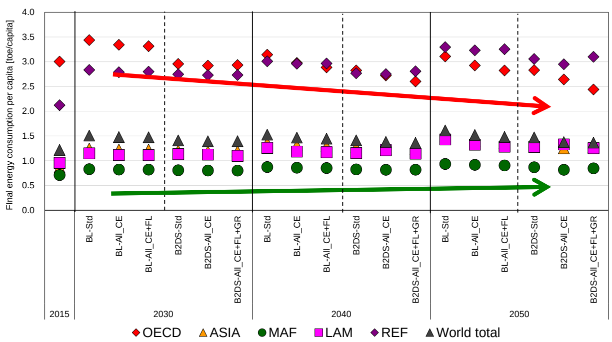


Figure 10 Final energy consumption per capita by region

Table 3 shows the changes in the total energy systems costs under the CE scenarios compared to those in the standard scenarios, and Figure 4 shows the CO_2 marginal abatement costs in B2DS. It is estimated that the promotion of CE induced by DX will lead to a significant reduction in energy systems costs. In particular, a significant cost reduction in the whole society induced by ride-sharing and car-sharing using fully automated cars can be expected, and also the changes in the residential sector, such as teleworking, and the reduction of food loss would have relatively high potential to reduce energy systems costs.

In addition, as Table 4 indicates, a reduction in marginal CO_2 abatement costs (about 20-30 %) can be expected in achieving long-term targets such as 2°C goal.

Table 3 Reductions in energy systems costs: under CE scenarios (unit: Billion USD/yr)

	Scenarios	Mobil	Resid	Build	Food	Ind	All CE	All CE +FL	All CE +FL+GR
Annual average in 2030-2040	Baseline	▲547	▲339	▲1	▲57	▲4	▲894	▲894	▲963
	B2DS	▲556	▲352	▲0	▲64	▲5	▲926	▲928	▲1038
Annual average in 2040-2050	Baseline	▲1601	▲459	▲1	▲74	▲7	▲1971	▲1971	▲2085
	B2DS	▲1635	▲477	▲6	▲90	▲14	▲2037	▲2038	▲2266

Note) The changes in the costs compared those in the standard scenarios for each emissions reduction target.

Table 4 CO_2 marginal abatement costs in B2DS (unit: USD/tCO_2eq)

	B2DS-Std	B2DS All-CE	B2DS All-CE+FL	B2DS All-CE+FL+GR
2040	68–310	57–238	57–240	50–195
2050	146–739	123–524	122–522	60–364

Note) The cost ranges are those due to the differences in emissions targets across countries

4. Summary

This fiscal year, as a consistent and quantitative scenario across regions/countries and sectors, modeling and preliminary calculations were performed in the DNE21+, the global energy assessment model, lining with the qualitative scenario “high wellbeing with low resource use (High-with-Low)” presented by the Narrative Group. We modeled, analyzed, and evaluated only CE that some DX can induce due to the difficulty of quantitative estimation. In addition, as for the spillover effects, only limited effects were considered due to the difficulty of quantitatively estimating. Despite these, the corresponding energy reduction and GHG emission reduction effects were evaluated. Additionally, a reduction in energy system costs and in CO_2 marginal abatement costs in the B2DS scenario (below 2°C, >66% probability) were estimated. This can be said to be a scenario that indicates the possibility of a "virtuous cycle between the economy and the environment" or "high wellbeing with low resource use."

However, the estimate of final energy consumption in the Low Energy Demand (LED) scenario addressed in IPCC SR1.5 is far below the estimate in this analysis. Thus, it is necessary to quantitatively model various measures which could be induced by DX, as well as social changes, such as CE that can be influenced derivatively, and conduct quantitative scenario evaluations. On the other hand, it is also essential to deepen our understanding of the reasons why the gaps occur with the LED scenarios. Further progress in quantitative and comprehensive analysis, and on the contrary, if gaps still exist, deepening understanding of those gaps will be indispensable for the evaluation in the next IPCC reports. In addition, it is essential to assess the energy reduction side, proceed with the analysis, including the rebound effect, and conduct a more comprehensive evaluation.

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Molecular Microbiology and Biotechnology Group

Members (As of Apr. 2023)

Masayuki Inui, Group Leader, Chief Researcher
Haruhiko Teramoto, Associate Chief Researcher
Kazumi Hiraga, Associate Chief Researcher
Hajime Terasaki, Associate Chief Researcher
Masato Miyamoto, Associate Chief Researcher
Yuya Tanaka, Senior Researcher
Masako Suda, Senior Researcher
Yukihiro Kitade, Senior Researcher
Naoto Kato, Senior Researcher
Satoshi Hasegawa, Senior Researcher
Akira Watanabe, Senior Researcher
Takahisa Kogure, Senior Researcher
Takeshi Kubota, Senior Researcher
Kiyoshi Oi, Senior Researcher
Tetsu Shimizu, Researcher
Akiyoshi Higo, Researcher
Natalia Maria Theresia, Researcher
Norimasa Kashiwagi, Researcher
Jyumpei Kobayashi, Researcher
Ryoma Hashimoto, Researcher
Naoki Saruya, Researcher
Yuki Nozaki, Researcher
Dyah Candra Hapsari Subagyo, Researcher
Takafumi Shimizu, Researcher
Dita Grinanda, Researcher
Miyuki Shintaku, Researcher
Takayuki Kuroishikawa Researcher
Junko Watanabe, Assistant Researcher
Yuko Ikenaga, Assistant Researcher
Shoko Minakuchi, Assistant Researcher
Miyuki Nagamori, Assistant Researcher
Kae Naito, Assistant Researcher
Noriko Ikeda, Assistant Researcher
Kazuyo Yoneda, Assistant Researcher
Mayu Koizumi, Assistant Researcher
Junko Nishi, Assistant Researcher
Kayoko Mori, Assistant Researcher
Motomi Iwashima, Assistant Researcher
Kayo Yoshida, Assistant Researcher
Aya Okada, Assistant Researcher
Maki Faulkner, Assistant Researcher

Development of a Biorefinery Technology that Contributes to Carbon Neutrality

1. Introduction

The global trend toward decarbonization is accelerating, and each country is actively implementing support for green research and development activities and support for the introduction of advanced green technologies. In October 2020, the Japanese government declared that Japan would be "Carbon Neutral by 2050," and therefore aims to reduce greenhouse gas emissions to net zero by 2050. Because bioprocess manufacturing proceeds under normal temperature and pressure conditions, CO_2 emissions are expected to be lower than for comparable chemical processes, which are manufactured under high temperature and high pressure conditions. In addition, unlike chemical processes, "bio-manufacturing" generally involves synthetic processes involving multi-step reactions within cells. Moreover, bioproduction of complex chemical structures containing a large number of carbon atoms are more competitive than alternative methods of generating these chemicals. At the 4th Conference for the Realization of New Capitalism in March 2022, Prime Minister Kishida positioned "bio-manufacturing" as one of the five fields of science, technology, and innovation that will be target for intensive investment in the future. At the conference, it was also stated that "'bio-manufacturing' will be promoted as a research field that can pursue both solutions to the problem of global warming and economic growth."

Rapid progress has been made in recent years, in biotechnology, synthetic biology, genome editing technology, and in similar scientific fields. Furthermore, technological innovation in “bio-digital technology,” a fusion of biotechnology with (digital) information technologies (i.e., internet of things, IoT, and artificial intelligence, AI) are also developing at a rapid pace. The anticipated "bio-digital technology" will accelerate the social implementation of "bio-manufacturing" that can convert a wide range of raw materials, including petroleum, biomass resources, and even atmospheric CO_2. It is therefore expected to make a significant contribution to achieving carbon-neutrality and/or carbon-negativity.

Given this background, and with the aim of helping the global environment and the economy to coexist, our group has been developing biorefineries. A biorefinery is a biofuel and green chemical production technology that uses renewable resources (e.g., biomass) as a raw material for processing by microorganisms. We have observed that coryneform bacteria (a typical industrial microorganism) show suppressed growth under reducing (anaerobic) conditions, but they maintain normal metabolic function. Under such conditions, these bacteria can metabolize saccharides to produce organic acids and related compounds efficiently. We therefore developed a growth-arrested bioprocess called the "RITE Bioprocess." In addition, we have established the essential technologies for industrial implementation of this process, as shown in the "complete simultaneous use of mixed sugar derived from non-food biomass" and "high resistance to fermentation inhibitors" sections (see Chapter 2).

Using these technologies, we seek to develop the world's most highly efficient process for producing biofuel products, including ethanol, isobutanol, and biohydrogens, among others, and green chemicals, including lactic acid, succinic acid, alanine, valine, tryptophan, shikimic acid, protocatechuic acid, 4-aminobenzoic acid, and 4-hydroxybenzoic acid. Currently, we focus on the development of production technologies for aromatic compounds, which are used as raw materials for higher value-added fragrances, cosmetics, pharmaceuticals, fibers, and polymers. (see Chapter 3).

In addition, to develop new technologies—and to integrate biotechnology and digital technology—we participated in the New Energy and Industrial Technology Development Organization (NEDO) "Smart Cell" project, the Cross-ministerial Strategic Innovation Promotion Program (SIP), and the NEDO "Bio-Manufacturing" project. We also promote research and development, for example, by using "Smart Cell Creation technologies" to improve the efficiency of biosynthesis and the production processes for highly functional chemicals that are difficult to produce using conventional synthesis methods. In July 2022, a project to demonstrate and commercialize the production of fragrances and carotenoids in collaboration with private companies using "Smart Cell Creation technologies" was adopted as a NEDO bio-manufacturing demonstration project. We are also participating in the NEDO Moonshot Project and are working on research and development of marine-degradable multi-lock biopolymers produced using non-food biomass (see Chapter 4).

In this overview, we first explain our core technology, i.e., the "RITE Bioprocess," as well as our new core technologies, i.e., "Smart Cell Creation technologies." Next, we introduce the development results we will target using these. We then describe national projects based on innovation in "bio-digital technologies," which have made remarkable progress in recent years. Finally, commercialization efforts are introduced.

2. The core technologies of RITE

2.1 "RITE Bioprocess"

RITE Bioprocess, developed by our group, 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 are described below (for details, see RITE Today 2022).

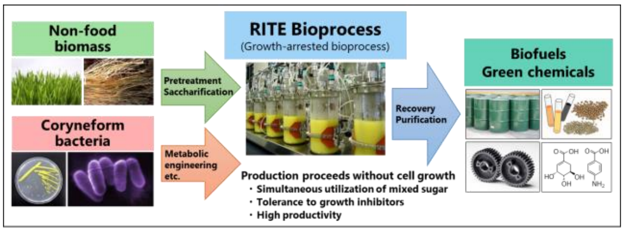

Fig. 1 Biorefinery concept using the “RITE Bioprocess”

2.1.1. Feature 1: Growth-arrested bioprocess

Anaerobic conditions and the removal of factors essential for proliferation allow the desired series of reactions to take place even when cell proliferation is arrested (Fig. 2). That is, nutrients and energy previously used for propagation can now be used for the production of the target substance. This has made it possible to use microbial cells extremely efficiently like a chemical catalyst, realizing a bioprocess with high productivity equal to or greater than that of ordinary chemical processes.

