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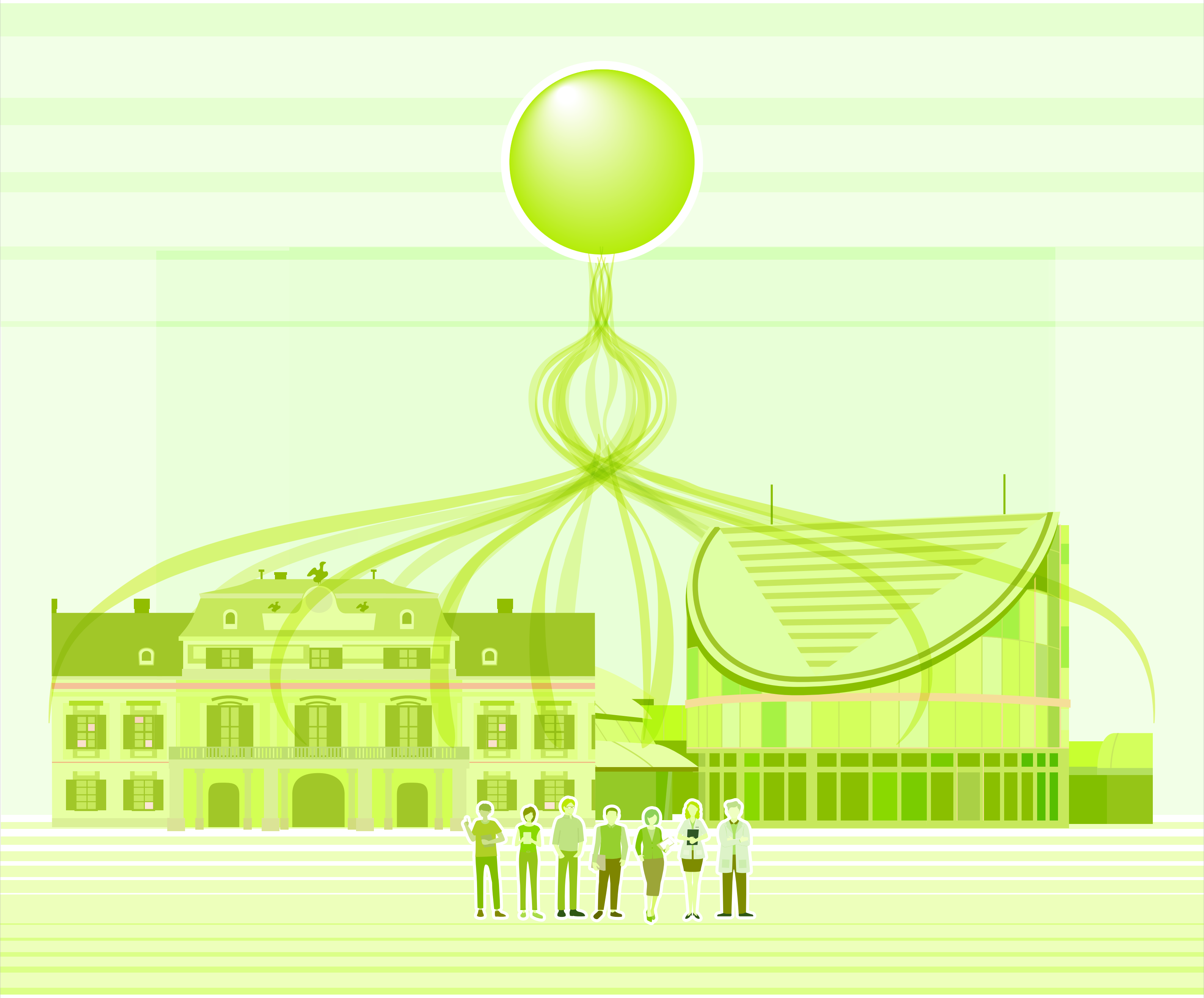

Feature: EDITS Energy Demand changes Induced by Technological and Social innovations

RITE Today 2022 Vol.17

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Leveraging Diversity to Drive Innovation

Kenji Yamaji
President / Director - General,
Research Institute of Innovative Technology for the Earth (RITE)

I was appointed president of the Research Institute of Innovative Technology for the Earth (RITE) in June 2021 and would like to take this opportunity to share my thoughts.

For over 30 years since its establishment, RITE has engaged with climate change solutions, including carbon dioxide capture and storage (CCS), biorefinery, and scenario analyses for climate change responses. During this time, engagement with climate change has gained much momentum at home and abroad, and I am confident that RITE has been of service to this development.

A recent major event in Japan pertaining to climate action was the government's notification to the United Nations in October 2021 of the country's Nationally Determined Contribution (NDC) under the Paris Agreement. In its NDC, Japan made the very ambitious pledge of reducing its greenhouse gas emissions to 46% below FY2013 levels by 2030 to achieve carbon neutrality by 2050. At the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26), not just Japan but many other countries raised their climate action targets to keep up with the goal of staving off temperature rises exceeding 1.5°C. I feel that these developments put ever higher expectations on RITE and that RITE must meet the expectations by advancing its research further. Carbon dioxide capture, utilization and storage (CCUS) and biotechnology are seen as very promising means of achieving carbon neutrality, and I believe they have entered a new phase toward practical application.

Research, however, must proceed one steady step at a time, and there are no shortcuts to a goal. There are numerous different technologies for achieving the goal of carbon neutrality set by many countries, including Japan. We must also remember the importance of electrification and decarbonization of electricity; hydrogen, CCUS, and other energy-related measures; and measures for agriculture, forestry, and fishing industries. For industries or areas where greenhouse gas reduction is difficult, we need to also study direct air capture (DAC) technologies for recovering CO_2 from the atmosphere to set off emissions. In addition to technological solutions, social innovation plays a significant role as well.

International developments warrant close attention. Japan's announcement during COP26 to drive "zero-emission thermal generation" through hydrogen and ammonia use earned the ironic Fossil of the Day Award, as did Norway for promoting both Norwegian gas and CCS and France for announcing the construction of new nuclear power reactors. But zero-emission thermal power, CCS, and nuclear power are all important climate change responses. Narrowing available options by excluding specific technologies will pose a major hindrance to attaining the challenging goal of carbon neutrality.

The fight against climate change is configured for burdens to be borne locally but benefits to be shared globally. As such, creating situations that would allow major countries to pull out, or excluding specific technologies, will damage international cooperation and invite the self-destruction of climate action.

Crucial to addressing climate change and other issues requiring long-term worldwide commitment is to maintain cooperation and integrity while acknowledging technological and cultural diversities. The latest innovation policies often point out the importance of ecosystems because harnessing diversity by bringing together different sectors—ventures and businesses, for instance, and industry and academia—is considered conducive to innovation.

RITE likewise looks forward to driving innovation in climate action by harnessing diversity.

To Achieve a Low Energy Demand Society through Technological and Social Innovation
－International Model Comparison Project EDITS－

Systems Analysis Group
Keigo Akimoto, Group Leader, Chief Researcher
Miyuki Nagashima, Senior Researcher
Ayami Hayashi, Senior Researcher
Atsuko Fushimi, Senior Researcher

1. Introduction

The Paris Agreement in 2015 set a goal to hold the global average temperature increase to well below 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C. Then, corresponding to the 2 °C goal as an emission reduction, a so-called carbon neutral (net zero emission) was agreed to balance the anthropogenic emission by sources and the absorption by the sink for greenhouse gases in the latter half of this century. Furthermore, while the demand for early carbon neutrality (CN) was increasing at home and abroad, in October 2020, former Prime Minister Suga declared that Japan would aim for CN by 2050. This is a goal that is consistent with the scenario of controlling temperature rises below 1.5 °C. After that, Japan said in April 2021that it would deepen its emission reduction target to a 46% reduction in 2030 and that it would take on the challenge of further reducing it by 50%. In addition, the 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change (UNFCCC) has concluded in November 2021, countries agreeing to pursue efforts to limit the rise in global average temperature to 1.5 °C.

To achieve CN, it is crucial to utilize a wide range of emission reduction opportunities such as renewable energy, nuclear power, and so-called Carbon Dioxide Removal (CDR) technology, including Carbon Capture Utilization and Storage (CCUS) and Direct Air Carbon dioxide Capture and Storage (DACCS). On the other hand, it is conceivable that energy conservation will continue to be the most critical issue in reducing CN emissions. In particular, the fusion of digital transformation (DX) and green transformation (GX) can bring about a virtuous cycle of the environment and the economy.

The Intergovernmental Panel on Climate Change (IPCC) published the 1.5 °C Special Report (SR15)[1) in2018. Various emission routes that achieve 1.5 °C were shown there, particularly the scenario[2) called Low Energy Demand (LED) drew attention. This scenario shows much less energy than the final energy demand, as shown by regular model analysis. The scenario is said to be possible to contribute not only to climate change countermeasures, but also to the simultaneous achievement of SDGs.

Figure 1 shows the world energy consumption by stage of energy use. Energy is wasted, particularly close to where it is the end-use. Energy is often consumed even though it is unnecessary and does not contribute to the service[3)]. For example, lighting is a classic example and often illuminates even when no one is present. Although motion sensors have become economical in recent years and have come to turn off automatically when there are no people, they are still often lit in vain.

We are not consuming energy for the purpose of consuming energy. As a result of an attempt to obtain a more satisfying service, energy is consumed and CO_2 is emitted. It is essential to determine whether the services we take for granted are indispensable and what services we genuinely need.

In the world, research on the Decent Living Standard (DLS: appropriate standard of living, minimum standard of living) is progressing, and according to the research, the world's end-use energy consumption is about 400 EJ/yr. and would be about 600 EJ/yr. over the year 2050. There are many analyzes that it would be about 400 EJ/yr., which is the same as the current level even with countermeasures for the 2 °C scenario, but some studies say that about 150 EJ/yr. from DLS is sufficient[4]. Indeed, the appropriate level may change since human needs are diverse; however, it is conceivable to be an important study for understanding the factors that cause a gap with actual energy consumption.

Noted that Reference 5) points out that the speed of technological progress of small-scale technology is often seen on the demand side, and while there is a demand for rapid carbon neutralization, it is necessary to take measures on the demand side.

Factors that induce measures on the energy demand side include the significant progress in digitalization technology and the buds of social change, especially among young people in Europe. Under these circumstances, Reference 6) points out the need to strengthen research on the demand side and research progress is expected, with a new chapter focusing on energy demand measures assigned in the sixth evaluation report of the IPCC Working Group 3 scheduled to publish in 2022.

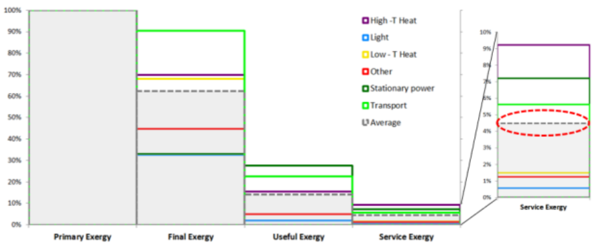

Figure 1 World energy consumption by stage of energy use（assuming100% primary energy consumption）[7]

This paper introduces the commissioned project “Model Comparison International Collaboration Project on Changes in Energy Demand by Technological Innovation” by the Ministry of Economy, Trade, and Industry (METI). This project is known as EDITS (Energy Demand changes Induced by Technological and Social innovations) and started in 2020, intending to induce a change in society by identifying opportunities for the realization of a low-energy demand society and presenting them as concrete and quantitative scenarios.

2. Possibility of realizing a society with low energy demand in various sectors

We examine the possibility of realizing a society with low energy demand by sector.

2.1. Home appliances

Changes in home appliances are being observed. Figure 2 shows that a variety of home appliances can now be replaced by smartphone functions. In addition, the power consumption of smartphones is becoming much smaller than that of home appliances. Even more important is the "embodied energy" of the product. The energy input at the manufacturing stage of a product is also greatly reduced when it is replaced by a smartphone. Of course, not all functions can be completely replaced, but the addition of other benefits (e.g., ease of mobility) will facilitate the re-placement, resulting in lower energy consumption and CO_2 emissions.

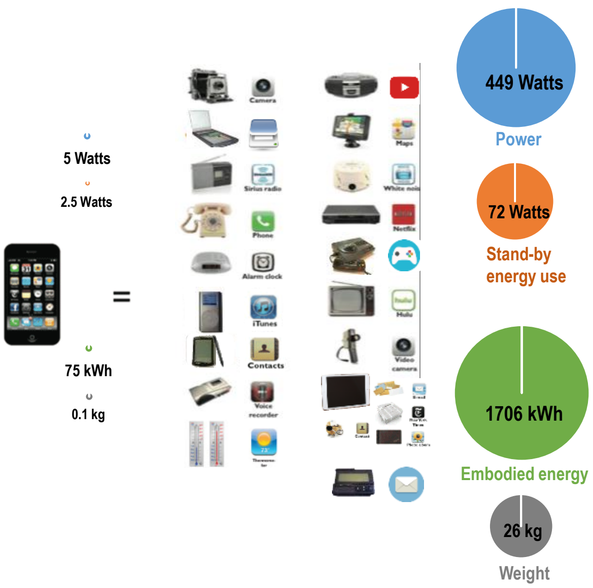

Figure 2 Substitution of home appliances and potential for low energy use[8)]

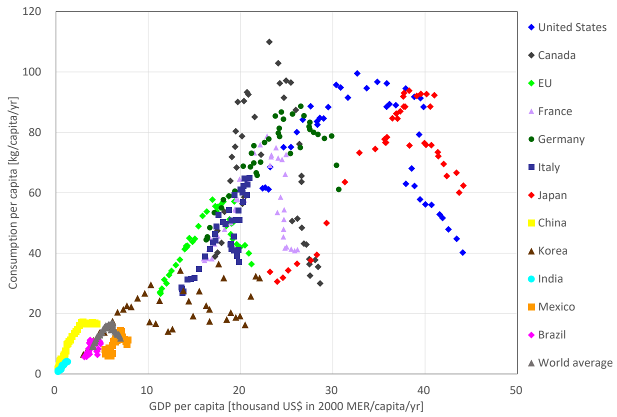

Figure 3 Transition in consumption of printing and writing paper[9)]

2.2. Paper medium

Paper has played a major role as a means of circulating information. On the other hand, paper and pulp is an energy-intensive industry that requires a large energy input in the manufacturing process. Figure 3 shows the transition in consumption of printing and writing paper. Recently, per capita consumption of printing and writing paper has been on a downward trend not only in developed countries but also in developing countries. The same trend is observed in the consumption of newspaper rolls. This is thought to be a result of the decline in paper consumption as the IoT progresses, making it relatively easy to obtain information using various digital devices. When digital devices first became widespread, there seemed almost no reduction in paper-based printing, but it appears that the combination of advances in devices and user familiarity is having an effect.

However, the consumption of corrugated paper continues to show an upward trend due to the increase in home delivery and other services.

2.3. Apparel

Apparel has been pointed out as having a high environmental impact due to its energy consumption from manufacturing to disposal and its short life cycle. For example, the study[10)] shows that the fashion industry is responsible for 8-10% of the global CO_2 emissions (4-5 billion tons per year) to the global environment.

In addition, according to the literature[11)], CO_2 emissions from the use of clothing in European households (washing, drying, ironing, etc.) are estimated to be 530 million tons per year. Although only rough estimates can be made, as the use of clothing and the maintenance of the same garment (how many times it is worn) depend on the choices of the individual consumer, it is estimated that the CO_2 emissions during the use phase of an average T-shirt account for half of its lifecycle emissions. For example, when estimating the life cycle emissions of a cotton T-shirt, if it is washed 50 times, 35% of the CO_2 emissions are attributed to the fiber production and 52% to the use stage. Although natural fibers emit less CO_2 at the fabric production stage than synthetic fibers made from petroleum, the low carbon footprint at the production stage may be offset at the use stage because natural fibers require more energy for washing, drying, and ironing than synthetic fibers.

Recently, apparel sales have been growing dramatically, and the reason behind this growth is the rise of fast fashion. Fast fashion refers to a type of clothing sales chain that emerged in the late 1990s and early 2000s and is characterized by the mass production of clothing that follows the latest design trends in a short cycle and sells it at low prices to encourage mass consumption. It is estimated that 50% of clothes are discarded without being worn, and for many clothes, the utilization rates are low, and those are waiting in the closet to be worn.

The fashion industry is also promoting products that are environmentally and socially friendly. E-Commerce sales allow brand companies to avoid the energy consumption of maintaining physical stores and the need to carry inventory. However, as mentioned above, purchasing clothes through e-commerce without trying them on increases the number of unused clothes that are thrown away because the size does not fit or the image is different. As a solution to this problem, virtual fitting and automatic body shape measurement technologies are being developed.

In addition, the trading of used clothing through the development of internet auctions is effectively the development of clothing sharing, which encourages the matching of supply and demand, improves the utilization rate of apparel products, and reduces waste.

For more information on apparel, please refer to the study [12].

2.4. Food

GHG emissions from the entire food system, including agricultural and fishery production, food processing, transportation, cooking, etc., were estimated to have accounted for 21-37% of total global emissions[13]. (These estimations are generally based on flows of products and services; however, it is expected to be even larger if the emissions from constructing fixed capital such as stores, and facilities are included.) On the other hand, it was estimated that roughly one-third of food produced for human consumption has been lost or wasted. The reasons vary by region, with overproduction aimed at maximizing revenues and high levels of waste at the consumption stage being common reasons in middle- and high-income countries[14]. If food demand can be predicted more accurately by utilizing Information and Communication Technology (ICT), which has made remarkable progress in recent years, it is expected to not only reduce food wastage but also save plastic containers, space in supermarkets, and energy for refrigeration/freezing and transportation, leading to reduced energy consumption and GHG emissions. It could contribute to the simultaneous achievement of the SDGs.

According to our study based on the input-output table for Japan[15], if the food wastage in vegetable and fruit cultivation, food industries, and households in Japan could be reduced by 50%, it would contribute to reducing total energy consumption in Japan by 0.04–0.08 EJ/yr. (0.2–0.4% of the primary energy supply in Japan) and GHG emissions by 5.9–8.4 million tons CO_2 eq/yr. (0.5–0.6% of GHG emissions). These figures focused on Japan are not so large due to the relatively small ratio of food wastage in Japan. However, if the food wastage could be reduced worldwide, including regions where there is much more potential for food wastage reduction, the impacts would be significant. Our preliminary estimation for the world shows that if the food wastage in the world could be reduced through the assumed measures, the world GHG emissions would be reduced by approximately 1.1 $GtCO_2$ eq/yr[16]. The regional diversity of the food system is very high, and there is uncertainty in estimating food waste reduction effects; therefore, continuous scrutiny and research are necessary.

2.5. Mobility: Car and ride sharing

Advances in digitalization have a significant effect on mobility. A change called "Connected; Autonomous; Service & Shared; Electric (CASE)" is now taking place. The utilization rate of private cars is estimated to be around 4-5%, and most of the time, private cars are underutilized. This is due to the convenience of being able to travel in a private space at any time and promptly, even at a high cost. However, if fully automated vehicles are realized, even if they become ride-sharing or car-sharing, convenience will not be largely compromised, and they could be available at a lower cost due to higher utilization rates. Therefore, with the exception of some cars as preferences and the like, ride-sharing and car-sharing could advance rapidly. Moreover, ride-sharing can directly reduce the energy consumption of vehicles, and car-sharing can reduce the number of vehicles and the use of materials such as steel and plastic, and lower the energy consumption required for their production. RITE has also conducted quantitative analysis using an integrated assessment model[17].