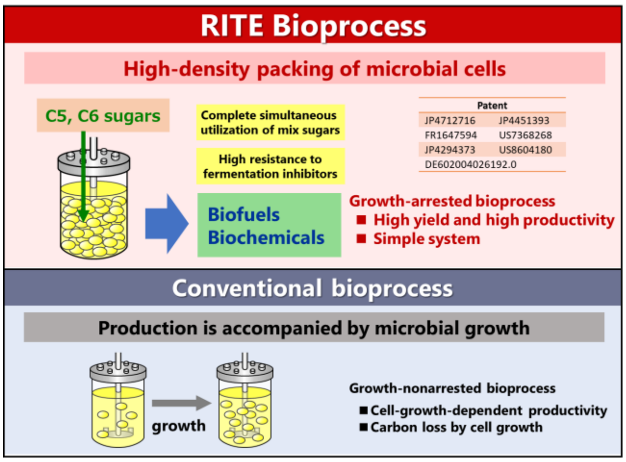

Fig. 2 Feature 1 of the “RITE Bioprocess”

(Growth-arrested bioprocess)

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

Most non-food biomass (cellulosic biomass) is composed of a mixture of C5 sugars such as xylose and arabinose and C6 sugars such as glucose.

Our group 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 a C5 sugar metabolism gene (Fig. 3). This has enabled full simultaneous utilization of C5 & C6 sugars and efficient utilization of cellulosic (non-food biomass) materials.

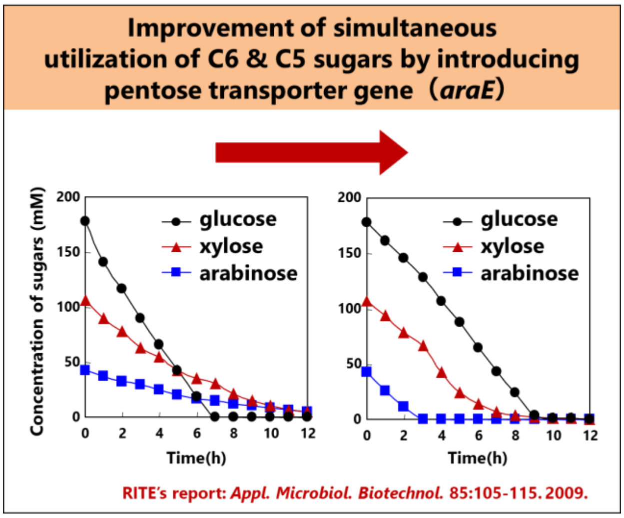

Fig. 3 Feature 2 of the “RITE Bioprocess”

(Simultaneous usage of mixed sugars)

2.1.3. Feature 3: High tolerance to fermentation inhibitors

RITE Bioprocess has demonstrated high resistance to fermentation inhibitors because the microorganisms do not proliferate as described above (Fig. 4). Therefore, it can be applied to the use of saccharification solutions containing various fermentation inhibitors, and even to the production of fermentation inhibitors.

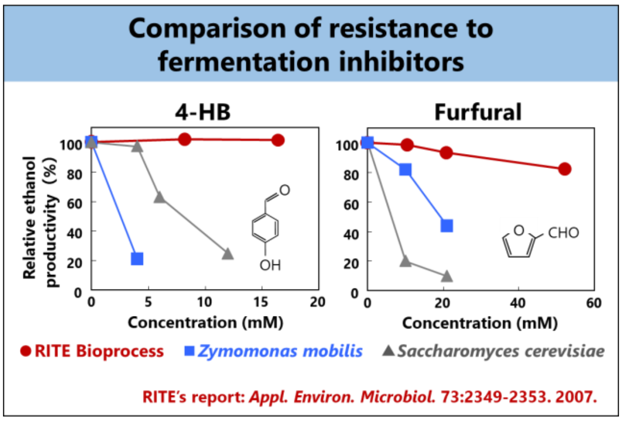

Fig. 4 Feature 3 of the “RITE Bioprocess”

(High tolerance to fermentation inhibitors)

2.2. New core technologies of RITE

In recent years, biotechnology has become more sophisticated, and new applications of IT and AI technology are becoming more common. In multiple national projects, we have collaborated with universities, research institutes, and companies to design and breed "biological cells with highly functionally designed and controlled functional expression" so-called smart cells (see Chapter 4). Some of these new and useful technologies are introduced below.

2.2.1. Smart Cell Creation technologies

In general, a "Smart Cell" is a finely designed cell in which protein and RNA expression is controlled by genetic modifications. More specifically, our group refers to cells whose functions have been designed using cutting-edge information analysis technology and biotechnology to maximize the production of target materials as "Smart Cells."

The technologies that efficiently create smart cells are called "smart cell creation technologies" or "smart cell design systems" (Fig. 5). Our group has participated in the NEDO Smart Cell Project (2016-2020) and the NEDO Bio-Manufacturing Project (2020-ongoing) and has developed these technologies. We have also demonstrated the effectiveness of these technologies by developing highly productive *C. glutamicum* strains.

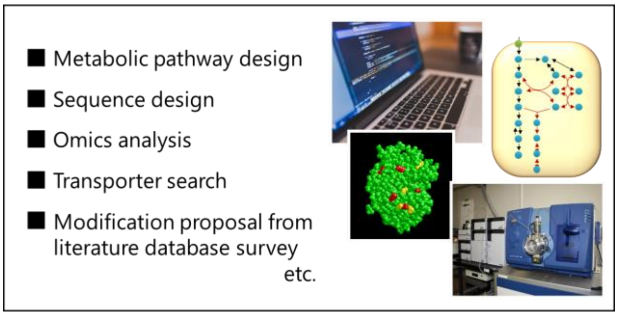

Fig. 5 Smart Cell Creation technologies

2.2.2. Continuous reaction system

Our group has developed biotechnological processes for the production of various compounds. During this development, we found that production can cease due to the cytotoxicity caused by the accumulation of the target compound itself in the reaction solution. For example, the production of catechol, which is under development in both the NEDO Smart Cell Project and the NEDO Bio-Manufacturing Project, generated sufficient cytotoxicity to cease production when using a conventional batch method. Therefore, in order to avoid cytotoxicity and maximize high production, we constructed a continuous reaction system that can selectively remove and recover the target compound from the reaction system. For example, by constructing a continuous reaction system that combines resin adsorption and membrane separation (shown in Fig. 6). When we applied it to catechol production, we achieved a very high catechol yield.

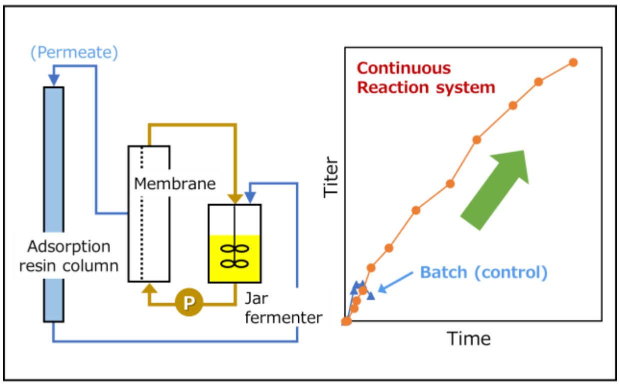

Fig. 6 A continuous reaction system using membrane separation and resin adsorption

2.3. Substances produced by the "RITE Bioprocess"

Fig. 7 shows some of the substances that are currently produced in high quantities by our group. As mentioned above, this process has resulted in highest recorded production yields for many materials. We are expanding from ethanol and biohydrogen to butanol and high-performance bio-jet fuel. We have also expanded from L-lactic acid, D-lactic acid, and amino acids to high-performance chemicals, including green chemicals that contain aromatic compounds.

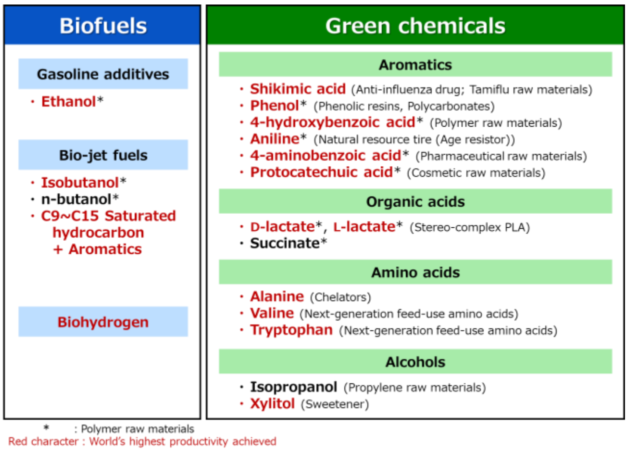

Fig. 7 Substances produced using the "RITE Bioprocess"

3. Target product development

3.1. Bio-jet fuels

Starting from ethanol (C2) or butanol (C4), jet fuel (C9-C15) can be produced via chemical conversion. Given the importance of replacing crude oil products with plant-derived raw materials for reducing CO_2 emissions from aircraft, industry groups are accelerating efforts to produce bio-jet fuels from plant-derived bioethanol or biobutanol. Jet fuel made from bioethanol or biobutanol is called ATJ ("Alcohol to Jet") fuel. Such fuels have been approved by the American Society for Testing and Materials (ASTM) and can be used for commercial flights.

Our group has developed a highly efficient bioethanol and biobutanol production process using the RITE Bioprocess. Moreover, this process is the world's most productive for the bioproduction of ethanol and isobutanol.

In the future, we will further optimize the RITE Bioprocess technology, integrate it with other elemental technologies, and utilize various non-edible raw materials. Ultimately, we aim to commercially produce jet fuel from bioethanol and biobutanol.

3.2. Biohydrogen

Hydrogen is a key energy carrier for realizing carbon neutrality because (i) its combustion generates only water; (ii) it can be produced from diverse energy sources, including renewables; (iii) it can be stored in large quantities for long periods; and (iv) it can be distributed and used for power generation, transportation, and industrial processes. However, current-generation hydrogen production processes use fossil fuels as a feedstock and therefore present problematic levels of CO_2 emissions. Therefore, a Basic Hydrogen Strategy was drawn up at the Ministerial Council meeting on Renewable Energy, Hydrogen, and Related Issues in 2017. This conference noted the importance of developing innovative technologies for CO_2-free hydrogen production to build a hydrogen society over the medium to long term (i.e., by 2050). Moreover, hydrogen strategies have been developed in many countries around the world. For example, the US Department of Energy launched the "Energy Earthshots Initiative," in which the first "Hydrogen Shot" was set as a challenging goal, i.e., reducing the cost of CO_2-free hydrogen by 80% within one decade. Regarding the promising CO_2-free hydrogen production pathways, fermentative hydrogen production from biomass/waste has been under development, as has large-scale hydrogen production in combination with CCUS from fossil resources and water electrolysis using renewables.