The OECD/ITF has developed a model based on actual data (population distribution, road and public transport network, weekday trip demand (time of day, OD (Origin-Destination)), trip preferences, etc.)[18]. In Dublin, Ireland, the study shows that if all private cars were replaced by shared cars, the current mobility could be supplied with less than 2% of that number of vehicles. If 20% of private cars were replaced (even without EVs), CO_2 emissions would be reduced by 22%.

2.6. Industries: 3D printing

3D printing (additive manufacturing: AM) is making progress. Compared to forming by making molds or modeling by cutting, AM can create complex shapes and, in many cases, can create lighter products with the same strength, which can lead to improvement in material efficiency. In addition, it is possible to manufacture products according to individual needs rather than mass production, and there is a possibility of avoiding mass production and mass disposal.

2.7. Behavioral transformation

Not only technology but also individual behavioral change and the resulting social change are also important. On the other hand, expecting behavioral change alone is unlikely to have a significant impact.

A synergistic effect between technology and changes in social awareness would lead to major social changes. Movements such as ethical consumption will also encourage companies to change their behaviors, and lead to response by society as a whole. For example, the rate of driver's license acquisition has been declining. This will lead to a reduction in the purchase of private cars, which will motivate companies to develop fully automated vehicles.

2.8. Rebound effect

On the other hand, there is a possibility of increased energy demand as a rebound effect.

According to the study[19], it is estimated that the global data center power consumption was 194 TWh in 2010 and increased to 205 TWh (about 1% of the global power consumption) in 2018. Electricity consumption is estimated to have increased by only +6%, whereas the calculated instance for the same period was +550%. The main factors behind the increase in energy efficiency are server efficiency, virtualization, storage drive efficiency and densification, data center infrastructure efficiency, and changes in server types. On the other hand, there is a possibility of the end of Moore's Law, and some studies estimate a significant increase in data center power consumption in the future (e.g., Ref. 20).

The rebound effect is not limited to the direct increase in electricity consumption by the IoT. For example, if fully automated vehicles increase convenience, they may make people switch from trains and buses, triggering new travel demand itself. Furthermore, from a macro perspective, even if consumption decreases in a particular field, it could have a rebound effect where energy consumption and CO_2 emissions increase due to a shift toward other consumption. In addition to the need for comprehensive analysis, it is also necessary to develop comprehensive policies for the real world.

3. EDITS project overview

Against this background and awareness of the problem, EDITS started as a commissioned project of METI in 2020.

3.1. EDITS objectives

The June 2019 G20 Karuizawa Action Plan states that "We recognize the importance of quantitative analysis on a better understanding future energy demand and the role of innovation of both sides driven by digitalization, Artificial Intelligence (AI), the Internet of Things (IoT), and the sharing economy. We encourage efforts to further refine and develop a full-range scenario across the economy for energy and climate models made by the global scientific community and international institutions and frameworks."

The EDITS project aims at the following three points.

1) Build an international research community with a focus on the energy demand side. Share the latest data, concepts, methodologies, and policy analysis on the energy demand side. Through them, deepen discussions on research and policy analysis, and promote mutual enrichment.
2) Develop cutting-edge demand models for environmental and climate policy analysis through international comparisons of methodologies and models. In addition, develop concepts and methodologies across academic, energy, and environmental disciplines, and expand them widely and internationally.
3) Make better policy recommendations through structured model experiments and simulations. Notably, build and leverage models to address new areas and service supplies such as policy making with synergistic effects on the integration of digitalization, sharing economies, SDGs, and climate goals. Evaluate demand-side policy potential impacts and barriers and others, including synergies and trade-offs with other goals of SDGs.

3.2. EDITS research group structure

The following working groups conduct research based on the themes to deepen the research, including the contents introduced in Section 2. Moreover, each theme also plans to be integrated. The coordination of the entire research executes with the International Institute for Applied Systems Analysis (IIASA) cooperation.

【Sectoral Modeling/Analysis/ Consideration】

- Industry Sector

  [Primary Theme] Comparisons between industrial sector models (theoretical, geographical/temporal/biophysical coverage, data availability, understanding of differences in methods, etc.), effects of material efficiency, etc.

- Building（Household）Sector

  [Primary Theme] Comparison between building sector models (regional differences, heterogeneity), the effect of the sharing economy and the impact of smart working on the commercial building sector, etc.

- Transport Sector

  [Primary Theme] Comparison of transport sector models (activity type (passenger/cargo), location (urban/non-urban), vehicle size, mode difference, etc.)

【Data Collection/Organization】

[Primary Theme] Demand-side micro data collection and sharing

【Sectoral Modeling/Analysis/ Consideration】

- Qualitative Scenario Examination/Development

  [Primary Theme] Qualitative scenario construction for low energy material demand in line with 1.5 ℃ goals and SDGs

- Development of Protocol for Model Analysis Comparison

  [Primary Theme] Execution of comparative analysis between models (model analysis comparison utilizing the characteristics of each model)

- Sector Integrated Analysis

  [Primary Theme] Development of evaluation framework based on qualitative scenarios (welfare and feasibility evaluation), etc.

Cross-sectoral themes focus on digitization, equity, lifestyle/behavior change, business models, and theory building.

Figure 4 EDITS Logos（From left to right, Industry, Billing, Transportation, Data and Narrative Working Groups）

The energy demand-side spans various sectors and is diverse from country to country. Therefore, as shown in Table 1, the EDITS project is currently is being pursued jointly by researchers with many specialized fields from many countries and regions to carry out the above themes. In addition, a wide range of researchers other than those listed in Table 1 participate and cooperate with the project.

4. Conclusion

The road to CN realization is steep. Therefore, it is necessary to mobilize all the various measures. Various measures on the energy demand side induced by digitalization can urge widespread use by reducing the barriers, “hidden costs.” The large-scale progress of digitalization is probable to create a "virtuous cycle of environment and economy," accompanied by changes in the consciousness of the younger generation. In addition, it may contribute not only to climate change countermeasures but also to the resolution of various SDGs.

Table1 EDITS participating universities research institutes

Research Institutes	**Description**
International Institute for Applied Systems Analysis (IIASA)	Coordination of the entire project with RITE, formulation of shared scenarios for international model comparison, collection of related information
OECD/ITF	Collection and analysis of transportation sector-related information
Stanford University	Support for formulating shared scenarios for international model comparison
University of Tokyo, Institute for Future Initiatives	Formulation of shared scenarios for international model comparison, coordination with participating organizations and researchers
Lawrence Berkeley National Labs (LBNL)	Collection and provision of various data such as energy demand technology
Utrecht University	Collection and provision of various data such as energy demand technology
Euro-Mediterranean Center on Climate Change (CMCC)	Evaluation of the impact of digitization technology on energy, collection of related information, analysis, and estimation by international model
Tsinghua University	Collection and provision of various data such as model improvement and analysis in China and related energy demand technology
UFRJ/COPPETEC	Collection and provision of various data such as model improvement and analysis in Brazil and South America, and related energy demand technology
Asian Institute of Technology (AIT)	Collection and provision of various data such as model improvement and analysis of India, South Asia, and Southeast Asia, and related energy demand technology
Osaka University	Japanese consumer sector model analysis
University of Wisconsin	US-related data collection, analysis support, impact assessment of digitization technology
University of California、	Data collection and analysis support related

Santa Barbara (UCSB)	to the United States
The Korean Society of Climate Change Research	Collection and provision of various data such as model improvement and analysis related to Korea and related energy demand technology
Central European University	European consumer sector model analysis
University of Natural Resources and Life Sciences, Vienna (BOKU)	Industrial sector model analysis
University of Freiburg	Model analysis of industrial sectors and related information
ISCTE - University Institute of Lisbon	Cross-disciplinary analysis of technology, industry, policy, and related information
Mercator Research Institute on Global Commons and Climate Change (MCC)	Collection and provision of various data such as German model improvement and analysis, related energy demand technology
University of East Anglia (UEA)	Analysis of lifestyle changes in Europe, and related information
University of Groningen	Analysis of the impact of environmental behavior and contextual factors on energy technology and acceptability

This EDITS project continues to provide research results that will contribute to the following IPCC report and promote measures on the energy demand side of governments and companies in each country. The energy demand-side measures, which EDITS considers to be the main target, are not to reduce energy and CO_2 directly but to indirectly reduce energy and CO_2 through changing and optimizing products and services, such as the development of digitization technology. Therefore, it is difficult to recognize directly for the government and society, and there is a possibility that the response may delay. Because of this, the goal of this project is to make the complicated system understandable and quantitatively visible and disseminate it to the government, companies, and society.

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Research & Coordination Group

Members (As of Dec. 2021)

Isamu Yagyu, Group Leader, Chief Researcher
Makoto Nomura, Deputy Group Leader, Chief Researcher
Yoshifumi Kawaguchi, Deputy Group Leader
Takayuki Higashii, Chief Researcher
Tetsuya Deguchi, Associate Chief Researcher
Yoshinori Aoki, Associate Chief Researcher
Kimihito Suzuki, Associate Chief Researcher
Jun-ichi Shimizu, Associate Chief Researcher
Yasuaki Minoura, Manager
Noritaka Mochizuki, Planning Manager
Sou Kuranaka, Planning Manager
Daisuke Kihara, Vice Manager, Researcher
Yuka Matsugu, Chief
Yumi Kobayashi, Researcher
Natsuko Yasumoto, Researcher
Nami Tatsumi
Michiyo Kubo
Mizuki Nagata

Research of the Decarbonized Society to Achieve Carbon Neutrality

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/center. These efforts lead to a creation of new policy implementation, R&D and innovation aiming at the global environment and the economy[1].

In 2021, the Cabinet approved the Sixth Strategic Energy Plan to show the approach to energy policy toward achieving carbon neutrality by 2050, so it is outlined at first.

1. Cabinet Decision on the Sixth Strategic Energy Plan

In October 2020, Prime Minister Suga declared the goal of realizing a carbon-neutral, decarbonized society by 2050 at the 203rd extraordinary Diet session[2]. In April 2021, the Plan for global Warning Countermeasures[3] was revised and announced to reduce greenhouse gas emissions by 46% in FY 2030 from its FY 2013 levels, while continuing strenuous efforts in its challenge to meet the lofty goal of cutting its emission by 50%.

In October 2021, the Sixth Strategic Energy Plan[4] has been formulated, showing the approach to energy policy toward achieving carbon neutrality by 2050 and presenting initiatives to ensure stable supply and reduce energy costs based on the major premise of ensuring safety, in order to solve challenges facing Japan's energy supply and demand structure while taking action against climate change (Fig.1).

In December 2021, while realizing carbon neutrality by 2050 and the reduction of greenhouse gas emissions by 46% in FY 2030, Ministry of Economy, Trade and Industry (METI) started to discuss "the Clear Energy Strategy"[5] to describe the feasible pass in not "a point" but "a line" in addition to finding the stable, cheap energy supply for the future. It is being formulated in about June 2022.

In the Clean Energy Strategy, the agenda for discussion is securing stable, cheap energy supply for the future and changing energy contents of each field of demand side including industry as well as the supply side.

・In the light of new GHG emission reduction target inFY2030, this outlook shows **energy supply and demand on the ambitious assumption that various challenges in both aspects of supply and demand** in promoting thorough energy conservation and expansion of non-fossil energy **will be overcome**.

・In implementing the measures towards this ambitious outlook, **degree and timing of implementation of the measures need to be carefully for stable supply of energy not to be impaired.**(e.g. If fossil fuel power sources are immediately curtailed at a stage prior to full introduction of non-fossil fuel power sources, stale supply of electricity can be impaired.)

		(FY2019⇒ previous energy mix)		Energy mix in FY2030 (ambitious outlook)	
Energy efficiency improvement		(16.55 million kl ⇒ 50.30 million kl)		62million kl	
Final energy consumption (without energy conservation)		(350 million kl ⇒ 377 million kl)		350 million kl	
Power generation mix Electricity generated : 10,650 TWh ⇒ Approx. 934 TWh	Renewable energy	(18% ⇒ 22～24%)	solar 6.7%⇒7.0% wind 0.7%⇒1.7% geothermal 0.3%⇒1.0～1.1% hydropwer 7.8%⇒8.8~9.2% biomass 2.6%⇒3.7~4.6%	36～38% ※If progress is made in utilization and implementation of R&D of renewable energy currently underway, 38% or higher will be aimed at.	(details of renewable)
	Hydrogen/Ammonia	(0% ⇒ 0%)		1%	solar 14～16%
	Nuclear	(6% ⇒ 20-22%)		20-22%	wind 5%
	LNG	(37% ⇒ 27%)		20%	geothermal 1%
	Coal	(32% ⇒ 26%)		19%	hydropower 11%
	Oil, etc.	(7% ⇒ 3%)		2%	biomass 5%
(＋ non-energy related gases/sinks)					
GHG reduction rate		(14% ⇒ 26%)		46% Continuing strenuous efforts in its challenge to meet the lofty goal of cutting its emission by 50%	

(Source) Outline of the Sixth Strategic Energy Plan（October, 2021 Agency for Natural Resources and Energy）

Fig.1 The Sixth Strategic Energy Plan － Points of outlook for energy supply and demand in FY2030(1)

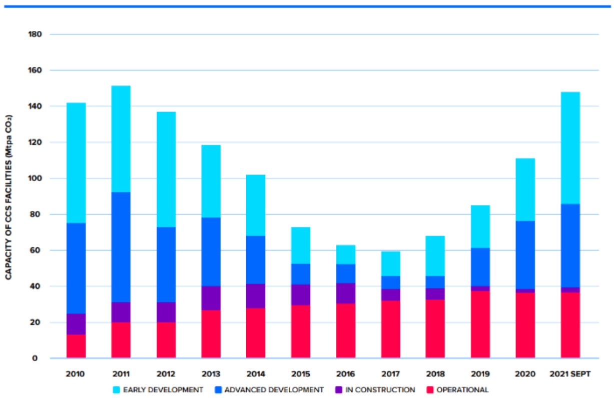
2. Research Activities

Last year, RITE studied the CCS (Carbon dioxide Capture) investigation research[6)] entrusted by METI which was the research related to the system design and business conditions for CCS industrialization, so it is outlined in the below.

2.1. The Trend of Commercial CCS projects in the world

Fig. 2 showed the trend of the facilities capacity (CO_2 possibility quantity) of the world's commercial CCS projects published by GCCSI (Global CCS Institute)[7)]. The quantity increased from 2010 to 2011, but decreased the half of 2011 in 2017.

The CCS projects need relatively big investment and a long time, so were postponed or stopped by various reasons before the last investment decision. Since 2018, they have increased again. It is guessed to be the influence of the Paris Agreement that took effect in 2016. The future reduction target became clear and each country recognized the large cut of CO_2 discharged by human and the importance of CCS projects to achieve the target. In 2021, the capacity increased to the same level in 2011.

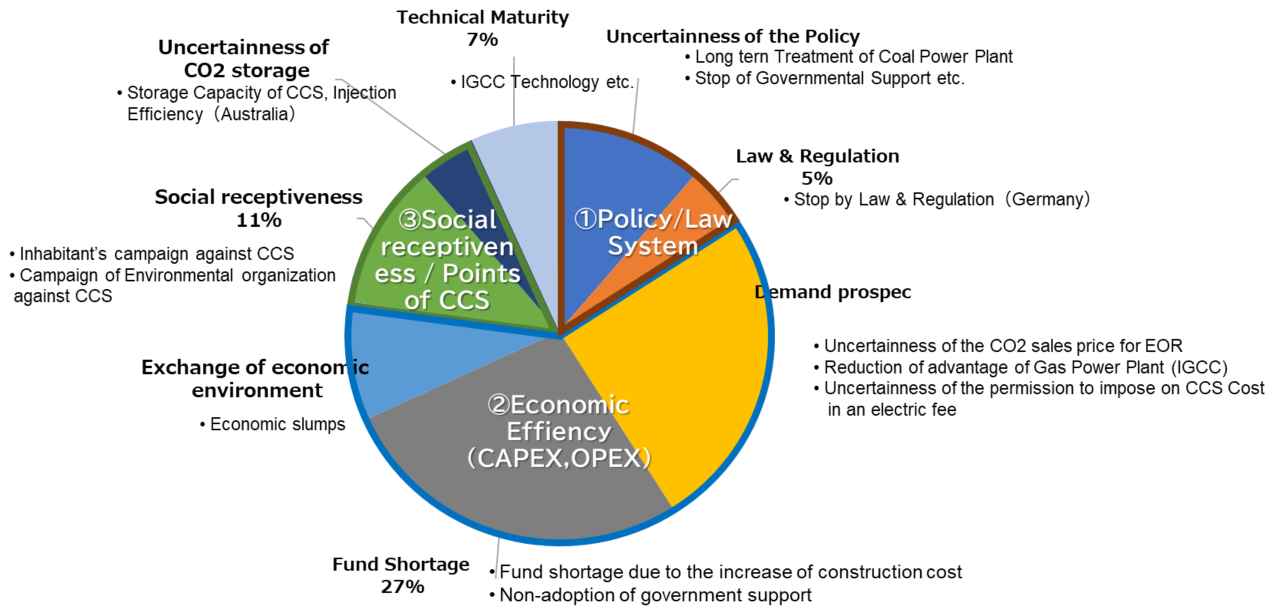


(Source) GCCSI, The Global Status of CCS 2021, P14, FIGURE 7 PIPELINE OF COMMERCIAL CCS FACILITIES FROM 2010 TO SEPTEMBER 2021 BY CAPTURE CAPACITY

Fig.2 The trend of commercial CCS projects in the world

2.2. Introduction Barrier of CCS

32 CCS projects were investigated and arranged that stopped abroad in the past to examine the framework of CCS's industrialization. According to 32 main cancellation reasons, the introduction barrier of CCS was ①Policy and Law Problem (16%), ②Economic Problem (61%) and Social Acceptability & Storage Points (16%).



（Source) METI's research report in 2020 https://www.meti.go.jp/meti_lib/report/2020FY/000266.pdf

Fig.3 The Barrier of CCS Introduction

2.3. Framework of the Business Environment for CCS Introduction

The introduction barrier of CCS projects was ①Policy and Law Problem, Economic Problem and Social Acceptability & Storage Points as mentioned above. It is important to lower the business risk with the uncertainty. Therefore, the business environments of CCS introduction showed ①CCS's Significance/Licensing, ② the Outlook of CCS Business and ③CCS business Precondition.

①Significance / Licensing of CCS（Correspondence of Policy/ Law System）:

a) The roadmap showing the clear policy, CCS introduction time, CCS cost target and etc. is necessary.
b) The comprehensive legal system corresponding to the life cycle of CCS (Survey, Injection, Management of Abandoned Mine, Responsibility Transfer etc.) is necessary.

②Outlook of CCS business (Correspondence of Economic Problem):

a) The earnings structure that profit is provided in consideration of additional cost and framework of financing (business model) is necessary.
b) Examination of Enforcement of CCS and the Clarification of the responsibility range of the CCS's company is necessary.

③CCS business Precondition（Correspondence Social Reception& Storage points）:

a) If people don't recognize the ccs as the rational technique for global warming measures, it may become negative to give CCS public support (subsidies) and social implementation. Therefore, the frame about the social acceptability improvement is necessary.

b) The performance uncertainty of storage quantity becomes the premise of the CCs introduction enforcement judgement. The framework to evaluate the exploration of storage points is necessary.

The CCS projects need long lead-time. It is necessary to early consider and build the CCS's framework to utilize the global warming measures technology.