Fermentative hydrogen production using microbial functions (biohydrogen production) can be a sustainable CO_2-free hydrogen production technology of the future, but a great increase in productivity is needed to establish an economically feasible biohydrogen production technology. The key to achieving this is the creation of highly efficient hydrogen-producing microorganisms through advanced biotechnology. Our group has developed a biohydrogen production process with a very high production rate (i.e., max 300 L H_2/h/L). This process uses the formate-mediated dark fermentative hydrogen production pathway. Building on this achievement, our group is now working on improving hydrogen yield from biomass-derived sugars by integration with photofermentation (Fig. 8). We have enhanced a heterologously expressed hydrogen production pathway that can utilize the excess reducing power not utilized in the formate-mediated dark fermentative hydrogen production pathway, and have also succeeded in establishing a photofermentative hydrogen producing microorganism by engineering regulators of hydrogen metabolism, carbon storage, and acetate metabolism.

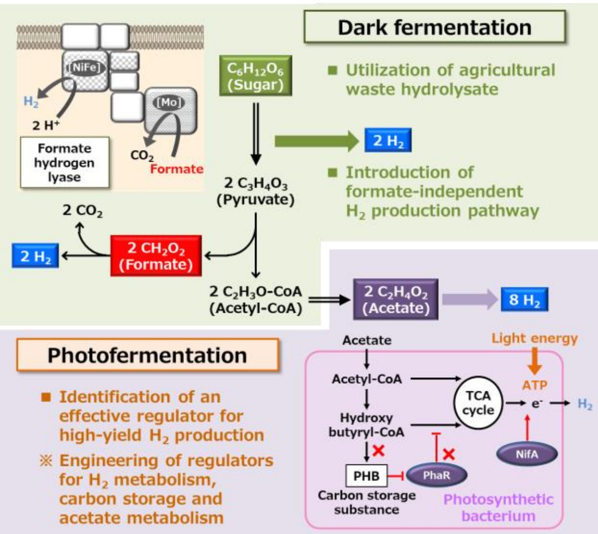

Fig. 8 Metabolic engineering of dark fermentative and photofermentative hydrogen-producing microorganisms

3.3. Green-aromatic compounds

Aromatic compounds are essential industrial chemicals for synthesizing polymers and various value-added chemicals for use in the pharmaceutical, nutraceutical, flavor, cosmetic, and food industries. Although they are currently derived from petroleum or natural plant resources, environmentally friendly biotechnological production from renewable feedstocks is desirable to create a sustainable society that is no longer dependent on petroleum resources and but maintains highly efficient production processes. Bacterial cells can synthesize various aromatic compounds, including amino acids (i.e., phenylalanine, tyrosine, and tryptophan), folate (vitamin B_9), and coenzyme Q, all of which are derived from the shikimate pathway. Therefore, by employing the metabolically engineered *C. glutamicum*, our group successfully established a highly efficient bioprocess for producing the aromatic compounds from non-food feedstocks. These include shikimate, an essential building block of the anti-influenza drug Tamiflu; 4-aminobenzoate, the building block of a potentially useful functional polymer; and aromatic hydroxy acids, having potential applications in the polymer, pharmaceutical, cosmetic, adhesive material, and flavor (vanillin) industries.

Since 2022, our group has also participated in the NEDO "Bio-Manufacturing" project with Takasago International Corporation. We are driving development of an "industrial smart cell" that can produce rose fragrance and a bioproduction system that can avoid microbial inhibition derived from fragrance materials (Fig. 9).

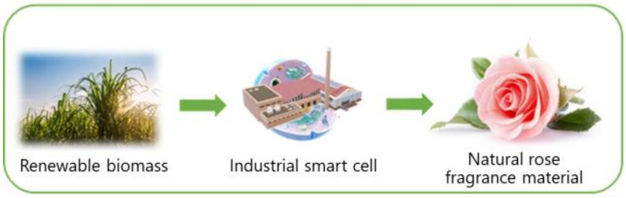

Fig. 9 Production of rose fragrance material

4. Fundamental technology development (national projects)

4.1. NEDO Bio-Manufacturing Project

We are developing Next-generation production technologies for the foundation of the bio-manufacturing industry in the "Development of bio-derived product production technology that accelerates the realization of carbon recycling" (NEDO Bio-Manufacturing Project).

Bio-based material production is expected to save energy relative to conventional chemical processes. In addition, the use of biomass as a raw material instead of fossil resources can greatly contribute to the realization of a carbon recycling society.

During the predecessor of this project, "Development of Production Techniques for Highly Functional Biomaterials Using Plants and Other Organisms" (NEDO Smart Cell Project), our group—in collaboration with universities, research institutes and companies—developed technologies to design and construct Smart Cells. We then demonstrated the effectiveness of these technologies by constructing hyper producer cells in a short period of time. To further promote the social implementation of Smart Cells, the Bio-Manufacturing Project will develop production process technologies including upscaling and purification.

Our group has been participating in this project, which started in 2020, from the first year, and is developing new technologies to solve the problems associated with the practical application of biomanufacturing technologies (Fig. 10).

In FY2022, we promoted the development of new technologies to help overcome product toxicity. In addition, we developed information analysis technologies to determine optimal components of culture media. This year, we will develop other useful technologies and verify their effectiveness. We aim to accelerate the social implementation of bio-derived products through the development of these technologies.

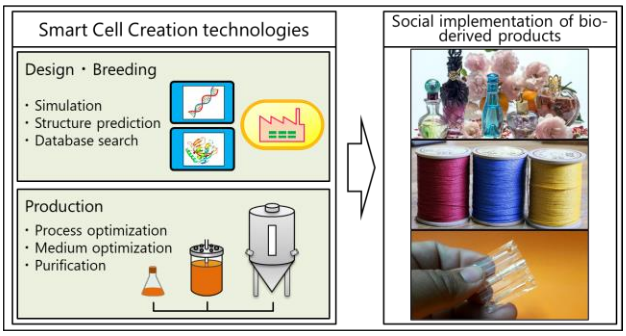

Fig. 10 Social implementation of bio-derived products using Smart Cell Creation technologies

4.2. NEDO Moonshot-type R&D Project（Development of Multi-lock Biopolymers Degradable in Ocean from Non-food Biomasses）

The project is carrying out research and development to introduce a "multi-lock mechanism" for plastic degradation. In other words, multiple stimuli such as light, heat, oxygen, water, enzymes, microorganisms, and catalysts should be required to trigger for start degradation, but prevent degradation and maintain durability and toughness when in use, and when accidentally dispersed in the marine environment, the multi-lock 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 have a negative impact on the environment due to runoff into the ocean.

In FY2022, our research group successfully achieved high production of several monomers requested by some companies by designing artificial metabolic pathways, constructing high production strains, and testing production conditions. In the future, we aim to further increase of the production titer through modification of the artificial metabolic pathway. In FY2022, we succeeded in improving the production concentration of plastic-degrading enzymes by introducing mutations, and achieved remarkable improvement of functionality. In the future, we aim to conduct research and development, including the development of technology to artificial control for the timing of the starting point of degradation of multi-locked plastics (development of new technology utilizing degradation enzymes).

(The HP of the project can be found at: http://www.moonshot.k.u-tokyo.ac.jp/en/index.html).

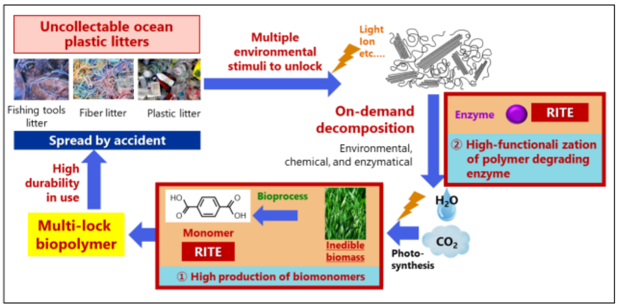

Fig. 11 Marine-degradable multi-lock biopolymers fabricated from non-food biomass

4.3. The Cross-ministerial strategic innovation promotion program (SIP)
(Development of biomonomers for high-performance plastics)

In bio-based material production, production of the target compound is made possible by a successfully constructing a specific biosynthetic pathway for that compound. Biosynthetic pathways are constructed using multiple enzymes, and the starting compound or substrate is converted via enzymatic reaction to a bio-compound, which in turn becomes the substrate for the next enzyme and undergoes conversion. More than 8000 enzymatic reactions are currently known, and by combining these in specific ways, biosynthetic pathways are improved and expanded.

RITE is participating in the theme “Technologies for Smart Bio-industry and Agriculture” of the SIP, a joint program between industry, academia, and the government designed to apply findings from basic research for practical and industrial applications beyond the scope of government ministries and traditional disciplines. The goal of this project is to realize a sustainably growing society and is made possible by manufacturing technologies that employ bio-capabilities developed by fusing biotechnology and digital resources.

Our group participates in the consortium “Development of Technologies for Functional Design and Production of Innovative Biomaterials.” This consortium aims to synthesize polymers with new functions—in response to market desire—using monomers bio-synthesized from biomass and other cheap raw materials. To date, ultra-high heat-resistant polymers and polymers used as battery materials have been successfully developed (Fig. 12). In order to design monomer biosynthetic pathways for constructing such polymers, our group, in conjunction with external research groups, has been developing and validating technologies for improving enzymatic function. We have focused on enzymes involved in the biosynthesis of monomer substrates underlying polymers of interest. In greater detail, we are developing technologies for the efficient selection of promising enzyme mutants from the activity data of many mutant enzymes using machine learning. We are also developing technologies for discovering novel enzymes possessing desired functions based on enzyme amino acid sequence data. These techniques have allowed us to improve the substrate specificity of target enzymes and enhance activity. In 2022, not only were we able to increase productivity by metabolic engineering and optimization of culture conditions, but we also produced monomers from a biomass-derived raw material provided by the collaborative consortium as a substrate. Moreover, we are verifying the effectiveness of enzyme modification technology by targeting a new enzyme involved in the biosynthetic pathway for aromatic diamine.

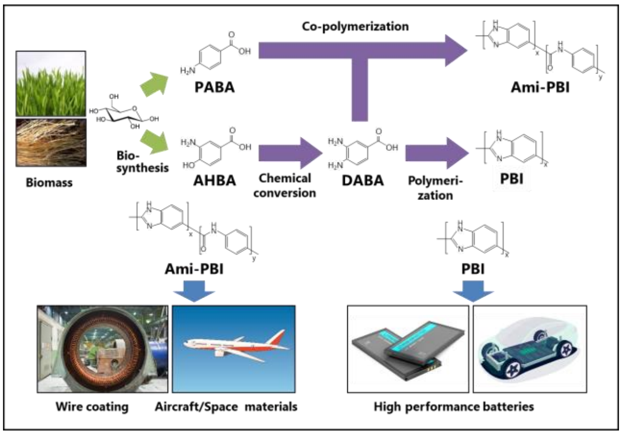

Fig. 12 Synthesis of developing monomers and polymers for polymer applications

5. Future industrialization of our technologies

5.1. 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, The Research Institute of Innovative Technology for the Earth (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 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's technology is capable of producing useful compounds in parallel with phenol production, the trade name of Green Phenol Development Corporation was changed to Green Chemicals Co., Ltd., (GCC).

Since GCC's phenol-producing technology and knowledge apply to the production of various other aromatic compounds (Fig. 13), we are developing a bioprocess for other high value-added chemicals and commercializing products that meet customer needs.

We are also making active use of non-food biomass resources. One of the candidate feedstocks we are focusing on is the squeezed residue (extra-liquid fractions) of orange juice lees. We are currently studying the potential use of various non-food biomass resources that have not yet received significant attention.

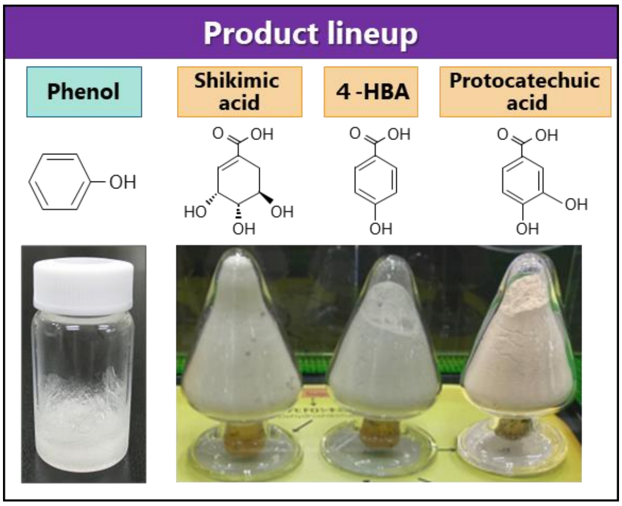

Fig. 13 Major product lineup of Green Chemicals Co., Ltd.

5.2. Green Earth Institute Co., Ltd. (GEI)

(Headquarters: Shinjuku-ku, Tokyo, Japan; Research Institute: Kisarazu City, Chiba, Japan. Mobara City, Chiba, Japan)

(Click here for GEI homepage)

GEI is a RITE-launched venture company established on September 1, 2011, to facilitate the quick commercialization of research results based on the RITE Bioprocess (described above). GEI is currently conducting joint research and commercialization activities with RITE to realize the practical uses of green chemicals and biofuel production technologies manufactured using microorganisms.

From August 2021, as a member of the core of the Greater Tokyo Biocommunity, as well as the global biotechnology community, GEI is implementing a bio foundry project (i.e., a NEDO-commissioned business) to build a biorefinery technology platform. This is in line with a cornerstone of the government's biotechnology strategy.

The company was listed on the TSE Mothers in December 2021. (Due to the revision of the Tokyo Stock Exchange's market divisions on April 4, 2022, the name of the listed financial exchange after that day will be the Tokyo Stock Exchange Growth Market.)

Currently, we are working with GEI to realize commercial production of a different type of amino acid, based on the successful commercial scale production of amino acids.

In addition to this, we are working together to develop other chemicals that can be used as raw materials for bioplastics and biodegradable resins, with the aim of realizing bio-production that contributes to sustainable development, as well as marketing for commercialization and scaling up for mass production.

5.3. Joint research with companies

In response to requests from companies, we are conducting joint research on the production of many substances other than the biofuels and green chemicals.

For example, we are conducting a joint research and development project with Harima Chemicals, Inc. as a NEDO-commissioned project regarding the development and demonstration of a mass production system for highly absorbent natural carotenoids.

We are also collaborating with Takasago International Corporation, again with support from NEDO, to demonstrate a rose fragrance production system using a continuous flow isolation method and a growth-arrested bioprocess.

We are also conducting joint research projects with many other companies, but it is not possible to introduce them all in detail here. In many of these cases, to realize early commercialization, research and development can be used to convert one of the company's products (i.e., substances currently derived from fossil resources) to a bio-derived version. In addition, we are conducting multiple medium- to long-term research and development projects to identify processes to generate bio-derived versions of the major products of these partner companies.

6. Closing remarks

In recent years, due to the development of "bio-digital technology" and accompanying research methodologies, the efficiency of smart cell development has dramatically improved, mainly related to the national projects introduced in Chapter 4. Moreover, efforts related to smart cell production demonstration have been carried out, improving their social implementation. As a result, a new industry (i.e., the smart cell industry) is being created. This is expected to have a large ripple effect not only on the energy sector but also in industrial sectors related to manufacturing (Fig. 14).

In 2023, our group will continue research and development related to the production of green chemicals including aromatic compounds and the production of biofuels such as biohydrogen. We will use the above-mentioned "RITE Bioprocess" and "Smart Cell Creation Technologies," and will participate in national projects and joint research with companies. Furthermore, we would like to contribute to the realization of carbon neutrality by developing practical production technologies at scale.

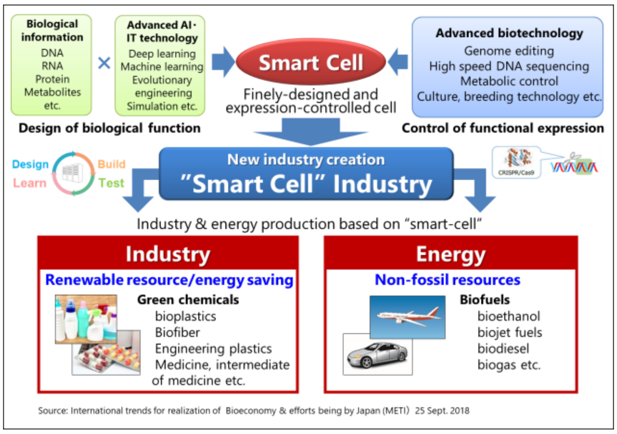

Fig. 14 Fusion of industrial/energy fields impacted by new bio and digital technologies

Since the "2050 carbon neutral" declaration in October 2020, inquiries from companies have increased, and the number of joint research projects with companies has also increased. However, our group continues to look for new research partner companies, in addition to those introduced in Chapter 5, Section 3. We also note the possibility that compounds that are difficult to produce in microorganisms can be manufactured in combination with other technologies, as in the abovementioned aromatic compound example. Therefore, if there is a compound that you want to make bio-derived, please contact us.

※ "RITE Bioprocess" is a registered trademark of RITE.

Chemical Research Group

Members (as of Apr. 2023)

Katsunori Yogo	Group Leader, Chief Researcher
Hidetoshi Kita	Chief Researcher
Masahiko Mizuno	Deputy Group Leader, Chief Researcher
Hiroaki Matsuyoshi	Deputy Group Leader, Chief Researcher
Naoki Kikuchi	Deputy Group Leader, Associate Chief Researcher
Koji Baba	Associate Chief Researcher
Firoz Alam Chowdhury	Associate Chief Researcher
Teruhiko Kai	Senior Researcher
Kazuyuki Kitamura	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
Hibiki Koterasawa	Researcher
Shuhong Duan	Researcher
Nobuhiko Fuchigami	Researcher
Vu Thi Quyen	Researcher
Lie Meng	Researcher
Soji Yamaguchi	Researcher
Hanako Araki	Research Assistant
Hiroyuki Ida	Research Assistant
Hiromi Urai	Research Assistant
Noriko Onishi	Research Assistant
Nobuaki Oono	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
Keiko Mori	Research Assistant
Misato Mori	Research Assistant
Atsushi Yasuno	Research Assistant
Naomi Yoshino	Research Assistant
Junko Yonezawa	Research Assistant

Challenges Associated with the Advanced Industrialization of CO_2 Capture Technologies

1. Introduction

The research and development of CO_2 capture and utilization (CCU) had been conducted separately by the Chemical Research Group and the Inorganic Membrane Research Center until the last fiscal year. To effectively collaborate on the R&D of both polymer and inorganic membranes, as well as CO_2 utilization, we have integrated these two research groups starting from fiscal year 2023 to establish a more competitive and productive organization. In the future, we will focus on promising CCU technologies for their early-stage practical applications. Additionally, we will increase the activities of the Strategic Council for Industrialization to support information exchange and technology cooperation on CCU. The current research topics of the Chemical Research Group are described as follows.

2. Technologies for CO_2 capture

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 Japan as well, in response to the 2050 Carbon Neutral Declaration in October 2020 and the Green Growth Strategy for the 2050 Carbon Neutral Declaration formulated in December 2021 (detailed in June 2021), to prevent global warming various efforts are being promoted in each of the technology fields. CCUS (Carbon dioxide Capture, Utilization, and Storage) / Carbon Recycling is an important innovative technology that enables carbon neutrality. In CCUS/carbon recycling, the combination of both 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.

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 capturing 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 various CO_2 capture materials, while keeping pace with the international trends of 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 process 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" 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. Recently, we started to develop new solid sorbents for low-concentration CO_2 capture at natural gas-fired power plants. Furthermore, Direct Air Capture (DAC), which captures CO_2 from the atmosphere, is proceeding as the NEDO Moonshot Research and Development Project. With the target of separating CO_2 from a high pressurized gas stream in a low-cost and energy-saving process, we have been developing membranes and membrane elements. They are potentially applied in Integrated coal Gasification Combined Cycle (IGCC) and blue hydrogen production.

Efforts have also been devoted to establishing the standardization of CO_2 capture. 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. In addition, we were awarded a NEDO project to establish a common base for evaluating CO_2 separation materials with standard methods, which started in 2022 and have initiated the establishment of Japan's first Real-Gas Test Center in RITE.

As for effective CO_2 utilization technology, we have been conducting carbonate fixation utilization amine technology and methanol synthesis utilization dehydration membrane technology. In carbonate fixation, calcium and magnesium from industrial waste are used and, after reacting with CO_2, produce high-purity calcium or magnesium carbonate. It is an environmentally friendly manufacturing method due to recycling both the carbon source and the metal source. In methanol synthesis, CO_2 emitted from power plants, steel mills, cement and chemical plants is reacted with hydrogen by a membrane reactor to synthesize methanol at high efficiency. We have been awarded a NEDO project for optimal system development for methanol synthesis from CO_2 jointly with a private company since 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. However, energy consumption in the process of solvent regeneration and the degradation of amines cause the cost increases in the chemical absorption method.

Focusing on the fact that the structure of amine molecules is closely related to these technological issues, RITE started a new amine solvent: since the COCS project (METI's Subsidy Project) started in 2004, RITE has been working on the development of a high-performance amine solvent that reduces the cost of CO_2 capture.

In the COURSE50 project (NEDO consignment project) since 2008 with the goal of reducing CO_2 emissions by 30% in the steelmaking process, RITE was working with Nippon Steel Corporation to upgrade the chemical absorption method. The chemical absorbent and process developed by the COURSE50 project were adopted by the energy-saving CO_2 capture facility ESCAP® of Nippon Steel Engineering Co., Ltd., which was commercialized in 2014.

ESCAP® Unit 1 was constructed on the premises of Muroran Works for general industrial use, including beverages. This is the world's first commercial facility using the chemical absorption method for combustion exhaust gas from a hot stove at a steelworks as a CO_2 source. In 2018, ESCAP® Unit 2 (Fig. 1) started operation at the Niihama Nishi Thermal Power Station. This is the first commercial facility in Japan to capture CO_2 by the chemical absorption method for combustion exhaust gas from coal-fired power generation as the CO_2 source. The recovered CO_2 is used as a raw material in a nearby chemical factory.

Fig. 1 Equipment of energy-saving CO_2 absorption process ESCAP® at Niihama Nishi power station, Sumitomo Joint Electric Power Co., Ltd.