3. Promotion of international partnership

3.1. IPCC

IPCC (Intergovernmental Panel on Climate Change) has been established in 1988 with a view to conducting a comprehensive assessment from a scientific, technical and socioeconomic standpoint 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). IPCC examines scientific knowledge on global warming and makes the reports contributing to three WGs, Physical Science Basis (WG1), In-fluence and Adaptation (WG2), Mitigation Measures (WG3).

In IPCC, the experts chosen among each country make the report, based on the dissertation 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 inter-national negotiations because 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). IPCC published WG1's report on the physical science basis in August 2021 and is going to publish WG2's report in February 2022, WG3's report in April 2022 and the integrated report in September 2022. RITE has also been supporting METI through information collection / analysis / report / advise etc.

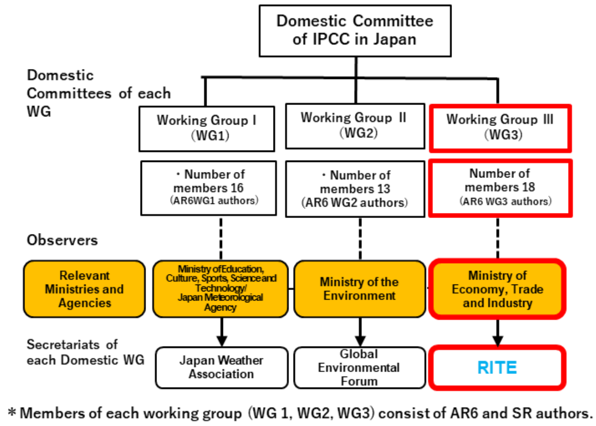


Fig.4 Committee structure and RITE

3.2. ISO

ISO (International Standard Organization) is an organization composed of 167 standardization bodies of various countries that gives the common standards and promotes global trade. It can provide safe, reliable and high-quality products/service to utilize ISO standards.

Carbon dioxide capture and storage (CCS) is one of the important options for global warming countermeasures because it has a great effect of reducing CO_2 emissions into the atmosphere. In the world, a number of CCS verification projects on a commercial scale are also implemented, and international collaboration is under way. The international standard plays an important role, contributing to the widespread use of safe and appropriate CCS technology.

RITE is a domestic deliberation organization on ISO / TC 265 (collection, transportation, and storage of CO_2) and is in charge of a secretariat of WG 1 (collection). Through these activities, we are conducting international standardization on design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the CCS field through international standardization (Fig. 5).

In January, 2022, twelve standards related to the CCS field have been published from ISO / TC265. The new WG related to CO_2 transshipment is established and is going to start the standard consideration next year. And Seven ones are under development including the present consideration.

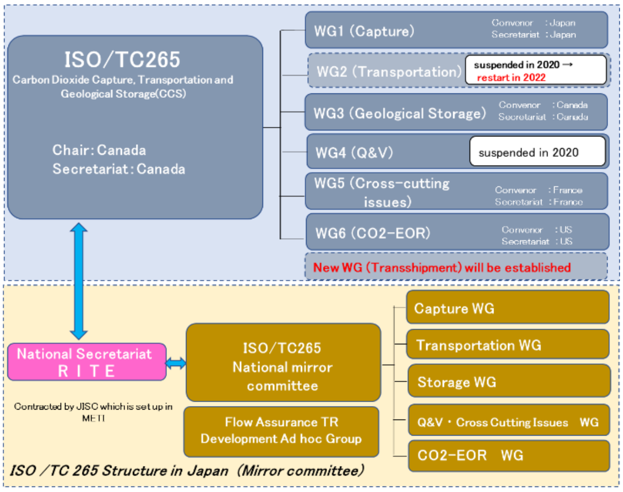


Fig.5 ISO/TC265 structure

4. Human development and industry collaboration

4.1. Human development

<Elementary and high school students>

RITE promotes extracurricular learning using research facilities for elementary, junior and senior high school students. And RITE also welcomes teaching requests where staff members visit schools using teaching materials and equipment. Such demands for human development are growing year by year. For example, we picked up CCS technology from RITE's research and explained the global warming mechanism. We are conducting activities based on the learning cycle such as deepening understanding through discussion and exchange of views (Fig. 6).

But because of Novel Coronavirus, we held classes and workshops for 54 students in 2021 (37 students in 2020, and 397 students in 2019). RITE wants to restart a class and a workshop as soon as the situation is improved.

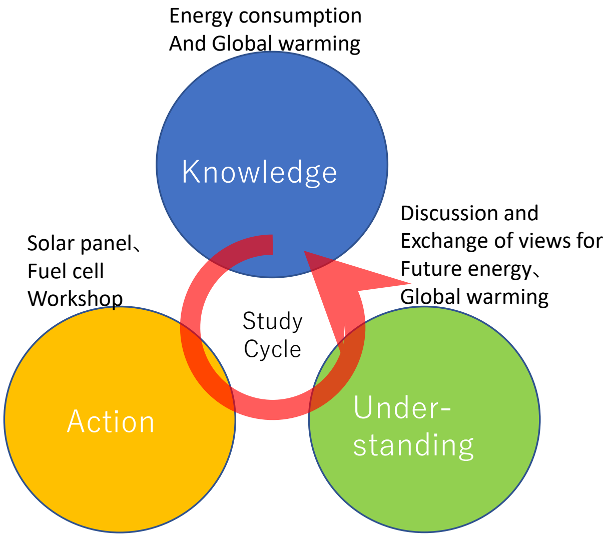


Fig.6 RITE and environment education
(Elementary, middle and high school students)

<University / Postgraduate student>

RITE is promoting collaboration of education with universities as part of human development sup-porting the next research and technology. We are accepting young talented people, mainly graduate students, to the research site. Here, we are developing education at the university and research guidance at the laboratory (Fig. 7). RITE established a university collaborative laboratory in the field of bioscience with Nara Institute of Science and Technology. Here we are conducting research and education aimed at realizing a recycling-type and low-carbon society by using renewable resources effectively using biomass as a raw material.

Also, RITE has established a university collaborative laboratory in the field of CO_2 capture with Nara Institute of Science and Technology.

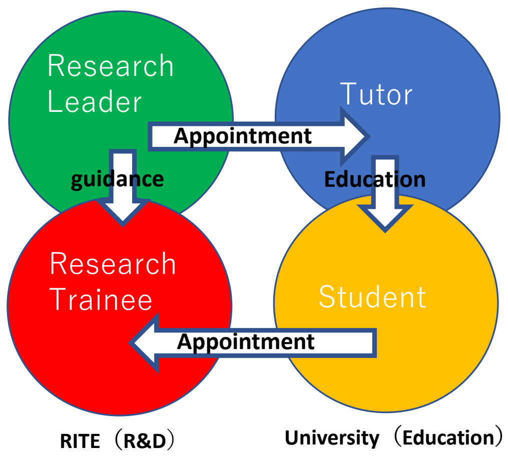


Fig.7 RITE and environment education (University / Post graduate student)

4.2. Intellectual property and industry collaboration

RITE acquires and manages intellectual property rights such as patents and know-how strategically and efficiently on results obtained in R&D.

To acquire patent rights brings up the opportunity which RITE cooperates with industries. As a result, it is possible to accelerate industrialization and simultaneously promote public interest and innovation as a public research institution. Intellectual property brings up opportunities to cooperate with industries. It is expected that a virtuous circle is created based on appropriate information management and contracts to create further intellectual property. It is also expected that the aspect of the intellectual property that enables related technologies to be used to support standards, such as collaboration with international standards (such as section 3.2). Based on the market and other re-search and development trends, RITE promotes intellectual property strategically.

RITE has established the IP management Committee which consists of RITE's leaders and the committee discusses and decides Invention certification, patent application to domestic and foreign, request for patent examination, patent maintenance and the approval of license contract.

As of the end of 2021, the patents during application and examination are 24 domestic and 21 foreign, and the patents owned by RITE are 98 domestic rights (11 of which are licensed to companies) and 53 foreign rights (13 of which are li-censed to companies). (Fig. 8).

As the example to licensed RITE's Intellectual property, the GEI company (cf. refer to biotechnology group 5.3) listed on the Tokyo Stock Exchange Mothers market in December, 2021 which gives the license fee related to the amino acid to RITE.

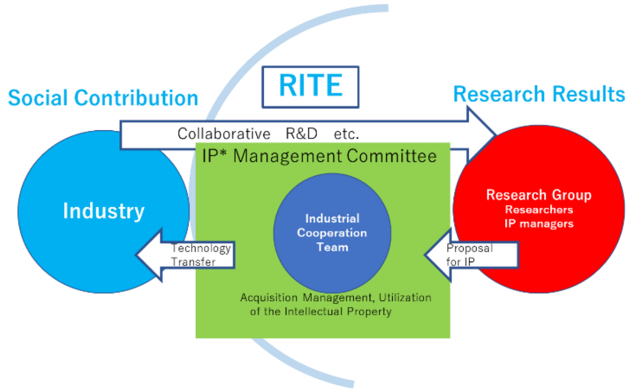


Fig.8 Strategic IP management and industrial collaboration

5. Conclusion

This year (2021) marked on the 10th anniversary of the Great East Japan Earthquake and the accident at the Tokyo Electric Power Company (TEP-CO)'s Fukushima Daiichi Nuclear Power Station.

In October, 2021, the Government of Japan decided the Sixth Strategic Energy Plan, in order to solve challenges facing Japan's energy supply and demand structure while taking action against cli-mate change.

To realize 2050 Carbon neutrality, Japan needs to establish and diffuse the innovative technology that isn't realized at the present, and the RITE's CO_2 Capture technologies are one of the most necessary technologies. But to realize 2050 Carbon neutrality is almost impossible only by remarkable efforts. It is necessary that RITE also promotes the social implementation proactively.

Reference

1) RITE, "The Role of RITE" (https://www.rite.or.jp/about/).
2) "Prime Minister Suga's Policy Speech at the 203rd extraordinary Diet session (https://www.kantei.go.jp/jp/99_suga/statement/2020/1026shoshinhyomei.html)
3) Plan for Global Warming Countermeasures (Cabinet Approval on October 22, 2021) (https://www.env.go.jp/earth/onanka/keikaku/211022.html)
4) Cabinet Decision on the Sixth Strategic Energy Plan（https://www.enecho.meti.go.jp/category/others/basic_plan/pdf/20211022_01.pdf）
5) Clean Growth Strategy (https://www.meti.go.jp/shingikai/sankoshin/sangyo_gijutsu/green_transformation/pdf/001_02_00.pdf)
6) RITE's CCS research report entrusted by METI (2020) (https://www.meti.go.jp/meti_lib/report/2020FY/000266.pdf) (https://www.meti.go.jp/meti_lib/report/2019FY/000145.pdf)
7) GCCSI, The Global Status of CCS 2021 (https://www.japanccs.com/wp/wp-content/uploads/2021/10/0-4-GCCSI_Jarad-Daniels.pdf)

Systems Analysis Group

Members (As of Dec. 2021)

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
Tsutomu Soejima, Senior Researcher
Noritaka Mochizuki, Senior Researcher (concurrent)
Joni Jupesta, Senior Researcher
Yuko Nakano, Researcher
Naoko Onishi, Researcher
Hitotsugu Masuda, Researcher
Teruhisa Ando, Researcher
Yuko Matsuoka, Researcher
Kiyomi Yamamoto, Assistant Researcher
Misako Saito, Assistant Researcher
Kiyomi Kitamura, Assistant Researcher
Sachiko Kudo, 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. This article presents the analyses on 1) the response measures for achieving carbon neutrality (Section 1), and 2) the emission reduction efforts including emission reduction costs for the 2030 emission reduction targets, and the impacts on whole economy (Sections 2 and 3).

1. Analysis on scenarios achieving carbon neutrality by 2050

Then Prime minister Suga stated that Japan seeks carbon neutrality (CN) by 2050 in October, 2022. The CN by 2050 will be consistent with the emission pathways for the below 1.5 °C of temperature goal. The new Strategic Energy Plan, the Climate Change Adaptation Plan, and the Long-term Strategy under the Paris Agreement were decided by the Cabinet of Japan in October 2021.

According to the request by the Strategic Policy Committee of Advisory Committee in Natural Resources and Energy, which had discussed the Strategic Energy Plan, RITE provided the analyses results for several scenarios for CN by 2050, using a global energy and climate change mitigation model, DNE21+ (Reference 1) and others) in May, 2021[2)]. This section introduces the overview of the scenario analyses.

1.1. Overview of caron neutrality

The overview of primary energy supply systems to achieve net-zero emissions is shown in Figure 1. Achieving CN requires decarbonized energy supply basically, however, energy saving is also important, if the least cost measures, and technological, social and economic constraints on each energy source are taken into account. Social innovations including sharing and circular economy associated with digital transformation (DX) will be a key for the CN as well as energy savings of each technology.

On top of that, renewable energy, nuclear power, and fossil fuels with CO_2 capture and storage (CCS) are required as primary energy sources, in principle. In Japan, because all of these energy sources have cost and potential constraints etc., hydrogen import from overseas will be also an important option as a cost-efficient measure. Hydrogen can be produced typically by renewables (green hydrogen) and fossil fuels with CCS (blue hydrogen). To increase more convenient uses of hydrogen, ammonia and synthetic fuels (synthetic methane and liquid fuels) synthesizing with nitrogen and carbon will play important roles.

Considering several large uncertainties in the outlooks of technologies, social constraints, and so on, several scenarios should be assumed and analyzed having consistency with total systems and costs, which enables a mathematical model to analyze whole energy systems quantitatively and comprehensively.

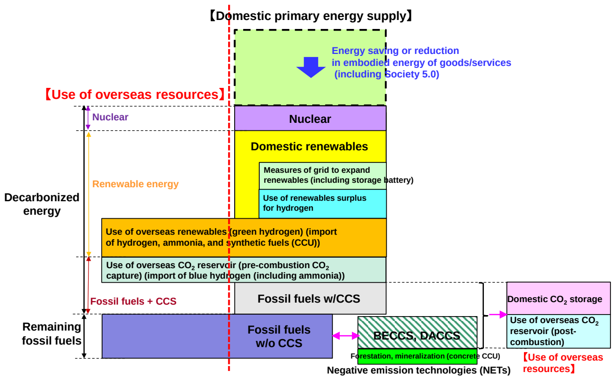


Figure 1 Overview of achieving net-zero emissions

1.2. Overview of model

Using a global energy systems model DNE21+ (Dynamic New Earth 21 plus), the emission reduction measures for carbon neutrality by 2050 are analyzed. DNE21+ is a global model with consistencies across 54 countries and regions, and intertemporal years up to 2100. In the model, global warming response measures for approximately 500 specific technologies can be evaluated in detail; energy supply technologies, such as electricity and hydrogen-based energies, CO_2 capture, utilization and storage (CCUS), and energy demand-side technologies in iron and steel, cement, paper and pulp, chemical, aluminum, transport, and some appliances of building sector are modeled with bottom-up treatments.

For analyzing large deployments of variable renewable energy (VRE) in Japan, the grid integration costs of VRE are estimated using a power systems model having 5 disaggregated Japan's regions and one hour time step, which was developed by the University of Tokyo and Institute of Energy and Economics, Japan (IEEJ). The grid integration cost curves of VRE are integrated into DNE21+.

1.3. Assumed scenarios

Tables 1 and 2 show the assumed scenarios for the CN in 2050. Here, as well as the CN of GHGs in 2050 in Japan, the globally least cost measures for the 1.5 °C goal are also assumed ("Offset emission credits of overseas" case). In addition, "Synthetic fuel utilization" case is analyzed.

Table 1 Scenarios assumed for model analyses

<table>
<tr><th colspan="2"></th><th>GHG emission reduction in 2050</th><th>Technology assumption (cost / performance)</th></tr>
<tr><td colspan="2">Offset emission credits of overseas (The least-cost measures in the world = Equal marginal abatement costs among nations)</td><td>Domestic emission reductions are endogenously determined.</td><td rowspan="3">Standard case
(Note: It is premised that RE is diffused due to suspected inertial force in high share RE scenario.)</td></tr>
<tr><td colspan="2">Reference case</td><td rowspan="8">▲100%
(For other than Japan, ▲100% for each western country, and ▲100% for the others as a whole)</td></tr>
<tr><td>Assuming high share of RE under Standard case</td><td>1. Renewable Energy 100%</td></tr>
<tr><td rowspan="6">Assuming each technology is further accelerated or expanded.</td><td>2. Renewable Energy Innovation</td><td>Acceleration of RE cost reduction</td></tr>
<tr><td>3. Nuclear Power Utilization</td><td>Expansion of nuclear power deployment</td></tr>
<tr><td>4. Hydrogen Innovation</td><td>Acceleration of hydrogen cost reduction</td></tr>
<tr><td>5. CCS Utilization</td><td>Expansion of CO_2 storage potential</td></tr>
<tr><td>6. Synthetic fuel Utilization</td><td>Acceleration of RE cost red. + Constraints of CO2 intern'l transportation</td></tr>
<tr><td>7. Demand Transformation</td><td>Expansion of car-/ride-sharing</td></tr>
</table>

Table 2 Scenarios regarding technology assumptions

<table>
<tr><th colspan="2">Scenario</th><th>Cost of renewable energy</th><th>Ratio of nuclear power</th><th>Cost of hydrogen</th><th>CCUS (Storage potential)</th><th>Fully autonomous driving (car- & ride-sharing)</th></tr>
<tr><td colspan="2">Offset emission credits of overseas (The least-cost measures in the world = Equal marginal abatement costs among nations)</td><td rowspan="3">Standard cost</td><td rowspan="2">Max. 10%</td><td rowspan="5">Standard cost</td><td rowspan="6">Domestic storage: max. 91 MtCO$_2$/yr; Overseas transportation: max. 235 MtCO$_2$/yr</td><td rowspan="8">Standard assumption: no fully autonomous cars</td></tr>
<tr><td colspan="2">Reference Case</td></tr>
<tr><td>Assuming high share of RE under standard case</td><td>1. Renewable Energy 100%</td><td>0%</td></tr>
<tr><td rowspan="6">Assuming each technology is further accelerated or expanded.</td><td>2. Renewable Energy Innovation</td><td>Low cost</td><td>Max. 10%</td></tr>
<tr><td>3. Nuclear Power Utilization*2</td><td rowspan="3">Standard cost</td><td>Max. 20%</td></tr>
<tr><td>4. Hydrogen Innovation</td><td rowspan="4">Max. 10%</td><td>Hydrogen production such as water electrolysis, hydrogen liquefaction facility cost: halved</td></tr>
<tr><td>5. CCS Utilization</td><td rowspan="3">Standard cost</td><td>Domestic: max. 273 MtCO$_2$/yr; Overseas: max. 282 MtCO$_2$/yr</td></tr>
<tr><td>6. Synthetic Fuel Utilization</td><td>Low cost</td><td>Domestic: max. 91Mt, Overseas: 0Mt</td></tr>
<tr><td>7. Demand Transformation</td><td>Standard cost</td><td>Domestic: max. 91 MtCO$_2$/yr; Overseas: max. 235 MtCO$_2$/yr</td><td>Realization and diffusion of fully autonomous driving and expansion of car- & ride-sharing after 2030, and decrease in material production due to reduction of the number of automobiles</td></tr>
</table>

1.4. Results

The GHG emissions in Japan are shown in Figure 2. Under the globally least cost measure for the 1.5 °C scenario, the 2050 emissions in Japan are estimated to be -63% compared to 2013. This is because there are larger potentials with smaller costs of CO_2 removal technologies (CDR) (or negative emission technologies: NETs) in the world than in Japan. Particularly the regions and countries where large potentials of bioenergy, VREs, and CO_2 geological storage exist could serve the opportunities of CDR such as bioenergy with CCS (BECCS) and direct air CO_2 capture and storage (DACCS) cost-efficiently.

While recognizing the emissions reduction opportunities in overseas, the domestic emission reduction measures should be considered. Even for achieving the CN within Japan, DACCS will be an important measure. However, if CO_2 storage potentials including the opportunities of transport of CO_2 to overseas are limited, the contributions of DACCS are reduced and the roles of synthetic fuels (synthetic methane and synthetic liquid fuels) will increase. Meanwhile, there are no feasible solutions for the 2050 CN in Japan for any assumed scenarios under the socioeconomic and other assumptions without DACCS.

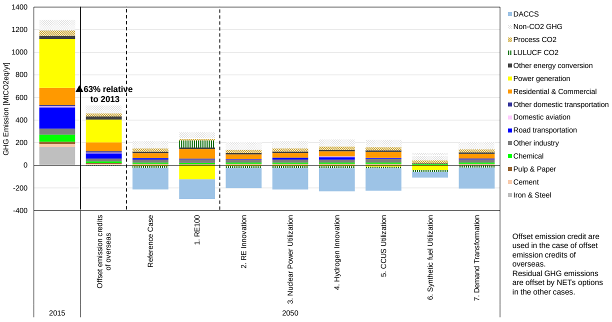


Figure 2 GHG emissions in Japan for CN by 2050

Figures 3, 4 and 5 show primary energy supply, electricity generation, and final energy consumption in Japan, respectively.

As seen in Figure 3, energy savings are important for all of the scenarios, and approximately 25% of primary energy savings can be observed. Renewable energy, CCS, and nuclear power will play important roles for the CN. The maximum constraints are assumed for the deployments of CCS and nuclear power, and the maximum deployments of both two will be the cost-efficient measures for the CN in Japan (only except for CCS transport to overseas in the CCUS utilization case). Although the cost reductions of VREs are assumed, the costs also increase as larger deployments of VRE, and wide ranges of costs are estimated for VREs accordingly. Thus, according to the estimations under the least cost of whole energy systems, combinations of deployments of several emissions reduction measures including DACCS and imports of hydrogen, ammonia and synthetic fuels can be estimated.

As contrasted with primary energy, electricity generations increase compared to the current levels in almost all the scenarios. Electrification is an important option for the CN. However, only in the RE100% case, electrification cannot be observed due to considerable increase of electricity including the grid integration costs of VREs. Balanced electricity mix will be a key even for the CN.

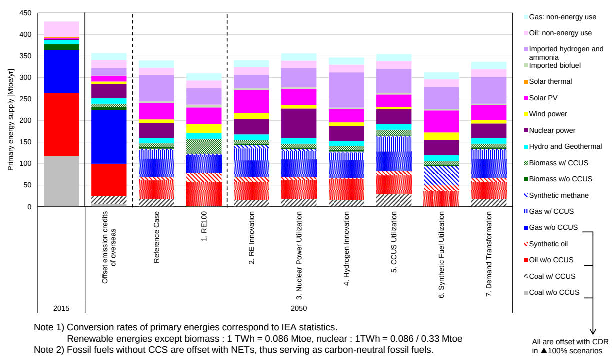


Figure 3 Primary energy supply in Japan for CN by 2050

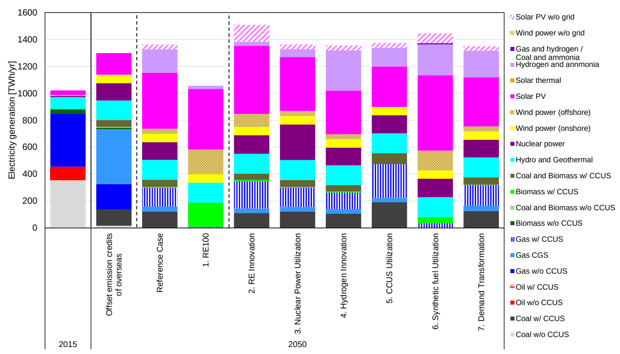


Figure 4 Electricity generation in Japan for CN by 2050

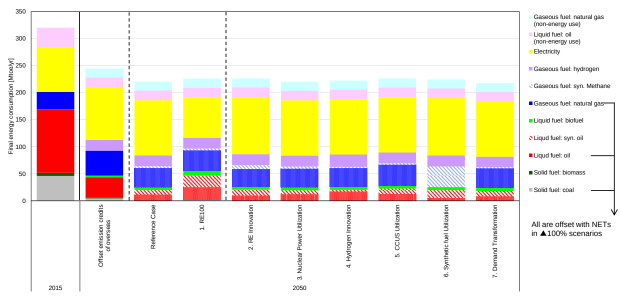


Figure 5 Final energy consumption in Japan for CN by 2050

In Figure 5, it can be observed that electrification in final energy is important, and hydrogen particularly for industry sector, synthetic liquid fuels for transport sector, and synthetic methane for building and a part of industry sectors will be cost-efficient for the CN in Japan. Meanwhile, considerable uses of natural gas will remain thanks to the emission offsets through DACCS.

CO_2 marginal abatement cost (carbon price) is estimated to be 168 $/t$CO_2$ in the globally least cost measure case for the 1.5 °C scenario ("Offset emission credits of overseas" case). On the other hand, the cost is estimated to be much larger and 525 $/t$CO_2$ in the Reference case which assumes to achieve the CN domestically. The costs can be reduced if several technological and social innovations are achieved, and it is necessary to seek the opportunities to induce innovations.

1.5. Implications from scenario analyses

DACCS will be able to play an important role under the CN as a back-stop technology. For achieving the CN internally, domestic DACCS will be also a cost-effective option. For achieving the CN in the world, it will be more cost-effective to deploy DACCS using affordable VREs and CO_2 storage potentials outside of Japan and offset the residue emissions of Japan through the emission credits. Since it is unclear that such options can work or not, the hedging strategy having several potential measures will be required. Hydrogen, ammonia, and synthetic fuels (synthetic methane and synthetic liquid fuels) are expensive options as well as DACCS, however, all of them can be the cost-effective options for the CN in Japan. The use of overseas resources should be also considered as the costs of VREs and CCU in Japan are high compared with those in some other countries. While VREs are highly important also in Japan, the grid integration costs as well as VREs are expected to increase according to large deployments of VREs. It is important to consider the whole energy systems including combinations of energy supply sources and energy demand-side measures as well as seeking the affordable emission reduction opportunities overseas.

All options should be pursued in order to achieve the CN as early as possible, as stated in the Sixth Strategic Energy Plan decided in October, 2021.

2. Evaluations on emission reduction efforts of the NDCs

2.1. Introduction

Under the Paris Agreement adopted at COP21 in 2015, all countries pledge nationally determined contributions (NDCs) for emission reduction targets after 2020 to the United Nations, and they are reviewed (Pledge and review). In 2015, the Systems Analysis group analyzed the emission reduction targets of the Intended Nationally Determined Contributions (INDCs) submitted before the adoption of the Paris Agreement based on various indicators (Reference 3), 4)).

By around the time of the leaders' summit on climate in April 2021, the emission reduction targets of NDCs had been raised, especially in developed countries. Japan deepened its emission reduction target, which was revised from the previous target of -26% (compared to 2013) in 2030, to -46%. Furthermore, Japan has declared to tackle to achieve -50% as a further ambitious goal. The Sixth Strategic Energy Plan was formulated, including the energy mix of Japan in response to its emission reduction target, and the plan for global warming countermeasures was revised (decided by the Cabinet in October 2021). On the other hand, China, India, and Russia have not deepened their emissions reduction targets. However, as China has the NDC target of CO_2 intensity of GDP and the outlook of GDP growth is lower than that estimated in 2015, the actual efforts on emissions reduction could be more ambitious than the expected efforts estimated in 2015.

Therefore, under the latest socioeconomic conditions including the impact of COVID-19 and their effects on baseline emissions, the emissions reduction efforts of the latest NDCs were evaluated by employing multiple indicators. The emissions reduction costs were estimated using a global assessment model for energy and climate change, namely DNE21+ model, which has been developed by the Systems Analysis Group. This study also assessed the interrelationship between the expected global emissions under NDCs and the long-term emission pathways for the 2 °C and 1.5 °C targets mentioned in the Paris Agreement, using the model (Reference 5)).

2.2. NDCs of major countries

Table 3 shows emissions reduction targets of the NDCs of major countries. Developed countries such as Japan, the United States, EU, and the United Kingdom have deepened their emissions reduction targets from those in the 2015 INDCs. However, since the base year for the reduction targets differs among countries, the emission reduction rates provided by each country should not be compared directly for measuring emissions reduction efforts. In addition, China and India serve CO_2 intensity targets, and some countries serve the targets of emissions reduction from their BAU emissions. To compare the emissions reduction rates based on the unified base year, it is necessary to convert the reduction rates which differ among the NDCs of countries to those unified in the specific base year. Figure 6 shows the unified rates of emissions reductions compared to 2013, which is the base year of Japan's NDC. Here, emissions in 2030 are calculated based on the historical records, the submitted emissions reduction targets, and the future GDP growth scenario for the countries having intensity targets. Compared to 2013, the UK has the lowest emissions among the major countries, followed by Switzerland and New Zealand. As discussed in Reference 3), the future population and economic outlooks vary across countries, and emissions reduction rates from the base year are estimated to be small in developing countries, whose economic growth rates are higher than in developed countries. Thus, even if the emissions reduction rates compared to the base year of developing countries are smaller than those of developed countries, it should not be necessarily evaluated that emissions reduction efforts are insufficient. Even for the comparisons of NDCs among developed countries, the emissions reduction rate compared to the base year will not be an appropriate indicator for measuring emission reduction efforts, because the historically cumulative efforts for emissions reduction differ across countries.

Table 3 Emission reduction targets of major countries

	Submitted emission reduction targets in 2030 of NDCs
Japan	-46% compared to 2013
United States	-50% to -52% compared to 2005
EU27	-55% compared to 1990
United Kingdom	-68% compared to 1990
Russia	-30% compared to 1990
China	-65% of CO_2/GDP compared to 2005
India	-33% to -35% of GHG/GDP compared to 2005

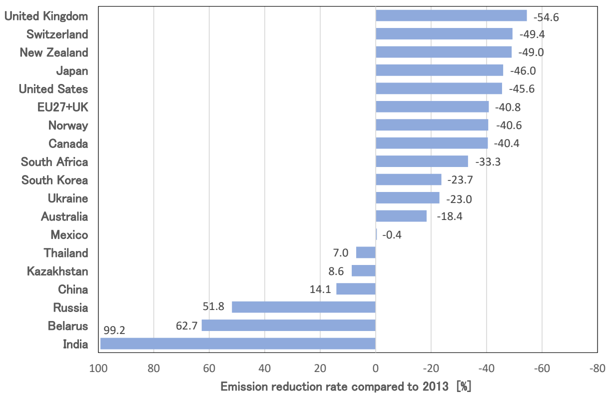


Figure 6 International comparison of emission reduction rate from the base year of 2005 for the NDCs

We also estimated emissions per capita, emissions per GDP, and emission reduction rate compared to BAU when the emission targets of NDCs are achieved. Emissions under BAU were estimated using the DNE21+ model.

2.3. Evaluations on emission reduction efforts of the NDCs using a global assessment model for energy and climate change

Figures 7 and 8 show international comparisons of CO_2 marginal abatement costs and emissions reduction costs per GDP, respectively. For Japan, the achievements of the power generation mix suggested in the Sixth Strategic Energy Plan (renewable energy: 38%, hydrogen/ammonia: 1%, nuclear power: 20%, LNG: 20%, coal: 19%, Oil: 2%) are assumed.

While the revised outlooks of production activities of several industries and transportation service demands were smaller than the previous ones including the impacts of COVID-19, many developed countries deepened their emission reduction targets as mentioned above. As a result, the estimated CO_2 marginal abatement costs and emissions reduction costs per GDP in many countries are higher than the previous estimates (Reference 4)). The CO_2 marginal abatement costs in New Zealand are very high (546 \$/tCO_2). Although the share of methane emissions in GHGs is high in New Zealand, the reduction potentials are limited according to the estimations by the US EPA, which are based on this study for the assessments of non-CO_2 GHG emission reduction measures. Therefore, significant emission reductions of energy-related CO_2 are needed, and the estimated marginal abatement costs rise considerably. If the emission reduction target of New Zealand is evaluated only for CO_2 emissions, the CO_2 marginal abatement costs are estimated to be 406 \$/tCO_2, which those costs are close to those of the United States and Canada. In particular, the estimations for land-use CO_2 and non-CO_2 GHG emission reduction costs are not easy, and careful treatments will be necessary.

Although China did not change the emission reduction target, allowable emissions are smaller than that in the previous estimation, because China has a CO_2 intensity target, and the outlook of GDP growth was changed downward. Then, the estimated CO_2 marginal abatement costs are higher than the previous estimates.

The emissions reduction costs per GDP include the impacts of net cost increase due to the decrease in export for fossil fuel exporting countries, and large increases in the costs can be observed in such countries like Russia.

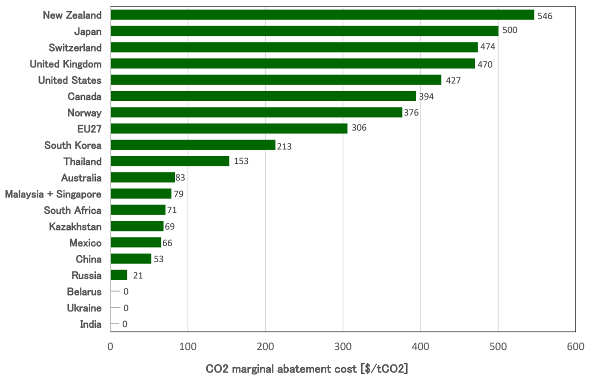


Figure 7 International comparison of CO_2 marginal abatement costs for the NDCs

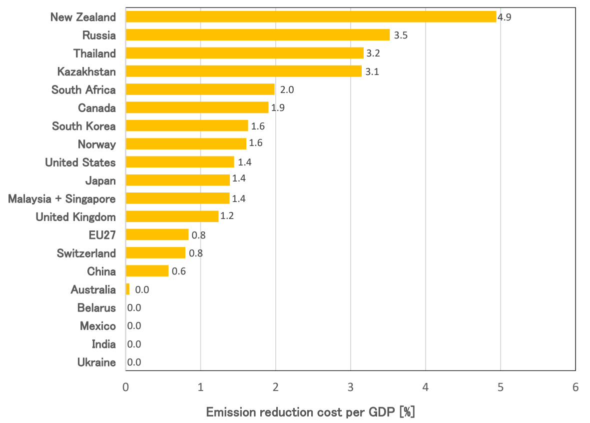


Figure 8 International comparison of emission reduction costs per GDP for the NDCs

Figure 9 shows the global GHG emissions outlook under baseline up to 2050 (zero marginal abatement scenario), and the emissions in 2030 under the NDCs, as well as the emission pathways under 2 °C (>66%) and 1.5 °C (>66%).

The estimated global GHG emissions in 2030 under the NDCs are about 50 $GtCO_2$/yr, which are consistent with those estimated by UNEP. The UNEP report emphasizes the gap between the expected global emissions in 2030 under the NDCs and the long-term emission pathways for the 2 °C and 1.5 °C goals of the Paris Agreement. However, according to the cost-efficient emission pathways under the carbon budget constraints, the expected emissions in 2030 under the NDCs could be consistent with the emission level to meet the 2 °C or 1.5 °C goal, if a certain degree of temperature overshoot is allowed through the deployments of CDR such as DACCS. The emissions could be in line with cost-effective emission pathways if large deployments of CDR are feasible.

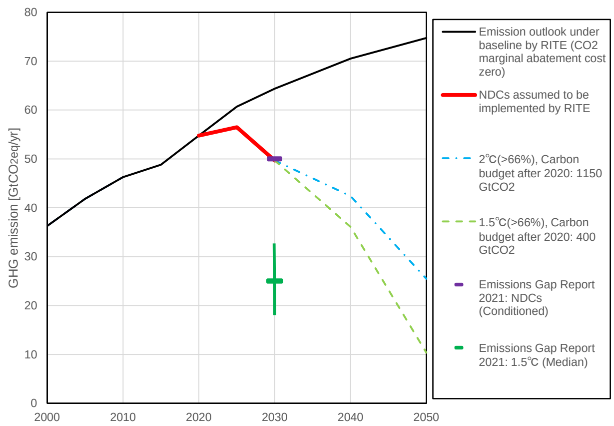


Figure 9 Expected global GHG emissions of the aggregated NDCs

2.4. Interrelationship between the expected global emissions in 2030 under NDCs and the long-term emission pathways for the 2 °C and 1.5 °C goals of the Paris Agreement

2.5. Suggestions from NDCs emission reduction effort evaluation

The Paris Agreement employs a "pledge and review" type framework. Even recognizing the differences in capabilities across countries, it is important to seek the equitable efforts, in order to maintain the Paris framework and to achieve effective global emissions reductions. Our analysis suggests that the emissions reduction efforts even under the latest NDCs might still be huge differences among the countries, and continuous reviews for the NDCs will be required.

3. Analysis on economic impacts of Japanese NDCs in 2030

3.1. Introduction

This section focuses on the economic impacts of the emissions reduction targets in 2030. Using a global energy-economic model, we evaluated the economic impacts of the latest Japanese target of 46% emission reduction (compared to 2013) along with the energy mix of the latest (Sixth) Strategic Energy Plan for 2030 (Reference 7)). We compared the impacts of the -46% target with those of the previous target of -26% based on the previous (Fifth) Strategic Energy Plan.

3.2. Methodology

The global energy-economic model, DEARS, which is used for this analysis, has a structure of dividing the world into 18 regions and integrating a top-down economic module and a bottom-up energy system module. The model is formulated as having an objective function of discounted global consumption utilities. The economic module has a computational general equilibrium modeling structure with an international input-output table based on the database of GTAP (global trade analysis project, Reference 8)) ver.9, representing industrial and trade structures by region and by sector. The energy system module represents simplified energy system flows explicitly and can deal with the constraints of the energy mix.

We assumed the baseline GDP (with average annual growth rate of 1.4%/year for 2010-2030 in Japan) based on "Economic and Fiscal Projections for Medium to Long Term Analysis" published by the Cabinet Office of Government of Japan in July 2021, considering COVID-19 impacts partially. We assumed the CO_2 emissions in 2020 with zero carbon price and considered the COVID-19 influences through the GDP assumptions.

The energy mix of the power sector in Japan in the baseline is assumed to be constant with that in 2019. The composition of the energy mix under the 46% reduction target in 2030 is assumed to be 19% for coal power, 20% for LNG power, and 2% for oil power; 16% for PV, 15% for wind (with 10 GW for offshore), 12% for hydro and geothermal, and 20% for nuclear power. The costs in the power sector were reflected based on the Power Generation Costs Analysis Working Group[9]. The unit costs of new power generation were assumed based on the lists of each power source, assuming an annual discount rate of 5%. The integration costs related to VRE were also based on the "estimation without considering power source location and grid constraints" (Reference 9)). The NDCs targets of the U.S and EU in 2030 were assumed to be 50% reduction (compared to 2005) and 55% reduction (compared to 1990), respectively.