In addition, our research results in COURSE50 showed 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. We are now on a new R&D stage and have continued to develop novel compounds and optimal formulations for practical use under the NEDO Green Innovation Fund Project for the development of hydrogen reduction technology using blast furnaces, which started in 2022.

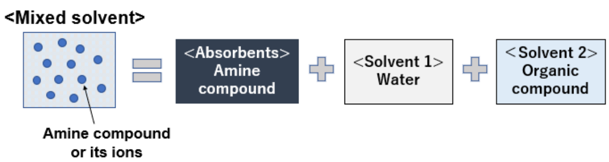

Fig. 2 Concept of mixed solvent

4. Solid sorbent method for CO_2 capture

Unlike a chemical absorbent in which amines are dissolved in a solvent, such as water, a solid sorbent is one in which 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.

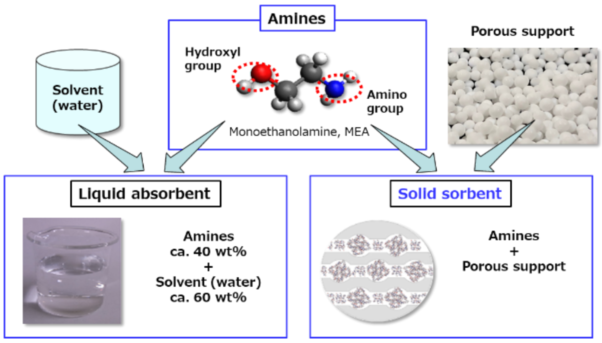

Fig. 3 Liquid absorbent and solid sorbent

1) For coal-fired power plants

In 2010, RITE started the development of 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 developed 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, scale-up synthesis of solid absorbent (>10 m^3), bench scale test (>5 t-CO_2/day), and real-gas exposure tests at a coal-fired power plant were conducted.

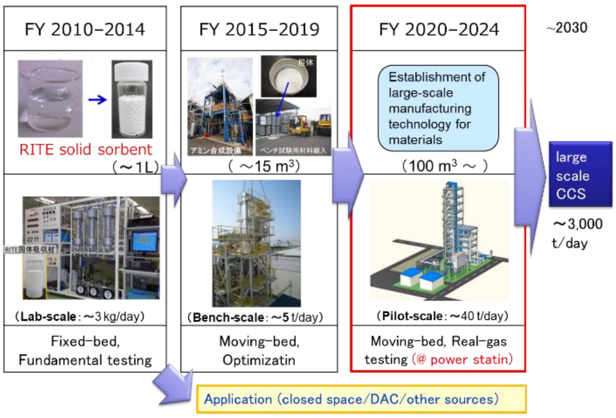

Fig. 4 Development roadmap of solid sorbent method for CO_2 capture

In 2020, RITE was chosen for the NEDO commissioned project with KHI. In this project, with the cooperation of Kansai Electric Power Co., Ltd., KHI constructed a pilot scale test facility (40 t-CO_2/day scale) at the Maizuru power plant and started trial operation in the second half of FY 2022.

RITE manufactured a 100 m^3 scale solid absorbent optimized on the basis of the results of the scale-up synthesis of solid absorbents and bench-scale tests and supplied it to the pilot test facility. In the future, we plan to conduct CO_2 capture tests from flue gas from the combustion exhaust gas emitted from the coal-fired power plant in FY 2023–2024.

We are also elucidating the material deterioration mechanism, developing the technology to suppress the deterioration of solid sorbents, 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 recovery with high accuracy in KHI's moving bed system.

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 device, which is difficult to observe in practice, and the calculation results are also used in material development.

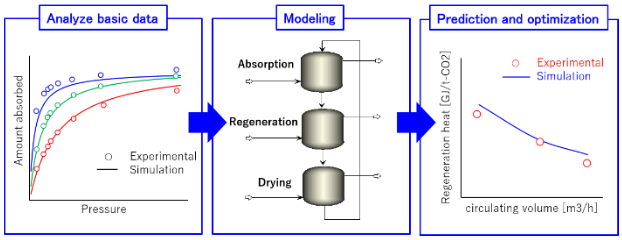

Fig. 5 RITE's simulation technology

2) For natural gas-fired power plant

In 2022, the Technology Development Project of CO_2 Separation and Capture in the Green Innovation Fund project has been 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 knowledge and technology accumulated during R&D histories in this field and the development of solid sorbent materials composed of developed amines and optimal support.

This project is a nine-year project from 2022 to 2030. After passing through the stage gate in Phase 1 (2022–2024), which focuses on the development of solid sorbent materials, we plan to proceed to Phase 2 (2025–2026), where development with bench test equipment will be carried out, and if it passes through the stage gate, we will proceed to Phase 3, where pilot demonstration tests will be conducted using actual exhaust gas at natural gas-fired power plant sites.

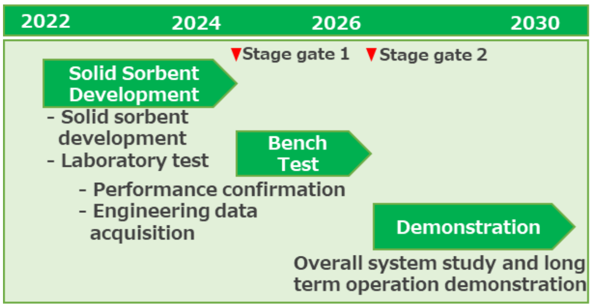

Fig. 6 R&D Schedule

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 with 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 pre-combustion.

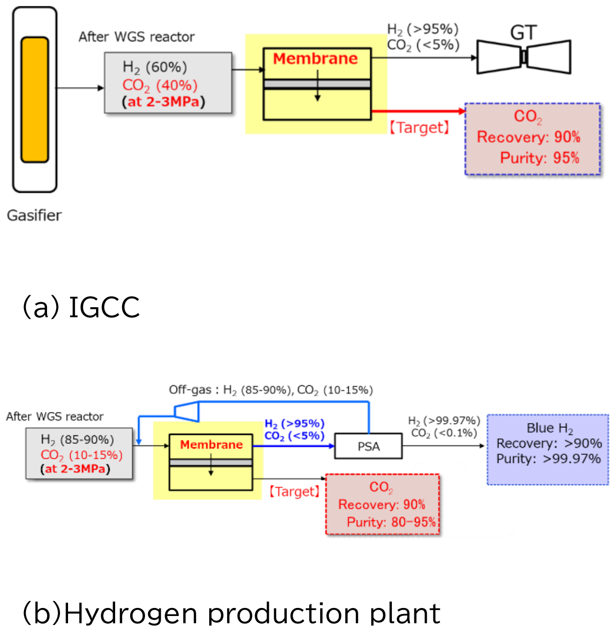

Fig. 7 Schematic of the IGCC and hydrogen production plant with CO_2 capture by CO_2 selective membrane modules

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.

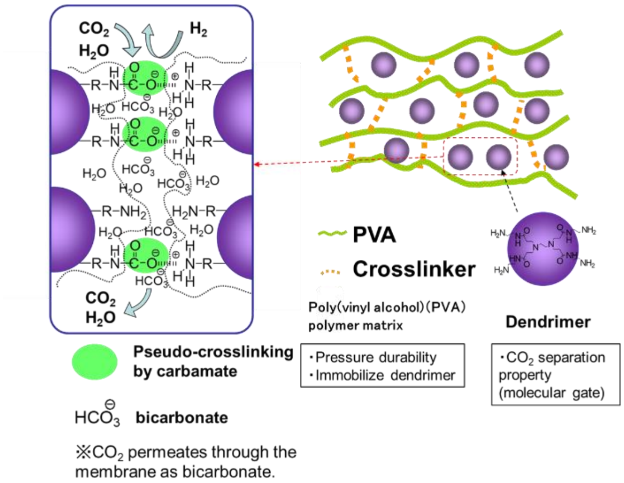

Fig. 8 Schematic illustration of the working principles of the molecular gate membrane

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 dendrimer/polymer hybrid 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 a private company) is researching new membranes, membrane elements, and membrane separation systems. So far, two-inch and four-inch membrane elements with enough pressure durability (2.4 MPa) were successfully prepared. In addition, we conducted pre-combustion CO_2 capture tests of the membrane elements using coal gasification gas.

In the new 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 are conducting 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.

In the current project, we are modifying the membrane materials to improve pressure durability. The dependence of separation performance on feed gas total pressure is shown in Fig. 9.

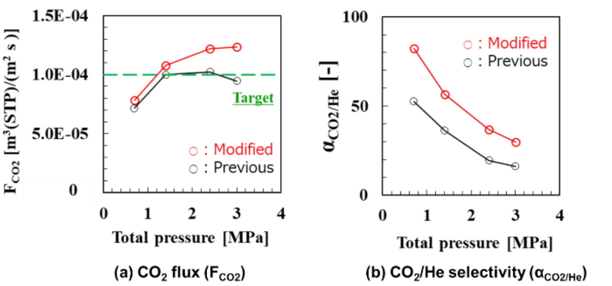

Fig. 9 Dependence of separation performance on feed gas total pressure.

Pressure durability of 3 MPa was obtained by modification of the membrane materials. In addition, separation performance was improved compared to the previous membrane, and we have the prospect of obtaining the target performance as membrane materials.

As for the development of the membrane elements, we succeeded in developing the membrane elements (ϕ = 10 cm, L = 40 cm) (Fig. 10). In the future, we will develop membrane elements using the modified membranes and develop larger-scale membrane modules.

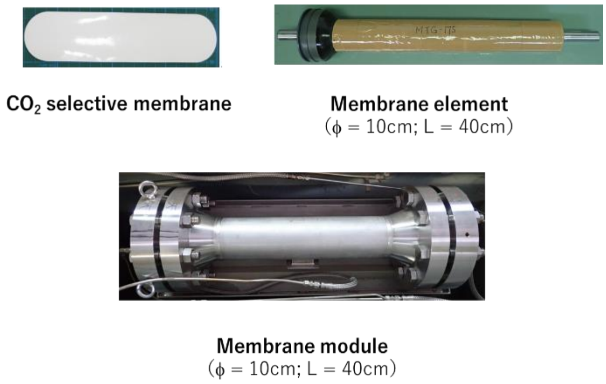

Fig. 10 CO_2 selective membrane, membrane element, and membrane module.
Membrane element: The structure with a large membrane area composed of the membrane, support, and spacer.
Membrane module: The structure in which the membrane element is placed.

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 innovation action plan of the Innovative Environmental Innovation Strategy, which aims to establish technologies that enable Beyond Zero by 2050.

RITE is working to develop high-efficiency CO_2 capture from the atmosphere and carbon circulation technologies in cooperation with Kanazawa University and Mitsubishi Heavy Industries, Ltd., in "(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 2025."