3.3. Results

Figure 10 shows the GDP changes for the 26% and 46% reduction targets, respectively, to compare the macro-economic impacts between the previous and new targets. The estimated GDP change for the 46% target in 2030 is relatively large at 4.2% decrease (relative to the baseline) while at 0.5% decrease in the 26% target. The carbon prices required for the 26% and 46% reduction targets are estimated at 105 and 534 $/tCO$_2$, respectively. In the 46% reduction case, although there is a positive effect of increased investment in low-carbon energy, the GDP is estimated to decline due to decreases in net exports and consumption. The net export decreases represent worsening international competitive conditions, mainly in the manufacturing sector, deteriorating relative prices. The consumption decreases result from price increases of goods and services caused by extension of energy price increases for the reduction target.

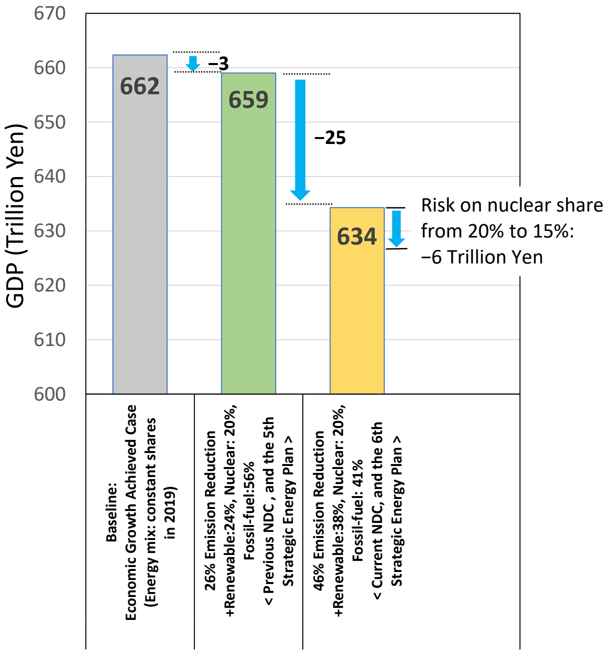


Figure 10 Real GDP in Japan(2030)

The GDP loss and CO_2 marginal abatement cost (carbon price) estimated in this study are smaller than the previous estimates (Reference 10)) even in the same 26% reduction target. This is because the previous estimation assumed the higher baseline GDP at about +0.2%/year of annual growth rate for 2010-2030 than this analysis and the higher cost of renewable energy generation.

Figure 11 shows sectoral production changes for the 26% and 46% reduction targets. The production changes in the energy-intensive and trade-exposed sectors such as iron & steel and chemical have adverse impacts at about 12-14% decreases (relative to the baseline), more significant than GDP changes corresponding to the sectoral average.

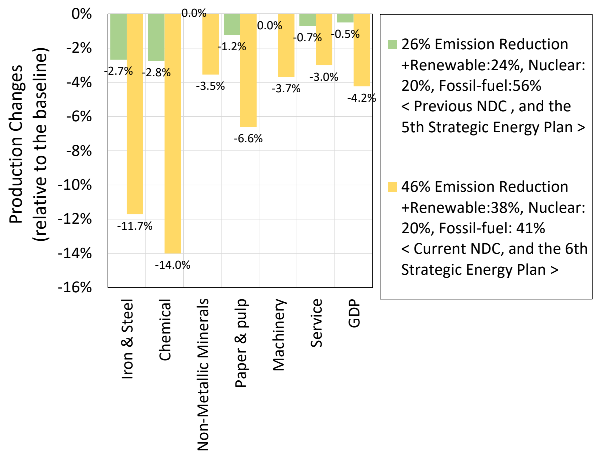


Figure 11 Changes in sectoral production (Japan, 2030)

Figure 12 shows the potential changes in electricity bills for the 26% and 46% reduction targets. The "effects of carbon price" in the figure stand for price impacts due to the penalty against the fossil-fuel power plants to carbon prices required for the reduction targets under implementations of the energy mix. The electricity expenditure in the 46% reduction target is estimated larger than that in the 26% target. It results from cost increases by carbon prices in the 46% target rather than the energy mix.

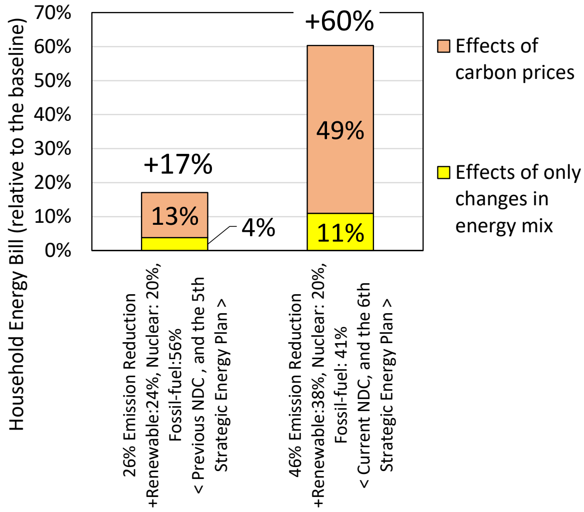


Figure 12 Impacts of household electricity bill (Japan, 2030)

Figure 13 shows the GDP losses with sensitivity analysis to the emissions reduction levels with shares of renewable and fossil fuels in the power generation. The GDP losses increase substantially when the emission reduction level changes from 35% to 46%. The result indicates that in the stringent targets, the potentials for mitigation measures on the energy supply side becomes smaller, and the need to respond to measures on the demand side, including the decreases in production activities, becomes larger.

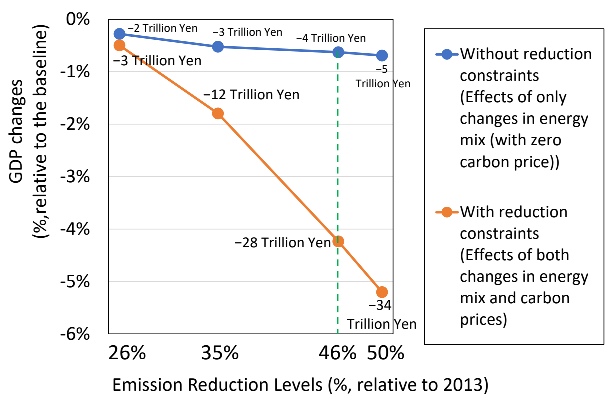


Figure 13 GDP impacts of emission reduction levels and shares of renewables/fossil-fuels

Note: In all the cases, share of 20% for nuclear power was assumed. The energy mix for 35% and 50% reduction levels were assumed to be interpolated and extrapolated using shares of the Fifth and Sixth Strategic Energy Plans, respectively.

3.4. Summary of economic impact analysis on the NDCs

The Japanese government raised the emissions reduction target for 2030 to 46% in response to calls for stronger actions for climate change mitigation both domestically and internationally. The estimated impact is about 4% GDP loss (relative to the baseline). Although investments for low-carbon energy increase, adverse consequences of trade and consumption are significant, resulting in decreases in net exports due to worsening competitive conditions and decreases in household consumption due to rising prices of goods and services. In the manufacturing sector, which is energy-intensive and vulnerable to international competition, such as the steel and chemical industries, the decline in output is expected to be considerably more significant than the GDP loss. In the household sector, the results also indicate the possibility of a substantial increase in household electricity and energy bills.

In this analysis, the solutions after achieving equilibrium are presented by the CGE (computation general equilibrium)-typed model. It should be noted that in the real transition processes, the adverse effects may be more severe in specific industries. In addition, since the difference in national/regional carbon prices required for achieving the NDCs is estimated to be extremely large (see the previous section), the impacts based on price elasticities will possibly work discontinuously in specific industries. The sufficient care for such industries should be taken in interpreting the results.

The international political and business environment, including the finance side, strongly encourages the commitment to more ambitious and stringent emission reduction targets, making it essential to strengthen efforts to address climate change. On the other hand, the 46% reduction target potentially has the risk of significant adverse impacts on the economy. This result indicates the importance of promoting appropriate transitions with inducing social and technological innovations.

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Molecular Microbiology and Biotechnology Group

Members (As of Dec. 2021)

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
Koichi Toyoda, Senior Researcher
Naoto Kato, Senior Researcher
Satoshi Hasegawa, Senior Researcher
Akira Watanabe, Senior Researcher
Takahisa Kogure, Senior Researcher
Takeshi Kubota, Senior Researcher
Shinichi Oide, 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
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
Kimiyo Kishi, Assistant Researcher

Development of a Biorefinery Technology that Contributes to Carbon Neutrality

1. Introduction

In October 2020, the Japanese government declared "2050 carbon neutral." Therefore, the government will reduce greenhouse gas emissions by 46% by 2030 and virtually zero greenhouse gas emissions by 2050. The aim was to attain a carbon-free society in 2050.

As a policy to realize this declaration, the "Green Growth Strategy Through Achieving Carbon Neutrality in 2050" was developed in December 2020 and revised in June 2021. Fourteen fields have also been set to achieve this goal. These fields are expected to grow as an industry and are considered indispensable for reducing greenhouse gas emissions.

Among these, ⑪ "The Carbon Recycling Industry" can be mentioned as a field in which biotechnology can influence. Specifically, it is the production field of carbon-recycled fuels, such as alcohol-to-jet (ATJ) and bio-alternative aircraft fuels using microalgae and carbon-recycled chemicals. Biomass resources, CO_2, waste plastics, and waste rubber are used as raw materials.

Biotechnological fields, such as synthetic biology and genome editing technology, have rapidly and recently advanced. In addition, the technological innovation of "bio-digital technology," a fusion of biotechnology and information technology (digital), such as IoT and AI, is rapidly developing. Therefore, "bio-manufacturing," using this bio-digital technology and bio-resources, is expected to significantly contribute to carbon neutrality and carbon negative.

Our group has been developing biorefinery technologies, which are technologies to produce biofuels and green chemicals using renewable resources (biomass) as raw materials using microorganisms, with the aim of balancing the global environment and the economy.

These are technologies that can contribute to ⑪ “The Carbon Recycling Industry” above. In this development, we have observed that although coryneform bacteria (typical industrial microorganisms) suppress their growth under reducing conditions, they maintain metabolic functions. They can metabolize saccharides to produce organic acids and related compounds efficiently. Therefore, we developed a growth-independent bioprocess “RITE Bioprocess®” and established “the complete and simultaneous use of mixed sugars derived from non-food biomass” and “high resistance to fermentation inhibitors” that are essential and elemental technologies for industrialization (see Chapter 2).

With these technologies, we are reporting the world’s highest level of high-efficiency biofuel products, including ethanol, butanol, green jet fuels, biohydrogens, and green chemicals, including lactic acid, succinic acid, alanine, valine, shikimic acid, protocatechuic acid, 4-aminobenzoic acid, and 4-hydroxybenzoic acid. Furthermore, we are currently focusing on developing production technologies for aromatic compounds, raw materials for higher value-added fragrances, cosmetics, pharmaceuticals, and so on (see Chapter 3).

Alternatively, we participated in the New Energy and Industrial Technology Development Organization (NEDO) “Smart Cell” project, SIP Strategic Innovation Creation Program, and NEDO “Bio-Manufacturing” project to develop the latest technology, integrating biotechnology and digital technology. Through these national projects, we are progressing with R&D to improve the efficiency of biosynthesizing high-performance chemicals, which were difficult to produce through conventional synthetic methods. Likewise, since 2020, we have participated in the NEDO “Moonshot” project and are working on researching and developing multi-lock type biopolymers that can be decomposed into the ocean using non-food biomass as a raw material (see Chapter 4).

This overview explains our core technology, the “RITE Bioprocess®,” and its features. Next, we will introduce these developments, highlighting their target uses. Then, as crucial technological development, national projects based on the “bio-digital technology” that has made remarkable progress will be described. Finally, we want to commercialize our efforts.

2. The core technology of our group “RITE Bioprocess®”

Our group has established the innovative bioprocess “RITE Bioprocess®” based on a new concept, “core technology of RITE.” This concept has achieved outstanding results in developing technologies for the highly efficient production of biofuels and green chemicals, such as amino acids and aromatic compounds. It has also been significantly evaluated in Japan and overseas (Fig. 1).

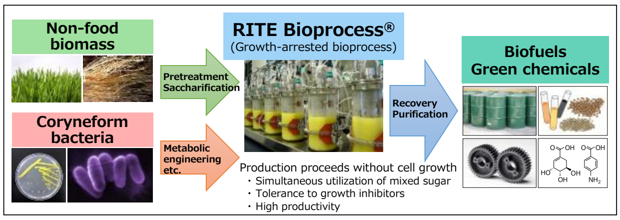

Fig. 1 Biorefinery concept using the “RITE Bioprocess®”

2.1. Features of the “RITE Bioprocess®”

2.1.1. Feature 1: Growth-independent bioprocess

In the “RITE Bioprocess®,” first, many coryneform bacteria that are highly and metabolically designed to help efficiently produce the target substance are cultivated. Then, after densely filling the reaction vessel with cells, the reaction is conducted in a state where cell division is stopped by removing anaerobic conditions and factors essential for proliferation (Fig. 2).

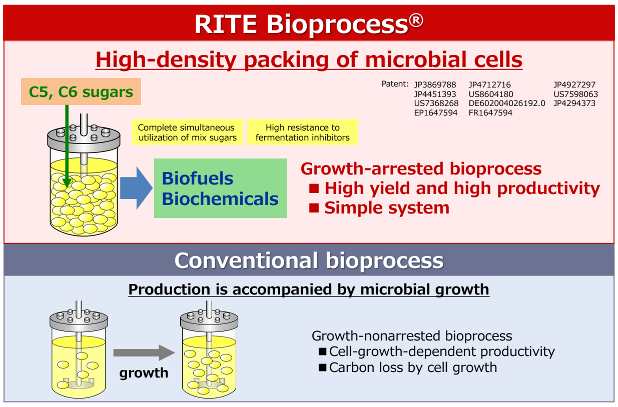

Fig. 2 Feature 1 of the "RITE Bioprocess®" (Growth-independent bioprocess)

The key to its high efficiency lies in the growth-independent bioprocess of producing compounds while suppressing the growth of microorganisms, which eliminates the need for nutrients and energy required for the development. Specifically, although raw sugar materials are not used for growth, they produce target substances, making it possible to use microbial cells remarkably and efficiently like a chemical catalyst. This method also achieved a bioprocess with high productivity equal to or higher than that of a typical chemical process.

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

Cellulose-based biomass comprises C5 sugars, such as xylose and arabinose, and C6 sugars, such as glucose. Therefore, simultaneously using C5 and C6 sugars is indispensable for efficient production processes using cellulosic biomass.

Coryneform bacteria into which a C5 glucose metabolism gene has been introduced have slower usage rates with xylose (C5 sugar) and arabinose (C5 sugar) than glucose (C6 sugar) (see the graph on the left in Fig. 3). Therefore, when the raw materials are continuously added, the C5 sugar accumulates, eventually decreasing the production efficiency of the compound.

Alternatively, by further introducing a C5 sugar transporter gene, we succeeded in increasing the usage rate of the C5 sugar to the same level as the C6 sugar (see the graph on the right in Fig. 3). Therefore, C5 and C6 saccharides can be used simultaneously, and cellulosic raw materials can be used efficiently.

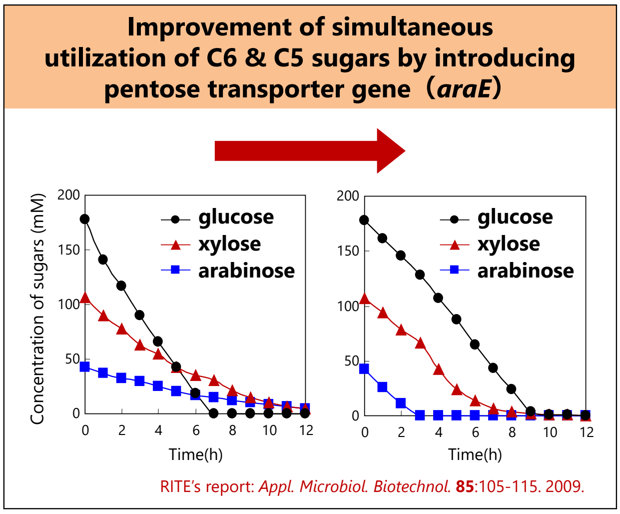

Fig. 3 Feature 2 of the "RITE Bioprocess®" (Simultaneous usage of mixed sugars)

2.1.3. Feature 3: High tolerance to fermentation inhibitors

Fermentation-inhibiting substances, such as phenols and furans produced during the pretreatment of lignocellulosic biomass, sturdily inhibit creating the target substance. Therefore, increasing the microorganisms (bacteria) resistance to the fermentation inhibitor is indispensable to produce the target substance efficiently. The "RITE Bioprocess®" demonstrates that it is highly resistant to fermentation inhibitors because it does not grow as described above (Fig. 4).

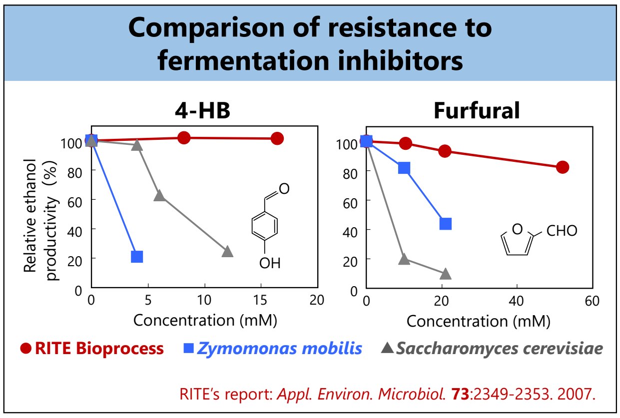

Fig. 4 Feature 3 of the "RITE Bioprocess®"
(High tolerance to fermentation inhibitors)

2.2. Main substances produced by the "RITE Bioprocess®"

Figure 5 shows some substances currently achieving high production by the group. As mentioned above, many materials have reached the world's highest level of productivity. Nevertheless, we are expanding from ethanol and biohydrogen to butanol and high-performance bio-jet fuel materials in biofuels. We also expanded from L-lactic acid, D-lactic acid, and amino acids to high-performance chemicals, such as aromatic compounds in green chemicals.

Biofuels

- Gasoline additives
  - Ethanol*
- Bio-jet fuels
  - Isobutanol*
  - n-butanol*
  - C9~C15 Saturated hydrocarbon + Aromatics
- Biohydrogen

Green chemicals

- Aromatics
  - Shikimic acid (Anti-influenza drug; Tamiflu raw materials)
  - Phenol* (Phenolic resins, Polycarbonates)
  - 4-hydroxybenzoic acid * (Polymer raw materials)
  - Aniline* (Natural resource tire (Age resistor))
  - 4-aminobenzoic acid* (Pharmaceutical raw materials)
  - Protocatechuic acid* (Cosmetic raw materials)
- Organic acids
  - D-lactate*, L-lactate* (Stereo-complex PLA)
  - Succinate*
- Amino acids
  - Alanine (Chelators)
  - Valine (Next-generation feed-use amino acids)
  - Tryptophan (Next-generation feed-use amino acids)
- Alcohols
  - Isopropanol (Propylene raw materials)
  - Xylitol (Sweetener)

*: Polymer raw materials
Red character: World's highest productivity achieved

Fig. 5 Examples of substances produced by the "RITE Bioprocess®"

3. Development of target products

3.1. Biofuel

3.1.1. Biobutanol

Butanol is more suitable as a gasoline additive than ethanol owing to its better physicochemical properties, including higher energy content, lower vapor pressure, and lower water solubility. It can also be used as a base material for producing bio-jet fuels using conventional chemical reactions. In turn, the bio-jet fuel synthesized from biobutanol can be used in airplanes. Airlines and aircraft manufacturers have paid considerable attention to the importance of bio-jet fuel as critical for reducing CO_2 emissions because it uses plant-based materials as feedstock instead of petroleum. The bio-jet fuel synthesized from butanol is called "alcohol-to-jet" (ATJ) fuel. In 2016, it cleared the standards of the America Society for Testing and Materials (ASTM) and became available for commercial flights.

Prior to these movements, we have been developing a highly efficient biobutanol production process using "RITE Bioprocess®". As part of this development, we conducted the "International Joint Research and Development Project for Innovative Energy Technology" by the Ministry of Economy, Trade, and Industry. In this project, through joint research with the US National Renewable Energy Laboratory (NREL), we developed biobutanol production technology using mixed sugar derived from non-food biomass as a raw material. In addition, through joint research with the US Pacific Northwest National Laboratories (PNNL), we proceeded with the development of technology to convert butanol into drop-in fuel such as jet fuel. Furthermore, our group improved the butanol resistance of the production strains, optimized the metabolic pathways of the production strains, and developed energy-saving butanol recovery technology. As a result, we have achieved the world's highest level of high productivity in the bioproduction of butanol (Fig. 6).

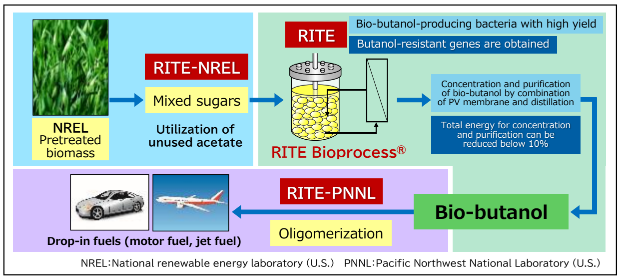

Fig. 6 Production of biobutanol and bio-jet fuel using the "RITE Bioprocess®"

Meanwhile, as an initiative for commercialization, RITE provided technical cooperation in the "Let's Fly by Recycling 100,000 Clothes!" project (2018–2020) sponsored by JAL. This project manufactured bio-jet fuels from used clothes collected in cooperation with JAL and JEPLAN, Inc., and our technology was selected for it.

The Green Earth Institute Co., Ltd. (GEI), a venture company originating from RITE, participated in this project together with RITE. Consequently, isobutanol was produced by the "RITE Bioprocess®" using coryneform bacteria developed by RITE. Hence, in 2020, the bio-jet fuel produced from this isobutanol passed the international standard ASTM D7566 Annex5 Neat for the first time as a purely domestic bio-jet fuel. The first flight equipped with domestic bio-jet fuel was realized on February 4, 2021 on JAL's Haneda-Fukuoka route.

Therefore, in the future, by combining these elemental technologies and various procedural knowledge, we propose to produce jet fuels from biobutanol for use and commercialization.

3.1.2. Green jet fuel

There is an urgent need to reduce the aviation industry's environmental load. As part of the reduction measures, electric or hydrogen aircraft are being developed, but considerable technical issues have been observed. Thus, disseminating drop-in biofuels derived from renewable feedstocks is unavoidable.

Petroleum-based jet fuels are mixtures of hydrocarbons comprising *n*-paraffins, isoparaffins, cycloparaffins, and aromatic compounds with 9–15 carbon atoms. So far, ASTM International has approved seven production pathways for bio-jet fuels, such as producing HEFA fuel by hydroprocessing fatty-acid esters and ATJ fuel by oligomerizing ethanol or isobutanol. In 2020, ATJ fuel coupled with our biobutanol production technology was also approved. However, these certified bio-jet fuels primarily consist of isoparaffins and lack other essential components: cycloparaffins and aromatics. Therefore, they do not meet ASTM standards on their own and should be blended with petroleum-based jet fuel to 50% or less when used.

To overcome this blending ratio limitation of certified bio-jet fuels, we are developing a high-performance green jet fuel containing cycloparaffins, aromatics, and isoparaffins. The novel jet fuel is expected to be used alone without being blended with petroleum-based jet fuel. In the R&D of high-performance bio-jet fuel, we achieved promising results, such as a novel biocatalyst that enabled cross-coupling reactions between C2 and C8 compounds to synthesize C9–C15 branched and cyclic compounds, which can then be chemically converted to jet fuel components (Fig. 7).

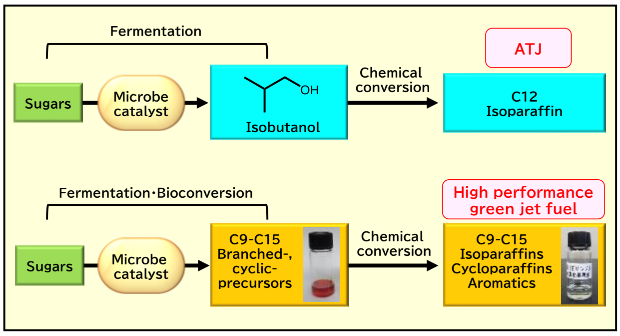

Fig. 7 R&D of a novel high-performance bio-jet fuel

3.1.3. Biohydrogen

Hydrogen is an energy carrier key to realizing carbon neutrality because (i) its combustion generates only water; (ii) it can be produced from diverse energy sources, including renewable ones; (iii) it can be stored in large quantities for long periods; and (iv) it can be distributed and used for power generation, transportation, and various industrial processes. However, CO_2 emissions during hydrogen production processes currently used are a problematic issue because fossil resources are used as feedstock. Therefore, a Basic Hydrogen Strategy was drawn up at the Ministerial Council meeting on Renewable Energy, Hydrogen, and Related Issues in 2017. The conference stated the importance of developing innovative technologies for hydrogen production, storage, and distribution to realize a hydrogen society over the medium to long term up to 2050. Therefore, hydrogen strategies around the world have moved. As noted, 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% in one decade.

Furthermore, although bioprocesses have significant potential for CO_2-free hydrogen production, innovative improvements in technology should establish a cost-effective process for producing biohydrogen. Therefore, along with Sharp Corporation, our group has developed a biohydrogen production process with an overwhelming production rate (max 300 L H_2/h/L) using the hydrogen production pathway via formate during dark fermentation. On the basis of this achievement, our group is now working on improving hydrogen yield from biomass by integration with photofermentation.

The formate-dependent hydrogen production pathway uses only a part of the reducing power generated by degrading sugars, such as glucose, derived from biomass. Subsequently, a high-yield hydrogen production pathway using both NADH and ferredoxin (Fd) as the reducing power was engineered and demonstrated to work. Our group also elucidated a unique regulatory mechanism of acetate metabolism in photosynthetic bacteria for use in photofermentation, which has been successfully applied to improve the acetate-hydrogen conversion efficiency (Fig. 8).

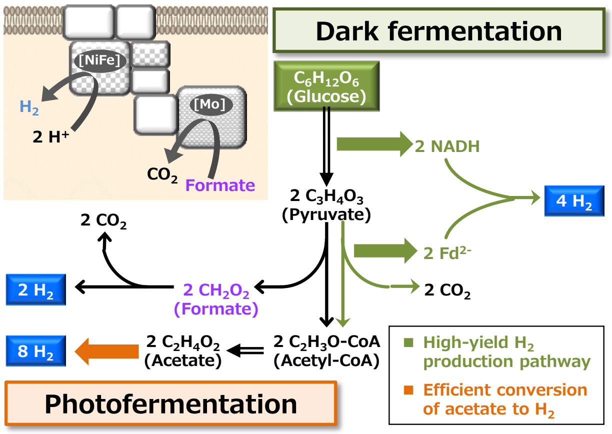

Fig. 8 Metabolic engineering of dark fermentative and photofermentative hydrogen-producing microorganisms

3.2. Amino acids (alanine and valine)

Usually, amino acid fermentation is conducted under aerobic conditions, where high productivity requires the aeration and agitation of the system to be adequately controlled. However, this process is difficult to achieve in large-scale fermenters because their internal oxygen concentration is not homogeneous. To overcome this problem, we have developed a new and genetically modified *Corynebacterium* strain using the "RITE Bioprocess®" to produce amino acids under anaerobic conditions. Furthermore, under anaerobic conditions, the technological hurdle for amino acid production is to balance the redox reaction without oxygen as an electron acceptor. To this end, we successfully introduced an artificial pathway for amino acid biosynthesis into microbial cells, solving the technological hurdle. Our group published this accomplishment in an international journal in 2010 (Appl. Microbiol. Biotechnol. 87: 159–165).

GEI was established in 2011 for industrializing the

"RITE Bioprocess®." In 2011, RITE and GEI began collaborative research on amino acid production using the "RITE Bioprocess®" and developed technologies for scaling up production, growing efficient production strains, and reducing production costs. Subsequently, in 2019, RITE succeeded in producing a strain that yielded the world's highest production concentration of L-valine with the best production efficiency. Furthermore, RITE has completed commercialization projects with GEI and overseas partners to achieve the commercial production of these amino acids. We aimed to produce this amino acid from renewable resources to reduce the life cycle carbon footprint.

In 2016, we succeeded in demonstrating the feasibility of L-alanine's production technique using commercial-scale facilities of our partner company, which was an important milestone for its industrialization. One of our group members also participated in the first operation and worked with local employees to lead the project to a successful conclusion. After an evaluation by the Food Safety Committee in August 2017, the safety of the L-alanine produced by our strain as a food additive was confirmed, allowing it to be made commercially available for this purpose besides its use for industrial applications. We are now working on a joint research project to produce other amino acids.

3.3. Green-aromatic compounds

Aromatic compounds are essential industrial chemicals used for synthesizing polymers and various value-added chemicals for use in pharmaceutical, nutraceutical, flavor, cosmetic, and food industries. Although they are currently derived from petroleum or natural plant resources, their environmentally friendly biotechnological production from renewable feedstocks is desirable to create a sustainable society that is no longer dependent on petroleum resources and has efficient production processes. Bacterial cells synthesize various aromatic compounds, including amino acids (phenylalanine, tyrosine, and tryptophan), folate (vitamin B9), and coenzyme Q, all of which are derived from the shikimate pathway (Fig. 9). Therefore, by employing the metabolically engineered *C. glutamicum*, we successfully established a highly efficient bioprocess for producing the following aromatic compounds from non-food feedstocks: 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 polymer, pharmaceutical, cosmetic, adhesive material, and flavor (vanillin) industries. Currently, we are seeking to develop new strains to produce useful aromatic compounds that the wild-type *C. glutamicum* is unable to produce. These strains will be achieved by introducing genes derived from versatile biological resources into the bacterium. The techniques developed in the Smart Cell Project, as described earlier, will also help to accelerate the development of strains and improve their productivity.

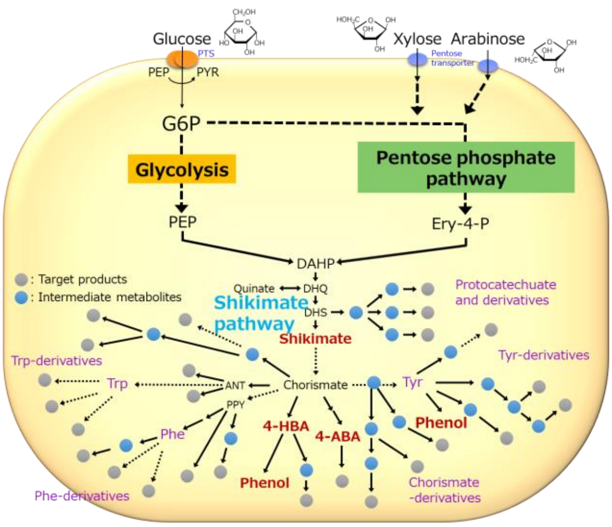

Fig. 9 The biosynthetic pathway for various aromatic compounds

4. Core technologies

4.1. The NEDO Carbon Recycle Project

On a national strategy, realizing the world's most advanced bioeconomy society in 2030, the development of material production technologies as the basis of the bio-manufacturing industry is an urgent issue. By utilizing biological functions, it is possible to produce materials from biomass without depending on fossil resources as raw materials. These technologies will contribute to the realization of a carbon recycling society.

In response to this social situation, NEDO launched a new project in 2020, "Development of Bio-based Production Technology to Accelerate Carbon Recycling." Participating institutions will develop and validate next-generation production technologies based on the fermentation technologies cultivated in Japan so far or that did not involve conventional methods.

Our Group participated in the predecessor of this project, "Development of Production Techniques for Highly Functional Biomaterials Using Plants and Other Organisms" (NEDO Smart Cell Project). Along with project participants (universities, research institutes, and companies), we developed technologies to design a Smart Cell (defined as a finely designed and expression-controlled cell). We also validated the technologies by breeding production strains in a short period of time.

In the Carbon Recycling Project, in addition to further improving the technologies developed during the Smart Cell Project, production process technologies, including scale-up and refining, will be developed. Furthermore, advanced bioproduction system platforms and peripheral technologies will be developed by creating information analysis technologies that can control production processes. These results will accelerate the social implementation of bio-based materials.

Our group participated in this project from the first year. Our target is catechol, a highly toxic aromatic compound. The aim is to develop "Industrial Smart Cell Creation Technology" to solve problems associated with the practical application of fermentative production technologies using production strains developed in the Smart Cell Project and accumulated omics data (metabolome, transcriptome, proteome). We will also validate the technologies (Fig. 10).

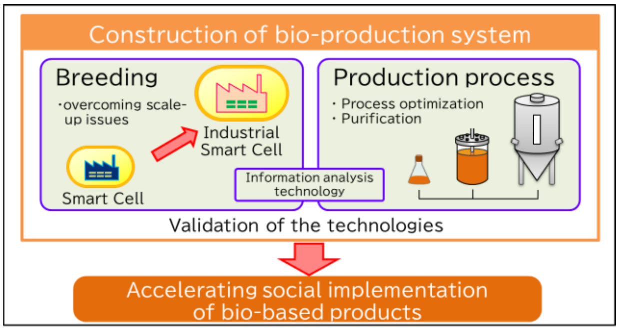

Fig. 10 Construction of an advanced bioproduction system platforms

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

RITE is participating in the theme "Technologies for Smart Bio-industry and Agriculture" in the SIP, which seeks to promote R&D, from the basic research stage to the final outcome, in a seamless manner by endeavoring to strengthen cooperation among industries, academia, and governments beyond the framework of government ministries and traditional disciplines. The theme aims to realize a sustainable growing society that uses manufacturing technologies developed through biotechnology and digital resources.

In the program, RITE participates in the consortium "Development of Technologies for Functional Design and Production of Innovative Biomaterials," which aims for synthesizing polymers with new functions desired by markets using monomers biosynthesized from cheap raw materials, such as biomass. Thus far, polymers with ultra-high heat resistance and those for battery materials have been developed (Fig. 11). To design the biosynthetic route for monomers comprising these polymers, the group led by RITE has been developing and validating technologies for functional modification of enzymes using enzymes involved in monomer precursor biosynthesis as targets. The technology enables the efficient extraction of combined functional mutations by providing a machine learning algorithm with data of many mutant enzymes to train it. The technology for seeking novel enzymes with desired functions using multiple amino acid sequence data from enzyme databases is also being developed. These technologies allowed us to modify the substrate specificity of target enzymes and improve their activities. In the fiscal year of 2021, through collaboration between the consortia, RITE has been working on the task to improve the productivity of the target monomer biosynthesized by a bacterial strain by optimizing its culture conditions. Thus far, the productivity of the monomer has successfully been improved twofold by seeking optimal culture conditions. Subsequently, RITE will evaluate the monomer's productivity using biomass-derived raw materials provided by a collaborative consortium.

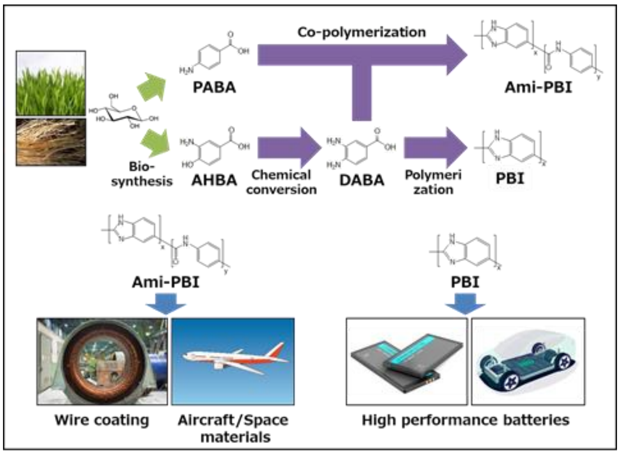

Fig. 11 Synthesis of developing monomers and polymers and polymer applications

4.3. The NEDO moonshot-type R&D project

Plastics are lightweight, inexpensive, and durable polymer materials indispensable for daily life. However, because they are chemically stable, they are not easily decomposed in the natural environment.

It has been reported that there is a typical trade-off between biodegradability and durability/toughness of polymers, such as plastics. Hence, biodegradable polymers are not durable because they degrade quickly in the natural environment and their mechanical properties are insufficient. Thus, only limited applications are possible. Although conventional plastics have excellent durability and toughness, their biodegradability is poor.

Suppose that it is possible to create new plastics with durability and toughness with biodegradability, these plastics can be used in several applications as environmentally friendly plastic. They can also be recycled. Notably, plastic litters scattered in the marine environment are challenging to recover and have a negative effect on the ecosystem.

Therefore, developing plastics that can control the timing and speed of biodegradation (multi-lock biopolymers) is critical for resource recycling.

In the NEDO moonshot-type R&D project "Development of Multi-Lock Biopolymers Degradable in Ocean from Non-Food Biomasses", we will introduce a "multi-lock mechanism" for plastic degradation to break the trade-off relationship between plastics. Hence, through multiple and simultaneous stimuli, such as light, heat, oxygen, water, enzymes, microorganisms, and catalysts during decomposition, the multi-lock mechanism will suppress the decomposition to maintain durability and toughness and prevent degradation. Products to be commercialized in this project are plastics, tires, textiles, fishing nets, and fishing gears made from non-food biomass. Material design guidelines for multi-lock biodegradable plastics will also be established through collaboration between industry, academia, and the government. In this context, our group is promoting R&D on the bioproduction of various monomers that can be used as raw materials for these products from non-food biomass materials. This project includes the functionalization of plastic-degrading enzymes that can be used in the multi-lock mechanism (Fig. 12)

(Here is the HP of the project: http://www.moonshot.k.u-tokyo.ac.jp/en/index.html).

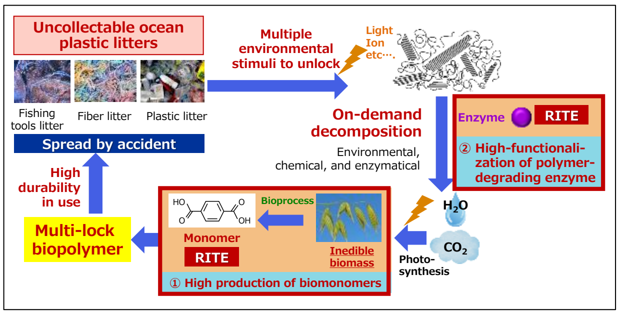

Fig. 12 R&D of marine-degradable multi-lock biopolymers made from non-food biomass for resource recycling

5. Toward the industrialization of our technologies

5.1. Green Chemicals Co., Ltd.

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

(Click here for GCC)

Currently, commercial phenol can only be derived from petroleum. We have taken on the challenge of developing the world's first bio-manufacturing process for biomass-derived phenol. The aim is to aid global environmental conservation and greenhouse gas reduction.