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

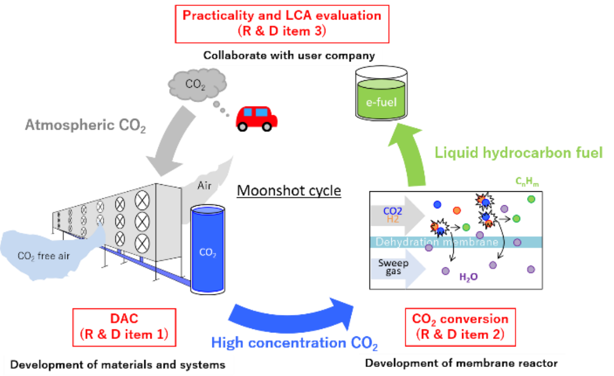

Fig. 11 Development of highly efficient DAC and carbon recycling technologies

RITE is trying to synthesize new amines suitable for DAC and transform solid sorbent materials into low-pressure drop structured materials. The developed materials are tested in the actual air around RITE. Because of the day-to-day variations in the conditions of the local atmosphere, we designed new equipment to control and test the effects of temperature, humidity, and CO_2 concentration in the atmosphere (Fig. 12).

Fig. 12 Lab test equipment for DAC

In addition, DAC system evaluation equipment that can evaluate solid absorbent structures of the size used in actual DAC facilities has been designed and manufactured by Mitsubishi Heavy Industries Engineering, Ltd. The equipment is installed on RITE premises and research and development that include scaling up technology have started

In order to realize an economically acceptable DAC, not only material development but also process development is important. RITE uses simulation technology to efficiently search for optimal operating processes.

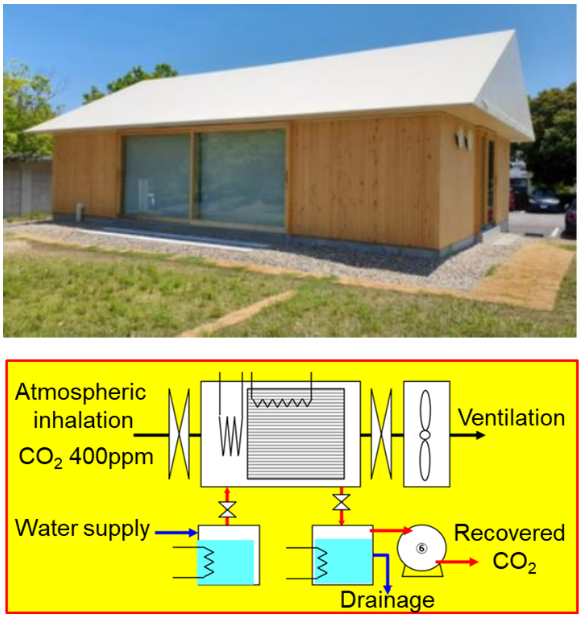

Fig. 13 Schematic image of DAC system evaluation equipment (below) and DAC experimental laboratory in RITE where equipment is placed (upper)

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 energies, 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 concentration.

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 items: (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 where three different CO_2 capture technologies can be evaluated with natural gas combustion gas. RITE has started to design CO_2 capture test facilities to evaluate CO_2 capture for exhaust gas, which assumes flue gases from NGCC power plants. The test facilities will be set up in FY 2024.

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. Installation and operation of a system of facilities where new CO_2 capture materials can be evaluated is strongly demanded. 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, this 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 produces water, which 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 "membrane" and "catalyst."

Methanol is an important intermediate for chemical products, and demand is expected to grow in the future. Methanol is mainly synthesized using syn-gas (mixture gases of CO and H_2); however, synthesis requires high temperatures and high pressures. Generally, Cu/ZnO-based catalysts are used with the reaction within the temperature range of 473–573 K. On the other hand, the one-pass yield shows low values owing to equilibrium limitations. This is remarkable in the methanol synthesis from CO_2 hydrogenation represented by the following reaction formula.

$$CO_2 + 3H_2 \rightleftarrows CH_3OH \text{ (methanol)} + H_2O$$

A membrane reactor as shown in Fig. 14 can be used to solve this problem. The produced water is removed from the reaction system, then this reaction will be promoted to the methanol production side.

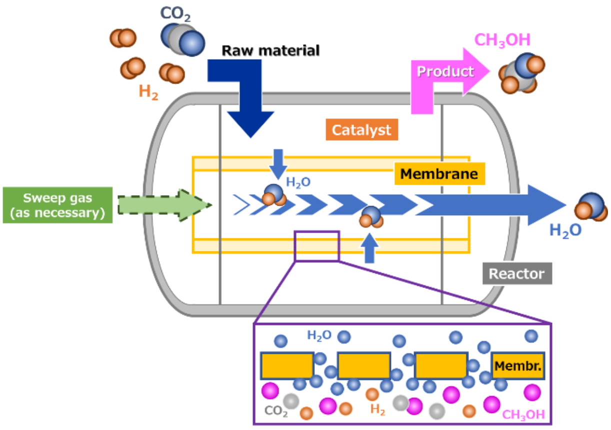

Fig 14 Schematic diagram of membrane reactor for methanol synthesis

At RITE, we successfully developed a novel hydrophilic zeolite membrane, which has higher hydrothermal stability and water/methanol permselective performance compared to the conventional LTA-type zeolite membrane. 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, RITE is conducting the NEDO project, Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation / Development, and the demonstration of technologies for CO_2 utilization. In this project, our ovel dehydration membrane with a practical length was developed in FY 2022.

9. 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 the CO_2 fixation by using by-products and waste containing alkaline earth metals is expected to build a sustainable society.

RITE developed a unique process over many years. From 2020, two Japanese private companies and RITE set up a study group to target steel slag and waste concrete and then use the alkaline earth metals extracted from these for use with the CO_2 emitted from factories and other facilities. We are cooperating in the development of technology for recovering carbonates, which are stable compounds, by reacting with CO_2 (Fig. 15).

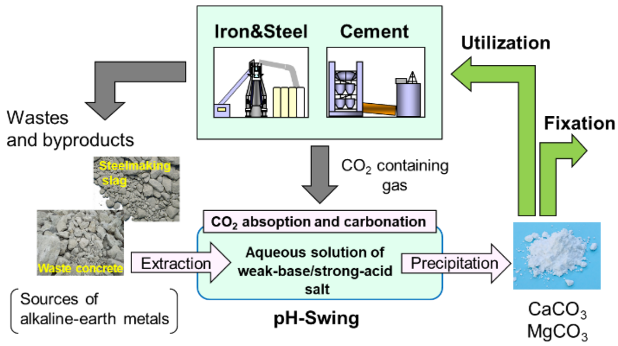

Fig. 15 CO_2 fixation as carbonates

10. Activities and efforts toward commercialization and industrialization

The core of the Industrial Collaboration Department of the IMeRC is the Industrialization Strategy Council. A total of 18 separation membrane and support manufacturers and user companies (as of January 2022) participate on this council. Our goal is to establish an inorganic membrane industry that contributes to innovative environmental and energy technologies by promoting a common vision for manufacturers and user companies, as well as a joint research plan involving national projects and other initiatives.

We are promoting a variety of activities, which include the following:

a) Sponsoring needs and seeds matching meetings toward the practical use of innovative environmental and energy technologies that use inorganic membranes, and the establishment and operation of a research group that will prepare the future roadmap

b) Planning joint implementation projects funded by the government and NEDO

c) Acceptance of researchers from council members to the Research Section of the IMeRC and the implementation of training workshops

d) Offering technical guidance from the IMeRC Advisory Board and Research Section

e) Hosting exclusive technology seminars for council members

f) Offering exclusive supply services (Needs and Seeds Technology Information) to council members

In 2021, because of the spread of the COVID-19 virus, we had to refrain from face-to-face activities, but we actively promoted study group activities and seminars via the Web.

Two study groups, the Membrane Reaction Process Study Group and the Common Infrastructure (Performance Evaluation) Study Group, have started new studies. The Membrane Reaction Process Study Group examined a computational platform that enables comparative studies of performance, energy balance, and cost, which are indispensable for the social implementation of membrane reactors. The Common Infrastructure (Performance Evaluation) Study Group conducted a basic study toward standardization of separation membrane performance evaluation methods with the aim of promoting the industrialization of inorganic membranes.

We also held a seminar for council members online. There were lectures from universities, member companies, and membrane-related companies on the latest R&D trends and the introduction of needs, seeds, and practical development cases of membranes, along with lively question and answer sessions. In addition, we conduct patent and literature searches related to the content of the lectures, and regularly provide members with needs and seeds information with comments from the IMeRC in the summary.

11. Conclusion

The Chemical Research Group will continue to actively participate in the development of technology for CO_2 separation and capture from various CO_2 emission sources. 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 its development toward a small-scale on-site demonstration at Expo 2025 Osaka, Kansai. As for membrane separation, in FY 2023, we will complete the fabrication of a prototype of a commercial-size membrane module and develop a plan for a field test with the aim of moving forward into the development phase. About the Real Gas Test Center, its detailed design will be conducted in FY 2023. We will survey potential users to determine the key configurations desired and to make the center user-friendly for domestic researchers working on CO_2 separation materials. It will open in FY 2024.

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 also 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.

Efforts will be 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.

CO_2 Storage Research Group

Member (As of Apr. 2023)

Ziqiu Xue, Group Leader, Chief Researcher
Nobuo Umeda, Deputy Group 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
Satoko Fuchikami, Vice Manager
Kimiko Nakanishi, Chief
Takayuki Miyoshi, Researcher
Masafumi Kotani, Researcher
Takeya Nagata, Researcher
Rasha Amer, Researcher
Jinrong Cao, Researcher
Ryota Okimoto, Researcher
Tomonari Minezaki, Researcher
Shoichiro Hozumi, Researcher
Junko Hirai, Research Assistant
Shiori Tsuji, Research Assistant
Yuko Himi, Research Assistant
Akemi Nishide, Research Assistant
Megumi Okumichi, Research Assistant
Megumi Sasaki, Research Assistant
Tokio Sasai, Research Assistant
Nae Hidaka, Research Assistant

Technology Demonstration, Knowledge Sharing and Non-technical Support for Implementation toward Commercial Deployment of Geological CO_2 Storage

1. Introduction

"CCS Long-Term Roadmap" which was compiled by the government in March 2023 says that CO2 geological storage-scale as of 2050 is 120-240 million tons. Aiming to start the CCS business in 2030, they are speeding up the development of the environment for practical use of CCS, including the legal system. At the same time as ensuring the safety of the CCS project, technology development for cost reduction, etc. is also required.

Technology development of CO2 geological storage technology in Japan started with a small-scale demonstration project (10,000 tons of CO2 injection) in the suburbs of Nagaoka City, Niigata Prefecture in the early 2000s, and various basic technologies were developed by the early 2010s. After that, a large-scale CO_2 injection demonstration project of a total of 300,000 tons was conducted at the off the coast of Tomakomai, Hokkaido.

CO_2 Storage Research Group is working on the practical application of CO_2 storage technology on the scale of 1 million tons per year (a project funded by the New Energy and Industrial Technology Development Organization (NEDO), called "Research and Development of CO_2 Storage Technology to implement safe CCS").

The main purpose of this project is to develop technology to improve the safety and economic efficiency of the CCS project and to prepare the conditions for the wide adoption of CCS. We have developed Distributed Temperature Sensing (DTS), Distributed Strain Sensing (DSS) and Distributed Acoustic Sensing (DAS) measurement technologies, and microbubble CO2 injection technology to improve storage efficiency. Currently, we are proceeding with technical demonstration project at domestic and overseas sites. We are also working on the development of methods to improve the social acceptance of CCS technology toward social implementation.