In February 2010, Sumitomo Bakelite Co., Ltd. and RITE established Green Phenol/High Performance Phenolic Resin Manufacturing Technology Research Association (GP Union).

In May 2014, GP Union was reorganized into Green Phenol Development Co., Ltd. (GPD), to accelerate the industrialization of our biomass-derived phenol-producing technology, named the "Two-Stage Bioprocess." This was the first example in demutualization of a technology research association. Then, in April 2018, GPD changed its name to Green Chemicals Co., Ltd. (GCC).

Since GCC's phenol-producing technology and knowledge apply to the production of various other aromatic compounds, establishing a bioprocess for each higher value-added chemical and commercializing products that meet customer needs are in progress (see Section 3.3).

The present three significant GCC products are shown in Fig. 13. In 2021, several companies started quality evaluation of 4-hydroxybenzoic acid (4-HBA).

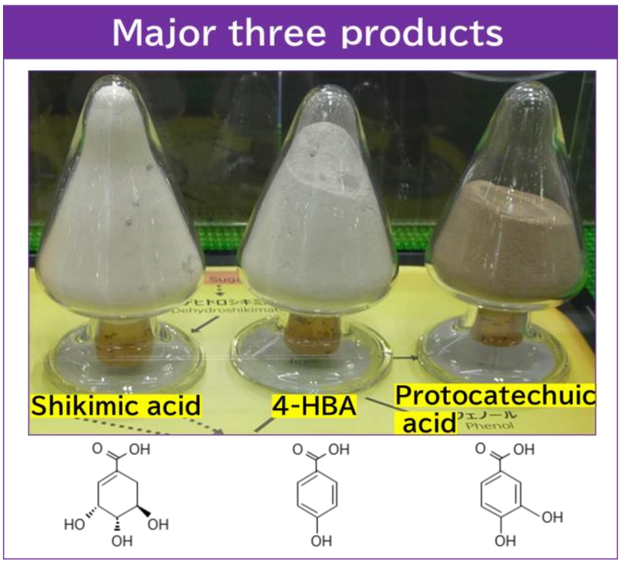

Fig. 13 Three major products of Green Chemicals Co., Ltd.

5.2. Green Earth Institute Co., Ltd.

(Headquarters: Bunkyo-ku, Tokyo, Japan; Research Institute: Kazusa, Kisarazu 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 those above-mentioned innovative "RITE Bioprocess®." GEI is currently conducting joint research and activities aimed at commercialization with RITE to realize the practical uses of green chemicals and biofuel production technologies manufactured using microorganisms. The company was listed on TSE Mothers in December 2021.

With amino acids, as mentioned earlier, GEI has succeeded in producing L-alanine and L-valine on a commercial scale using the production strain developed by RITE (see Section 3.2). In addition, the Ministry of Health, Labor and Welfare confirmed the safety of L-alanine as a food additive, paving the way for its use in the food industry.

However, based on bio-jet fuels made from non-food biomass, which are highly expected to reduce CO_2 emissions from aircraft, GEI is continuously conducting joint research with RITE in this area and is working toward commercialization. Due to this initiative, we succeeded in producing "Japan's first purely domestic bio-jet fuel flight" on February 4, 2021, for the JL319 flight (from Haneda Airport to Fukuoka Airport) (see Chapter 3.1).

Furthermore, GEI is developing green chemicals in cooperation with RITE for marketing, commercialization, and scaling up the mass production.
GEI will continue to influence developing biorefinery businesses toward realizing a society that does not rely on fossil resources.

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 introduced in this overview. Although these contents cannot be presented here, they include the following:

A) At an early stage, we will take measures to change the substance, the company's main product, from fossil resource-derived to bio-derived, toward "2050 carbon neutral." Here, it is being implemented as a medium- to long-term R&D project.

B) At an early stage, we will take measures to change the major raw materials purchased from other companies from fossil resource-derived materials to bio-derived materials toward "2050 carbon neutral." This project is also being implemented as a medium- to long-term R&D goal.

C) Changing the substance, a product of the company, or the substance and raw material from fossil resources to bio-derived ones is another goal. With this project, substances that can be commercialized quickly at high unit prices are being implemented as short-term R&D goals.

6. Closing remarks

Due to the abovementioned technological innovation of "bio-digital technology," the understanding of life phenomena by the "data-driven" approach of discovering the law from huge life information has recently progressed. Under such a background, research on the biology of synthesis that accumulates data and understands biological functions by repeating the Design-Build-Test-Learn (DBTL) cycle is also rapidly developing.

All the national projects introduced in Chapter 4 also use these technological innovations, new knowledge, and methods to achieve dramatic improvements in development efficiency. In these projects, the biorefinery technology using the abovementioned smart cell also plays a significant role as a core technology and is expected to have a tremendous ripple effect in the industrial (manufacturing) and energy fields (Fig. 14).

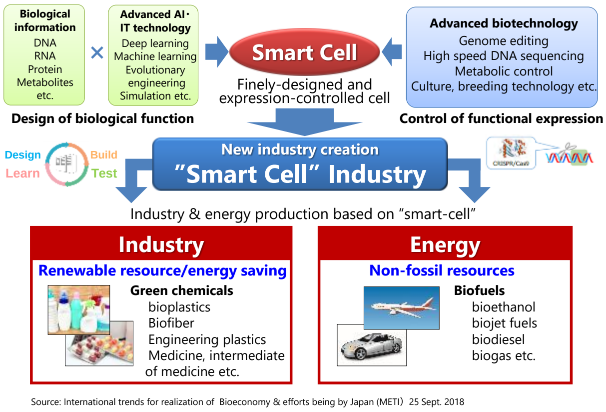

Fig. 14 Fusion of industrial/energy fields changed by bio and digital processes

In 2022, the group will continue to research and develop green chemicals, such as aromatic compounds, and biofuel production using the "RITE Bioprocess®" and "industrial smart cell design system." In addition, we also want to focus on developing practical production technologies and contribute to the "realization of carbon neutral by green bioprocesses."

Since the declaration of the "2050 carbon neutral" in October 2020, inquiries from companies have increased, and the number of joint research projects with companies has also increased. However, the group is looking for research partner companies, including cases other than those introduced in Chapter 5, Section 3. There is also a possibility that compounds that are difficult to produce microorganisms can be highly manufactured using the latest elemental technologies' developmental results, such as the abovementioned aromatic compounds. 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 Dec. 2021)

Shin-Ichi Nakao, Group Leader, Chief Researcher
Toshiyuki Hasegawa, Deputy Group Leader, Chief Researcher
Katsunori Yogo, Chief Researcher
Koji Baba, Associate Chief Researcher
Teruhiko Kai, Senior Researcher
Kazuya Goto, Senior Researcher
Firoz Alam Chowdhury, Senior Researcher
Toshinori Muraoka, Senior Researcher
Kenichiro Yasuhara, Senior Researcher
Makoto Ryoji, Senior Researcher
Fuminori Ito, Researcher
Tomohiro Kinoshita, Researcher
Takayasu Kiyokawa, Researcher
Quyen Thi Vu, Researcher
Shuhong Duan, Researcher
Nobuhiko Fuchigami, Researcher
Lie Meng, Researcher
Hanako Araki, Research Assistant
Noriko Onishi, Research Assistant
Hidenori Ogata, Research Assistant
Kumiko Ogura, Research Assistant
Mai Kashima, Research Assistant
Kozue Kataoka, Research Assistant
Keiko Komono, Research Assistant
Ryuichi Shirai, Research Assistant
Rie Sugimoto, Research Assistant
Takashi Teshima, Research Assistant
Yozo Narutaki, Research Assistant
Yoichi Fujiwara, Research Assistant
Keiko Mori, Research Assistant
Misato Mori, Research Assistant
Miku Yamada, Research Assistant
Naomi Yoshino, Research Assistant
Junko Yonezawa, Research Assistant

Challenges Associated with the Advanced Industrialization of CO_2 Capture Technologies

1. 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 2050 Carbon Neutral formulated in December 2021 (detailed in June 2021), various types are available. Efforts to prevent global warming are being promoted from various areas. 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 the reuse of separated and recovered CO_2 from fuels and materials by treating CO_2 as a carbon resource (CCU), and the storage of separated and recovered CO_2 underground (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 is required to achieve carbon neutrality, and direct air capture (DAC) of CO_2

from the atmosphere, which has been attracting attention recently, is particularly important. In the Carbon Recycling Technology Roadmap (Ministry of Economy, Trade and Industry) revised in July 2021, DAC was added as a new technology field with 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. 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 separating and recovering CO_2 emitted from large-scale sources.

The Chemical Research Group studied the different CO_2 capture technologies with a special focus on chemical absorption, adsorption, and membrane separation methods. This work involved the development of new materials and processing methods, as well as investigations of capture systems. The Group's studies have thus far generated significant outcomes and assisted in the progress of research in this particular field.

Specifically, we developed high performance chemical absorbents, and chemical absorbents with particular promise were selected for application in a commercial CO_2 capture plant owned by a private Japanese company.

With regard to solid sorbent technology, we have been engaged in research and development of solid absorbent materials with high CO_2 efficiency recovery and low energy consumption and have found solid absorbent materials and systems with good CO_2 desorption performance at low temperatures. Currently, in the NEDO consignment project, we are preparing for a scale-up test using actual combustion exhaust gas from a coal-fired power plant in collaboration with a private company.

Membrane separation is expected to be an effective means of separating CO_2 from high-pressure gas mixtures at low cost and with low energy requirements. As a member of the Molecular Gate Membrane module Technology Research Association, RITE has been developing membranes to selectively capture CO_2 from pressurized gas mixtures containing H_2, such as those generated in the integrated coal gasification combined cycle (IGCC) at low cost and with low energy use. We are also developing membranes with large areas using the continuous membrane-forming method and developing membrane elements for the mass production of membranes and membrane elements in the future. In addition, we evaluated the separation performance and process compatibility of our membrane elements using coal gasification real gas and are proceeding with development aimed at commercialization.

In addition, as part of the NEDO moonshot R&D project, we have begun studying technologies for capturing CO_2 from the atmosphere by direct air capture (DAC) and using it as fuel or raw materials. While promoting the development of amine compounds suitable for the separation and recovery of low concentration CO_2, we are working on the development of a DAC system that can separate and recover CO_2 from the atmosphere with high efficiency in cooperation with Kanazawa University and private companies.

As described above, RITE is working on the development of innovative technologies that will be the foundation for a wide range of next generation, leading-edge research and development for CO_2 reduction and aiming to establish technologies that can be implemented in society. In addition, we joined the International Test Center Network (ITCN) and now actively use overseas networks towards the commercialization of CO_2 separation and recovery technology.

*COP 21: 2015 United Nations Climate Change Conference

2. 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.

Energy consumption in the process of solvent regeneration and the degradation of amines are factors in the cost increases of the chemical absorption method. Focusing on the fact that the structure of amine molecules is closely related to these factors, 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 is working with Nippon Steel Corporation to upgrade the chemical absorption method. The chemical absorbent and process developed by the COURSE50 project was 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 the combustion exhaust gas from a hot blast furnace at a steelworks as a CO_2 source. In 2018, ESCAP® Unit 2 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 from the combustion exhaust gas of coal-fired power generation as the CO_2 source. The recovered CO_2 is used as a raw material in a nearby chemical factory.

In addition, the latest research found the possibility of further reducing energy consumption by using the absorption solvent with an organic compound instead of water and continues to explore new ones. The solvent can control the reaction mechanism of CO_2 absorption and the effect of polarization.

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

3. 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 using a solid sorbent, the heat of vaporization and sensible heat caused by the solvent can be suppressed, so reduction of CO_2 capture energy can be expected.

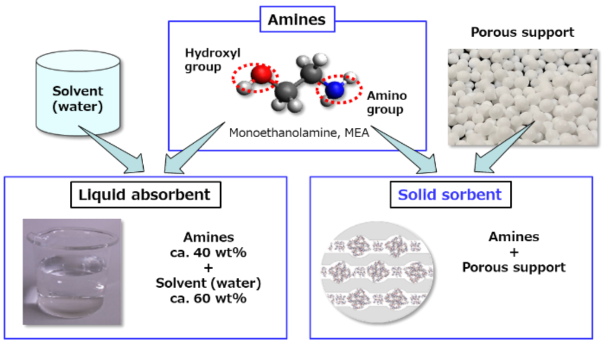

Fig. 2 Liquid absorbent and solid sorbent

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 succeeded in developing a new amine suitable for solid sorbents, and in a laboratory scale test, 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 businesses that use amine-based solid absorbents, this business 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., 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.

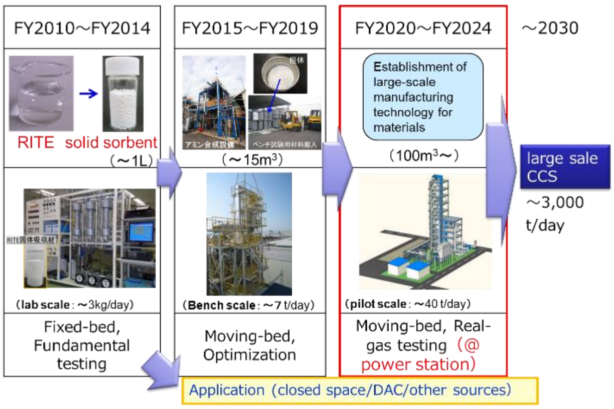

Fig. 3 Development roadmap of solid sorbent method for CO_2 capture

In 2020, RITE was adopted by the NEDO commissioned project with Kawasaki Heavy Industries, Ltd. In this project, with the cooperation of Kansai Electric Power Co., Ltd., a pilot scale test facility (– 40 t-CO_2/day) will be constructed at the Maizuru power plant, and CO_2 capture tests from the combustion exhaust gas emitted from the coal-fired power plant will start in 2022.

Currently, RITE is proceeding with the production of solid absorbents on a 100 m^3 scale optimized on the basis of the results of the scale-up synthesis of solid absorbents and bench scale tests for pilot scale tests. We are also elucidating the material deterioration mechanism, developing deterioration prevention technology, and studying efficient operating conditions using process simulation technology.

4. 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. 4). For this reason, we are currently developing novel CO_2 selective membrane modules that effectively separate CO_2 during the IGCC process.

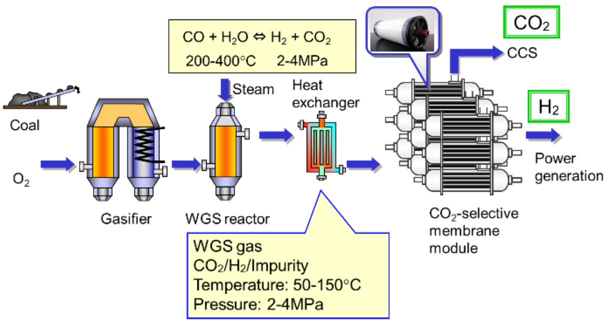

Fig. 4 Schematic of the IGCC process with CO_2 capture by CO_2 selective membrane modules

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. 5 presents a schematic that summarizes the working principles of a molecular gate membrane.

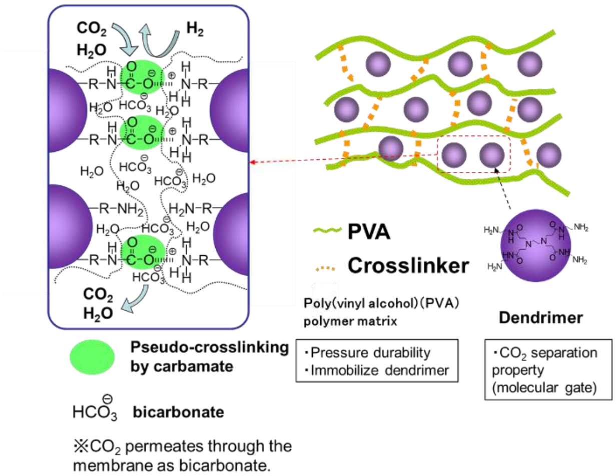

Fig. 5 Schematic illustration of the working principles of the molecular gate membrane

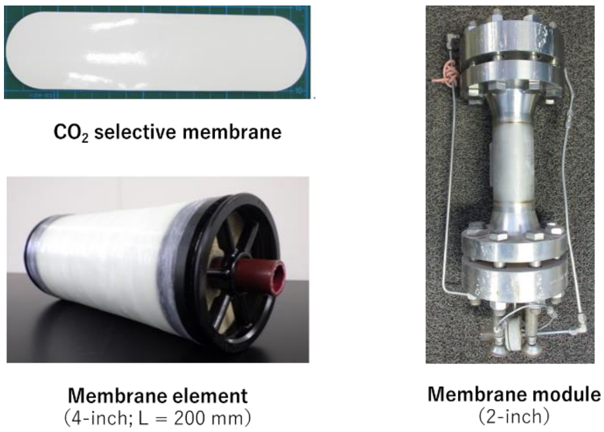

Fig. 6 CO_2 selective membrane, membrane element, and membrane module.

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.

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 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 (Fig. 6), and membrane separation systems.

Based on the achievements of the project by the Ministry of Economy, Trade and Industry (METI), Japan, the CO_2 Separation Membrane Module Research and Development Project (FY 2011–2014) and CO_2 Separation Membrane Module Practical Research and Development Project (FY 2015–2018), we developed the membranes with large areas using a continuous membrane-forming method while developing membrane elements in the NEDO project, CO_2 Separation Membrane Module Practical Research and Development (FY 2018–2021). As a result, 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 four-inch membrane elements using coal gasification gas, and it was confirmed that the membrane elements were durable against the real gas (containing impurities, such as H_2S).

In the new NEDO project, CO2 Separation Membrane System Practical Research and Development/Development of CO2-H2 membrane separation systems using high-performance CO2 separation membrane modules, we plan to conduct the practical research and development to improve the separation performance and durability of the membrane elements, to scale up the membrane modules and to design the membrane systems suitable for the CO_2 utilization process based on the results of the previous projects.

5. CO_2 capture technology from the atmosphere

RITE has been conducting a national project in the NEDO Moonshot R&D Project with the development of a highly effective direct CO_2 capture method from air and carbon recycling technologies in collaboration with Kanazawa University and private companies. This project is a part of the Environment Innovation Strategy launched by the Japanese government in 2020 that aims to establish technologies that enable Beyond Zero by 2050.

A method of capturing CO_2 directly from the atmosphere called Direct Air Capture (DAC) is one of the negative emission technologies. Seven research themes on DAC have been adopted in the Moonshot R & D Project. Fig. 7 shows our R & D items and a carbon cycle society as our goal.

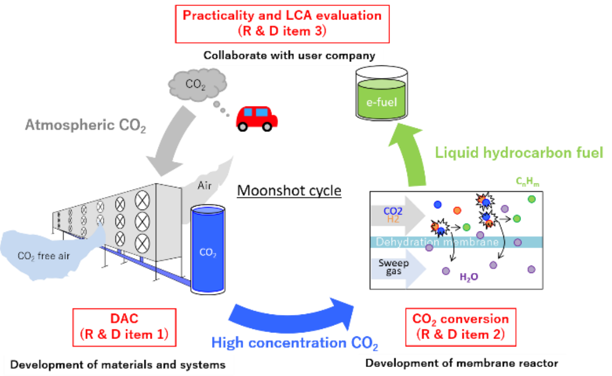

Fig. 7 Development of highly efficient DAC and carbon recycling technologies

RITE is trying to synthesize new amines suitable for DAC and transform solid sorbents into low-pressure drop structured materials. Developed materials are tested in the actual air around RITE. Because of the day-to-day variations in the local atmosphere's conditions, we designed new equipment to control and test the effects of temperature, humidity, and CO_2 concentration in the atmosphere (Fig. 8).