Regarding optical fiber measurement technology, we are also accumulating know-how such as verification of effectiveness and measurement system operation for practical application to domestic CCS projects at large-scale CO_2 injection sites in the United States. About the matching of emission sources and storage sites and about the economic improvement (cost reduction) of domestic CCS projects", we are considering the " Storage Resource Management " (SRM) method based on existing geological information and underground exploration data. In addition to the conventional storage potential assessment, we are also developing a CCS cost estimation tool that enables optimal business planning by SRM. In addition, our group has been developing frameworks for creation of social consensus (Social License to Operate, SLO) which is useful for domestic CCS projects by advancing conventional Public Acceptance (PA) and Public Outreach (PO) approaches.

2. Major Research Topics and Outcomes

2.1. Optical fiber measurement technology development and demonstration

In geological carbon storages, it is required to confirm that the injected CO2 is stored subsurface safely. We need to monitor integrity of wells and CO2 pipelines to obtain deformation change due to the increase of formation pressure, area of pressure propagation and leakage detection. The Distributed Fiber Optic Sensing (DFOS) technology is highly prospected for this monitoring purpose.

The DFOS measures spatially continuous data along the optical fiber (OF) cables, as the OF cable itself works as sensors. A single OF cable with multiple fibers enclosed can be a multi-sensor system to obtain acoustic (Distributed Acoustic Sensing: DAS) temperature (Distributed Temperature Sensing: DTS) and strain (Distributed Strain Sensing: DSS), simultaneously. This system can reduce the cost significantly compared with the case which many sensors are installed separately.

Our research group has developed the monitoring system with the DFOS technology through the laboratory experiments and field measurements. Currently we demonstrate our monitoring systems at various sites in Japan and overseas. At the domestic site, we evaluate the sensitivities of the newly developed OF cable, and verify the effectiveness of the DFOS monitoring system under the practical environment such as the injection at multiple wells. At the CCS site in North Dakota (ND), USA, we demonstrate the integrated monitoring system with DAS, DTS and DSS using the developed OF cables.

The CCS project in ND, USA injects 180,000 tons of CO2 annually captured from the ethanol facility into the deep saline aquifer approximately 2,000 m below ground surface. The CO2 operation was started at mid of June, 2022 and over 100,000 tons of CO2 was stored at the end of March, 2023.

Our DFOS system is used for CO2 monitoring in this project. Fig. 1 shows the map of the ND CCS site and a schematic diagram of the monitoring system with the DFOS technology. Simultaneous measurement systems of DAS (acoustic), DTS (temperature) and DSS (strain) is implemented by installing the developed OF cables at four wells (an injection well, an observation well, two shallow groundwater observation wells) and the CO2 pipeline. Table 1 summarizes the monitoring targets of each measurement system.

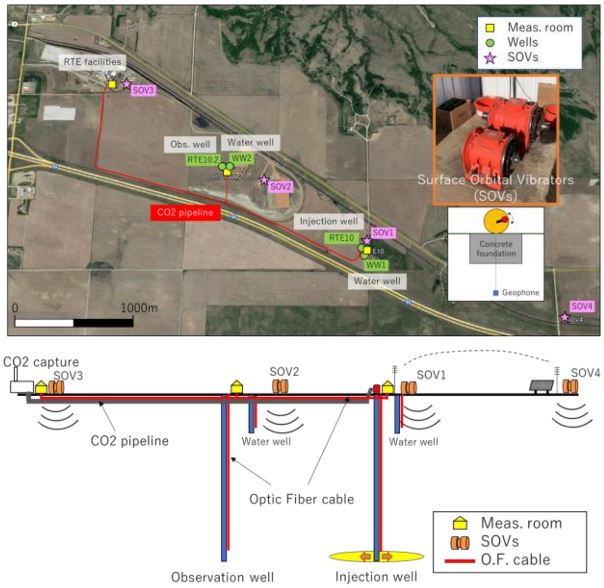

Fig. 1 Monitoring system with O.F. sensing

Table 1 Monitoring targets

DAS (Acoustic)	CO2 plume, induced/natural seisimicity
DTS (Temperature)	Well/pipeline integrity
DSS (Strain)	Geological stability of reservoir/cap rock

The borehole seismic with DAS (DAS-VSP) is used at two of deep wells to capture a CO2 plume subsurface. The VSP (Vertical Seismic Profiling) is one of the exploration seismic techniques and has advantages for high resolution and quality imaging due to the short distance between the target and receivers compared to the surface seismic. The OF cable works as the permanent seismic receivers installed behind the well pipe, which reduces the operation time and costs significantly especially for repeated surveys and also reduces the acquisition errors due to the gap of the receiver locations. The OF cable with small dimensions is installable behind the well pipe even at the injection well.

Repeated 3D seismic surveys are typically carried out every one to several years for the purpose of capturing the CO2 plume. In order to fill this temporal gap, we implemented surface orbital vibrators (SOVs), which can acquire data much more frequently. The SOVs are permanent vibration devices that transmit vibrations in the strata by rotating eccentric weights at high speed. In addition, there is no need for on-site operators for data acquisition, as remote operation and automatic controls are available. At the ND site, four SOVs are installed around the site and operated every day.

Fig. 2 shows DAS results excited by SOVs installed at the offset of about 60 m and about 1,000 m from the injection well, respectively. Direct P-waves continuing from the upper left to the lower right propagate from the surface to the underground (down-going), while waves continuing from the upper right to the lower left represent reflected waves propagating upward from the underground (up-going). Reflected P-waves, which are the main signals in VSP data processing, are well recorded with the good signal-to-noise ratio. The zero offset VSP recordings, which were obtained by the source sweepings at the closest SOVs, are used to detect the CO2 plume immediately after the start of injection, and other VSP recordings with certain offsets are used to capture the area of the CO2 plume. We are currently conducting time-lapse analysis of repeated VSP recordings.

Fig. 3 shows the DTS result at the injection well before and after the start of injection. The color contour chart clearly shows spatial and temporal temperature changes. While the temperature distribution along the well due to the geothermal gradient is consistent before the start of injection, the temperature drops by about 20 °C immediately after the start of injection. This represents that the low-temperature injected CO2 cools surrounding ground temperature. Moreover, even after the start of injection, repeated short-term temperature rises and drops are observed. This indicates the process in which cooled temperature tends to recover to the original formation temperature due to the temporary suspension of injection.

Spatially continuous DSS (strain) from the deep underground to the surface is performed to monitor the deformation of the strata caused by the CO2 injection. In the ND CCS project, we also monitor ground surface deformation using the satellite data in order to evaluate the relation between the ground surface deformation and CO2 injection at the deep strata.

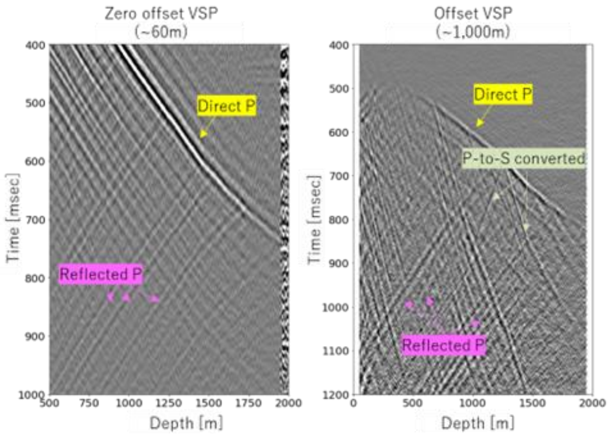

Fig. 2 SOV-DAS records

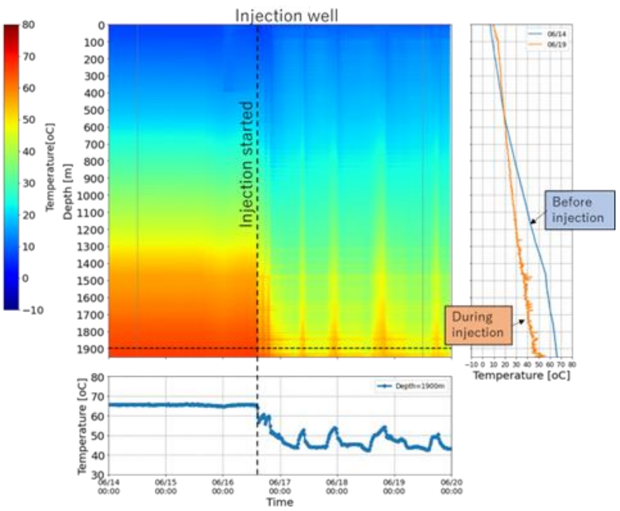

Fig. 3 DTS result before/after start of injection

On the other hand, at the Otway site in southwestern Victoria, Australia, a field experiment is underway for aiming to detect CO2 leakage from shallow faults using the DFOS monitoring system. Fig. 4 is a cross-section showing the layout of a newly drilled injection well (Brumby 3), an observation well (Brumby 4) and two existing wells for the CO2 leakage detection test. In previous research by CO2CRC, an Australian research institute, a well was drilled through a shallow fault zone and DTS (temperature) was measured using OF cables. As the DTS monitors the temperature change at only a small range around the installed cables, we drilled two new wells with the newly developed OF cables installed for high performance DSS (strain). These OF cables are also available for DTS (temperature) and DAS (acoustic).

A CO2 injection test is scheduled in this summer. The CO2 will be injected at the injection well (Brumby 3) and some of CO2 gas will move toward the ground surface along the fault zone. We expect that the DFOS monitoring system at the observation well (Brumby 4) detects this CO2 migration.

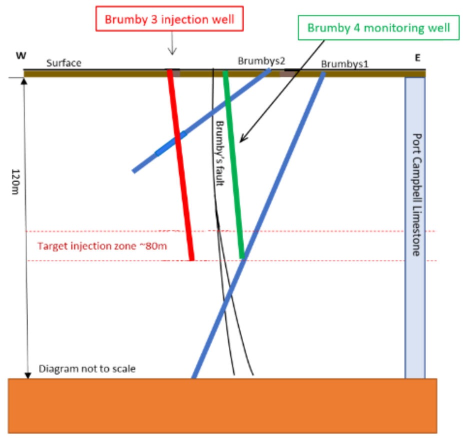

Fig. 4 Well layout at Otway site

2.2 SRM method development: development of cost estimation tool

As the Storage Resource Management (SRM) method development, we are developing a method for effectively utilizing the underground storage capacity (resource) at the CO2 storage site and a tool for evaluating the cost of the entire CCS project. The entire CCS project includes the stages of CO2 capture, transportation, and storage, and we aim to enable cost estimates corresponding to various options for CO2 emission sources, transportation methods, and injection amounts.

2.2.1 Features and configuration of the Tool

Our research group is developing the CCS cost estimation tool that allows even non-experts to appropriately estimate the cost of CCS, and that experts can also use for various CCS case studies. As for the specifications of the tool, in addition to trial calculations for individual cases, it is equipped with a mechanism that can collectively process multiple cases. And in addition to comparison studies for each case, studies that combine cases are also possible. The features of the tool under development are described below.

1) User friendly interface: The input interface has been devised so that the user can enter the necessary data appropriately without hesitation while looking at the screen, and can give instructions to execute calculations. If the screen is difficult to understand or the operation is complicated, the user cannot input specifications correctly, which leads to incorrect results or wastes operation time. Therefore, a easy and clear input interface is important. Fig. 5 shows the case selection screen. From this screen, it is possible to call up the specification confirmation screen and execute calculations.

Fig. 5 Case selection screen

In addition, the output interface is also important. Calculation results are output as a table on the web screen, but because they can be easily copied and pasted, they can be imported into Excel or dedicated graph creation software, and graphs can be created freely. By using the output from this tool, Fig. 6 shows CCS costs by transport volume and by distance in case of using pipelines and ships. It should be noted that the pipeline here is assumed to be an onshore type.

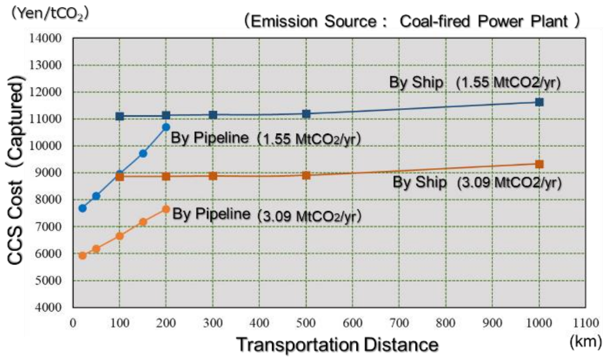

Fig. 6 CCS costs by transport volume and distance for pipelines and ships

2) Installation of DBMS (database management system): A general-purpose DBMS was installed for the purpose of easily and safely managing data in each study case for each user. It is also important to install the DBMS in order to make the interface, data management part and calculation engine independent. Completion of the cost estimation tool does not mean that the entire series of development ends. And continuous maintenance, such as rule changes, rule additions and data updates are required. This tool aims to improve maintainability by increasing the independence of each part.

3) Developed as a WEB system: No special operations of software or update are required on the user side, and it can be used only with a browser. Also, because all calculations are processed on the server, they are not affected by the capabilities of the user's PC or platform. Therefore, it is possible to use smartphones and pads in the meeting room to change specific specifications and to recalculate.

2.2.2 Development progress and future development plans

Fig. 7 shows the modules that have been installed so far (red frames) and the modules that are planned to be developed (blue frames).

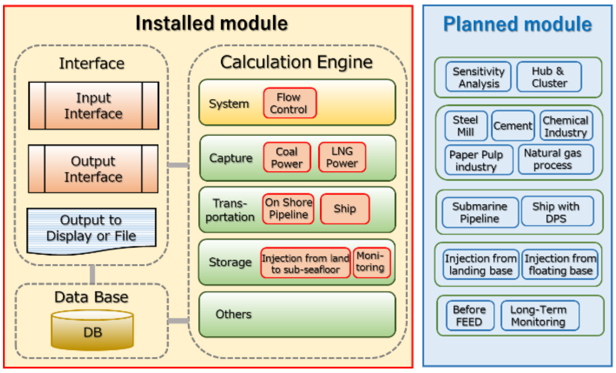

Fig. 7 Modules installed so far and modules to be developed

For capture, coal-fired power plants and LNG-fired power plants have already been installed. For transportation, it is possible to calculate "the pattern of land pipeline" and "the pattern of which, as one of ship transportation, loading from land and transporting it over the sea and then unloading it on land again". In the case of storage, it is possible to calculate the pattern of injecting water from the land into the sub-sea level with a sloping well. From now on, we plan to gradually develop the modules shown on the right side of the figure. In the coming modules, in addition to the cost calculation of each process, we plan to add calculation functions that extend the basic functions such as sensitivity analysis and hub & cluster.

In the first stage of development (until the end of FY2023), we plan to specialize in the trial calculation of the costs required for CCS. But in the future, we plan to develop them so that we can also use them for considering business models, by installing functions to calculate economic indicators that take incentives into account, etc.

2.3. Methodology for the Creation of Social Consensus (Social License to Operate, SLO)

The social consensus, including the local community, is essential to implement CCS projects. One of the key issues in the creation of social consensus (Social License to Operate, SLO) methodology is how business developers should communicate with residents so that they understand the need for CCS and support the project.

From the perspective of communication between business developers and residents, CCS business's significant character is the extremely low awareness of CCS among the general public. In a recent awareness survey, 14% of the respondents said they knew about CCS, and 42% said they had heard the word CCS. It was a situation that almost half of them had never even heard the word CCS. For this reason, the primary purpose of initial communication for CCS projects is to raise awareness of CCS, that is, to make residents get to know CCS.

The Barendrecht project in the Netherlands is a notable CCS project that was canceled due to opposition from residents. It has been pointed out that the reasons for residents' opposition were the lack of a lots of important aspects of risk communication, such as the fairness of procedures and trust. However, what is noteworthy here is that it is believed that the residents did not fully understand the CCS (project). Initially, residents were not considered as stakeholders and were not adequately informed. In addition, after the residents' opposition became apparent, providing of information from public was regarded by the residents as ``propaganda of the CCS supporters,'' and the providing of information to the residents did not function enough. Since the residents did not obtain sufficient information, it is possible that their opposition was not based on their understanding of CCS or the project. In other words, there is a possibility that the opposition was based on information heard from reliable people (celebrities, media, etc.) or many people. In such cases, decisions may be made based on wrong information. In fact, in Barendrecht 's case, the cover of a magazine is illustrated as a picture of a volcanic eruption spewing CO_2 out into the city, something that cannot happen. One of the importance of raising awareness of CCS in the early stages of the project is to increase the number of people who understand CCS and the CCS project and can decide whether to approve or disapprove of the project.

Literature on communication points out that it is important for business developers to listen to the opinions of residents/citizens and engage in dialogue (two-way communication) rather than giving one-sided explanations (one-way communication). However, this is not necessarily the case for communications in the early stages of a CCS project. Even if opportunities for dialogue are created, there is a risk that many people will not positively participate. It has also been pointed out that many people are unwilling to spend their precious time and effort to cooperate in solving social issues. Others may prefer passive (one-way) communication. In case of two-way communication, they feel that they must express their opinions, and feel a heavy mental burden. For this reason, it is considered important that the burden of participation is small and that it is easy to participate, rather than whether one-way or two-way communication, in the early stages of a project.

Lectures, exhibitions, and science cafes are held as scientific events to spread science and technology, especially to make people who have little interest in science and technology more familiar with science and technology. These scientific events are also suitable for early-stage communication events of CCS projects due to their low participation burden. However, many science events are known to have a very low participation rate of people who have little interest in science and technology, on the contrary to their purpose. However, even in science events, the participation rate of people with low interest in science and technology increases if the theme is related to their personal interests or directly related to their lives. From this point, it is considered necessary to hold two types of communication events in the early stages of CCS projects: events focused on science and technology, and events focused on matters directly related to people's lives.

Also, from the viewpoint of easiness for participation, it is effective to hold the event online. Due to the corona crisis, some of the events that had been held face-to-face until then were now held online, but there is a report that, thanks to the online event, people who had less participation in face-to-face events are now participating. However, while it is easy to participate in online events, it also has the disadvantage that it is easy to not concentrate on watching or to stop watching in the middle.

What has been described so far is only about communication at the beginning of the project. And the importance of two-way communication increases as the project plan becomes concrete. It is necessary for the business developer to have two-way communication with the residents and reflect the results in decision-making, instead of explaining the decisions made by the business developer to the residents and making them accept it. This becomes important for the smooth implementation of the project. In addition, in parallel with such events, public relations activities using the web, SNS, pamphlets, etc. are also necessary from the initial stage of the project in order to raise awareness of CCS and the CCS project.

Our research group is also creating a QA collection that can be referred to when explaining CCS to residents and answering questions from residents. It is said that the main fears and concerns that the general public feels about CCS are CO2 leakage and triggering of earthquake. Therefore, the QA collection particularly focuses on these two themes. A (Answer) is based on scientific knowledge including the research and development results of our research group so far, but we try to make the explanation understandable even without prior knowledge.

In order to reach agreement by residents and citizens, it is important that they come to understand CCS technology itself, and it is also important that they come to know the benefits of conducting CCS projects. In case of overseas CCS projects, they introduce the amount of investment and the increase in the number of employees which are brought by the implementation of the project. In case of facilities of about 1 million tons/year, which they regard as a commercial scale, it is reported that capital investment's amount of approximately 100 billion yen is expected. It is also reported that the employment effect is several thousand during construction and several dozen during operation. In the United States, it has also been shown that implementing CCS without decommissioning coal-fired power plants is effective in preventing unemployment and the decline of local industries. In this area, there is a coal mine adjacent to the coal-fired power plant. Since most residents are involved in power plants and the coal industry, the closure of coal-fired power plants will have a negative impact not only on residents, but also on the survival of municipalities. In Japan as well, there are concerns that the tax revenues of local governments will decrease dramatically due to the closure of oil refineries, ironworks, coal-fired power plants, etc., which are sources of large amounts of CO 2 emissions. CCS, as a decarbonization option, can contribute to sustainable regional operations, with substantial local benefits.

For the commercialization of CCS, it is necessary to envision a CCS business model that suits the situation in each region of Japan. We developed an emission source database to grasp CO2 emissions. CO_2 emissions were converted from summary results of greenhouse gas emissions which are based on thermal power generation handbooks and greenhouse gas emissions calculation, reporting, and publication system, and sorted out as direct emissions. The emission source database contains location information and it can be shown on maps. Even if the amounts of emissions from individual companies is small, grouping emission sources as a regional cluster will be useful in considering a hub-and-cluster approach to CCS. By integrating the emission source map and the potential capacity map of CO2 storage sites owned by RITE, we devised ways to make it easier to visualize the business image. Furthermore, by adding port information, it has become possible to plan transportation routes from emission sources to reservoirs, including not only land routs but also sea routes. Currently, we are also developing the CCS cost estimation tool, and are compiling the SLO method so that we can examine the merits of implementing CCS from an economic point of view as well.

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
29 Jul. 2022	Kyoto Prefectural Nishimaizuru High School	15
22 Nov. 2022	Nara Prefectural Narakita Senior High School	17
20 Jan. 2023	Seikaminami Junior High School	7

◆Environmental Education (Workshop)

Date	Title	Number of participants
2 ,4, 5, 8,10 Aug. 2022	Craft and Science Experiment to Learn about the Future Energy	121
22 Aug. 2022	Trial Package Tour in Seika Town – Let's make memories of summer	13
23 Feb 2023	Keihanna Science Festival 2023 – Global Warming and CCS Study Workshop	25

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Research Institute of Innovative Technology for the Earth

Research Institute of Innovative Technology for the Earth

URL: www.rite.or.jp/en
Email: pub_rite@rite.or.jp

9-2 Kizugawadai,
Kizugawa-shi, Kyoto
619-0292 JAPAN
TEL.+81-774-75-2300