Fig. 8 New designed lab test equipment for DAC

In order to realize an economically acceptable DAC, not only material development but also process development is important. We introduce a simulation technology to reveal the most suitable process without chemical/time consuming. This environmentally friendly development technique will be also used in the Moonshot R&D Project.

6. CO_2 fixation

CO_2 fixation (CO_2 mineralization) has the same basic concept as enhanced weathering, which is one of 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. Especially in recent years, early implementation of the CO_2 fixation by using by-products and wastes 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 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 as carbonates, which is a stable compound, by reacting with CO_2 (Fig. 9).

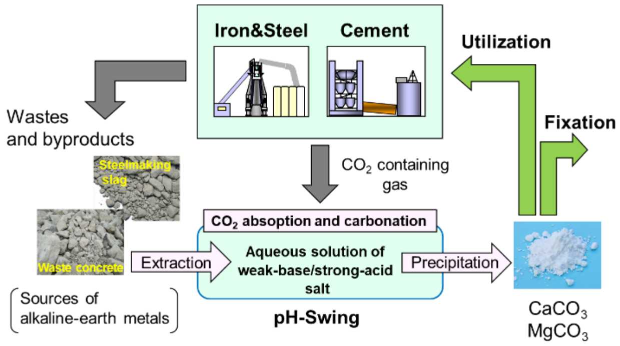

Fig. 9 CO_2 fixation as carbonates

7. Conclusion

As stated above, the Chemical Research Group has energetically promoted the development of CO_2 separation and recovery technology mainly as the chemical absorption method, the solid sorbent method, and membrane separation. The chemical absorption method has been deployed from the demonstration stage to commercial machines for blast furnace exhaust gas and combustion exhaust gas from coal-fired power plants and has already been put to practical use as a CO_2 separation and recovery technology. In the solid sorbent method, we have begun studying combustion exhaust gas from coal-fired power plants for a 40 t-CO_2/day scale pilot test, which is planned for FY 2023-2024. In membrane separation, we confirmed the separation ability of CO_2 and H_2 in an actual gas test using a membrane element from coal gasification gas. In addition, we are working on the development DAC technology newly adopted in NEDO's Moonshot R&D Project and CO_2 fixation technology using steel slag and waste concrete.

The Chemistry Research Group will work vigorously on individual research topics with these themes. For the themes close to the practical stage, we will carry out scale-up studies and actual gas tests with the aim of establishing the technology at an early stage. At the same time, we would like to develop innovative technologies and propose CO_2 separation and recovery technologies that can save more energy and reduce costs.

In particular, in sustainable development scenarios for decarbonization in the future, it is said that the contribution of CO_2 capture from natural gas and biomass combustion will increase, and negative emission technologies, such as DACCS, are also required. Therefore, in the future, it is necessary to proceed with technological development so that it can handle these lower-concentration CO_2 emission sources. As the CO_2 concentration decreases, the amount of gas to be treated increases and the high oxygen concentration also increases. Therefore, it will be important to develop materials with lower cost and higher deterioration resistance and system development corresponding to them.

CO_2 Storage Research Group

Members (As of Dec.2021)

Ziqiu Xue, Group Leader, Chief Researcher
Kenji Uchida, 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
Ryozo Tanaka, 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
Kazuhito Tokita, Senior Researcher
Satoko Fuchikami, Chief
Kimiko Nakanishi, Chief
Takayuki Miyoshi, Researcher
Masafumi Kotani, Researcher
Takeya Nagata, Researcher
Rasha Amer, Researcher
Hiroto Yoshikawa, Researcher
Jinrong Cao, Researcher
Ryota Okimoto, Researcher
Hirokazu Ishige, Researcher
Tamaki Sato, Researcher
Junko Hirai, Research Assistant
Shiori Tsuji, Research Assistant
Yuko Himi, Research Assistant
Akemi Nishide, Research Assistant
Megumi Okumichi, 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

With the successful projects of CO_2 capture and storage (CCS) from natural gas processing, Sleipner and Snøhvit in Norway, CCS has been considered a key feasible measure to mitigate global warming. Recently, large-scale CCS projects have been planned and commenced in the United States (in the North America), Canada and Australia.

Japan has successfully completed a 10,000 ton CO_2 injected pilot project in Nagaoka, Niigata, followed by a 300,000 ton CO_2 injected demonstration project in Tomakomai, Hokkaido.

Commercial deployment of large-scale CO_2 geological storage requires safe injection and storage of more than 1 Mt/y. The CO_2 Storage Research Group as a member of the Geological Carbon Dioxide Storage Technology Research Association has conducted 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 project has been addressing the development of technologies for safety management, efficient injection and effective resource utilization for large-scale CO_2 reservoirs, including the non-technical support for facilitating social implementation and deployment of CCS. Our outstanding outcomes up to now are the safety management system for injection; the optical fiber measurement technology for strain, acoustic and temperature; the microbubble CO_2 injection technology.

Based on these outcomes, the CO_2 Storage Research Group has moved forward in 2021 toward commercial deployment of CCS by technology demonstration, improvement of economics, risk mitigation, and facilitation of implementation. Regarding the technology demonstration, we have been applying and verifying our optical fiber measurement technology at large-scale storage sites overseas. For the improvement of economics and risk mitigation, we have been developing a new measure to enable a comprehensive investigation of the storage opportunity in Japan, which is called CO_2 Storage Resource Management, SRM.

The CO_2 Research Group has been compiling the Practical Guidance for Geological CO_2 Storage as reference manual for CCS developers. It will be available for developers and usable for their overseas deployment of CCS. Furthermore, our group has been developing frameworks for creation of social consensus (Social License to Operate, SLO) by advancing conventional Public Acceptance (PA) and Public Outreach (PO) approaches. We have a plan to apply and demonstrate our SLO methodology for domestic CCS deployment at a full scale.

The CO_2 Research Group continues to contribute to CCS deployment not only by technical demonstrations for commercial deployment but also by sharing our knowledge and facilitating the social implementation of CCS.

2. Major Research Topics and Outcomes

2.1. Optical fiber measurement technology development and demonstration

For ensuring safe CO_2 geological storage, it is essential to monitor the location of injected CO_2 plume, the deformation of geological formation induced by pressure rises, and the area of pressure propagation.

One of the suitable technologies to enable these monitoring is the Distributed Fiber Optical Sensing (DFOS). DFOS technology is capable of acquiring spatially continuous data because the optical fiber itself is the sensing receiver. This feature of the DFOS enables monitoring of the deep direction continuous data when installing the optical fiber cable along the wellbore. Moreover, the DFOS can work as a multi-sensor system to capture temperatures, strains and acoustics simultaneously by installing multiple optical fibers together. The system is potentially much cheaper than a case where many sensors are installed.

The CO_2 Storage Research Group has been developing the technology of the optical fiber measurement and demonstrating it in the field in Japan and overseas as below.

Two conventional designs of optical fiber cable have been used for optical fiber measurements. One is the Telephone line type, which consists of multiple optical fibers covered by soft resin, and the other is the Armored type, which outer jacket made of twisted wires. We have designed a noble optical fiber cable for better installation and sensitivity that contains multiple fibers filled with resin in a stemless tube, called the SUS tube type.

The performance of the new cable was tested and compared to the other two conventional cable types by the Water Injection test in a domestic site. The test was conducted by installing three cables of a different type to a well while injecting water to another well nearby. Fig.1 shows the test result. The new cable is more sensitive than the other conventional cables to monitor the minute geological strain caused by injecting water.

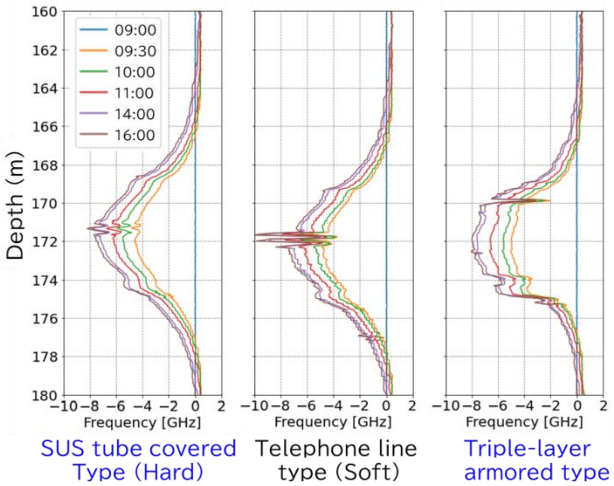

Fig. 1 Strain of Geological Formation by Water Injection Test for different types of optical fiber cable

The demonstration of our DFOS has been conducted at three overseas sites for different purposes through 2023.

We will monitor the behavior of injected CO_2 in addition to the stability of formation and the integrity of well by applying the DFOS at the large-scale CO_2 injection site in North Dakota, USA. We have installed the optical fiber cable to the wellbore, enabling us to monitor CO_2 injection. By demonstrating our DFOS at the large-scale site, we will complete the development of measurement technologies: multiple sensing, Distributed Acoustic Sensing (DAS) and Vertical Seismic Profiling (VSP).

At the site in Australia, a demonstration test using our DFOS for monitoring formation stability has been conducted. We will monitor CO_2 migration along shallow faults and deep formation stability by installing the optical fiber cable in the well near the faults.

We have been demonstrating our DFOS to monitor deformation of seabed surface by installing the optical fiber cables in a shallow seashore of German offshore by joining the international cooperation project and sharing information with several research partners including the Norwegian Geotechnical Institute (NGI).

2.2. Development of Storage Resource Management (SRM) System

The Storage Resource Management System (SRM) is a measure of the improvements in storability and economics of CCS. Two main subjects are;

- Accomplish an effective utilization method of geological storage capacity (resource) for large-scale CO_2 reservoirs.
- Develop an economic assessment tool to estimate overall CCS business costs including risk costs associated with operations.

Fig. 2 shows the scope of the SRM system in terms of a CCS business covering the entire CCS value chain from capture, transport and storage. This includes a time sequence from a screening of regional potential to long-term management after the closure of CO_2 storage sites. The economic assessment tool will be developed to estimate overall CCS business costs including risk costs associated with operations.

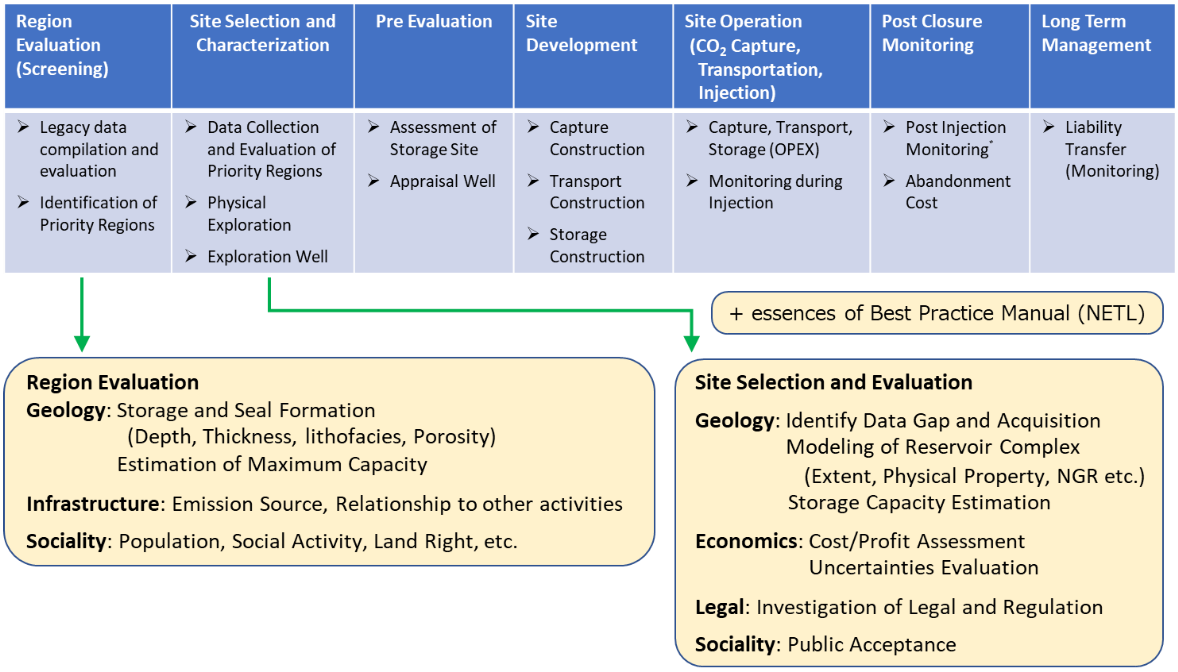

Fig. 2 Scope of SRM system in CCS business

Both the proper selection of CO_2 storage sites and the effective utilization of reservoirs are pivotal factors in the economic assessment. Our group has been addressing the following technical developments;

- Geological modeling for large scale reservoir.
- Techniques of optimizing a layout of CO_2 injection wells and pressure management wells.
- Methodology of CO_2 behavior simulation and long-term prediction.

The measure to evaluate and manage storage resources will be built by expanding these technical elements.

For the establishment of the effective utilization of reservoirs, we refer to the international standard, ISO 27914: 2017 Carbon dioxide capture, transportation and geological storage - Geological storage and CO_2 Storage Resources Management System (SRMS) by Society of Petroleum Engineers (SPE, 2017). ISO 27914 defines the requirements and recommendations to facilitate safe and long-term sequestration of CO_2 in deploying commercial CCS that minimize the risks to the environments, natural resources and human health. SPE SRMS provides classification framework for accounting the storage capacity of CO_2 from “undiscovered” to “commercial”. While it provides generic guidelines, uncertainties in geological evaluation and technical risks associated with selected sites must be handled based on each CCS business project.

It is crucial to consider the origin of geological formation in order to estimate uncertainties in geological evaluation. RITE’s CO_2 geological storage potential survey (Fig. 3) is the existing geological information that concludes the estimation of CO_2 storage quantity utilizing base data of oil and gas resource exploration conducted (RITE, 2006). It was derived from the distribution of deep saline aquifers at depths below 800 m where CO_2 is in a supercritical state. Deep saline aquifers are consisted of alternation of sand and mud. Due to uncertainties in homogeneity and continuity of geological formation, detailed investigation needs to be conducted. Advancing the investigation of uncertainties will update the storage resource data more precisely.

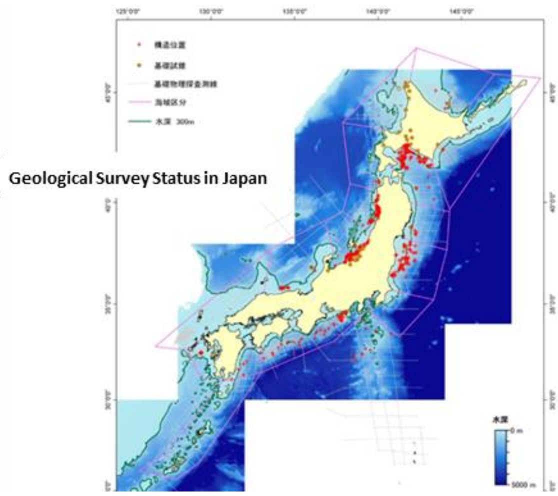

Fig. 3 Distribution map of anticline structure in Japan by base physical exploration survey.

The distance between a CO_2 storage site and an emission facility is a key factor in determining the mode and cost of CO_2 transportation, which impacts the economics of CCS business. Low cost and Low risk business models have been investigated by matching nearby emission sources with several assumed storage sites selected based on geological data and storage capacity estimation (Fig. 4). This business model investigation is aligned with the business development that will gradually expand as described in the METI report. However, there are data gaps in some regions for assuming storage sites and different kinds and volumes of emission sources (coal-fired power plant, iron and steel, chemical plant). By identifying several candidates for CCS business site, our group will share knowledge of geological survey in the regions and propose CCS business models that enable early deployment. In addition, the cost estimation tool for CCS business will be developed. All CCS value chains (capture, transport and storage) will be taken into account in the tool for calculating overall CCS business cost. It will contribute to the development of financing and insurance for CCS business.

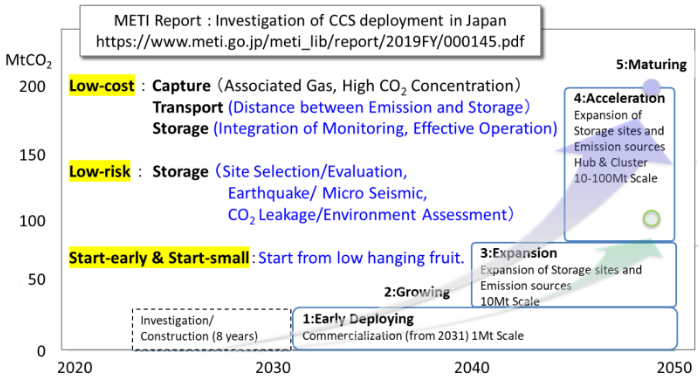

Fig. 4 Concept of the Early Realization CCS Business Model.

2.3. Creation of Social Consensus, Knowledge Sharing and Technical Support to Deploy CCS

The deployment of CCS at scale requires frameworks for CCS business, public understanding and social consensus as well as technology advancement and commercialization. To support CCS business, our research group has compiled guidance for developing an Incident Response Protocol for CCS developers and operators (Japan Specific IRP) and has been producing Practical Guidance for Geological CO_2 Storage. To enhance public understanding and create consensus in society, we have also been working on the development of frameworks for creation of social consensus (Social License to Operate, SLO).

2.3.1. Incident Response Protocol (Japan Specific IRP)

It is essential to have clear procedures and plans, *i.e.* protocols at hand, for the case where any incident occurs in order to secure security, to take appropriate emergency response in a geological CO_2 storage operation and also to retain public support. An incident is defined here as an event which has risks to delay or interrupt geological CO_2 storage development and operation. Potential incidents include abnormality in operation such as those in wells and CO_2 reservoir; events that can cause abnormality in operation such as intensified earthquakes, typhoons and identification of unknown faults; adverse impacts on subsurface and the external environment such as the deformation of formations and surface, CO_2 leakage and induced seismicity; and adverse impacts on the ecosystems, resources and assets such as changes in the ecosystems, CO_2 contamination in drinking water, damage to human lives, health and houses. (See Fig. 5)

We call incident response protocols for CCS developers and operators to conduct a geological CO_2 storage project in Japan as a Japan Specific IRP and have developed guidance for developing one.

For the Japan Specific IRP, we define three emergency levels in accordance with degree of impacts on the external environment. Level 1 is when there is no adverse effect derived from the emergency; Level 2 is when adverse effect may appear if the situation becomes worse; and Level 3 is when there is being adverse effect. When incident happens, the developer or operator judges an emergency level, forms a response team based on the level and then takes appropriate technical and social responses to the emergency. The technical responses include investigation and monitoring of the incident; remediation of portion where incident occurs; and mitigation, prevention and restoration of the effect. The social responses include correspondence with administrative organizations; and communications with local stakeholders, the general public and mass media. The guidance contains a number of examples for responses to each listed potential incident.

As a complement to the Japan Specific IRP, we have produced a Q&A book. The book covers answers based on scientific evidences to anticipated questions regarding to impacts of earthquakes on CO_2 reservoir, seismicity induced by CO_2 storage operation, effects of CO_2 leakage on human, living organism and the environment.

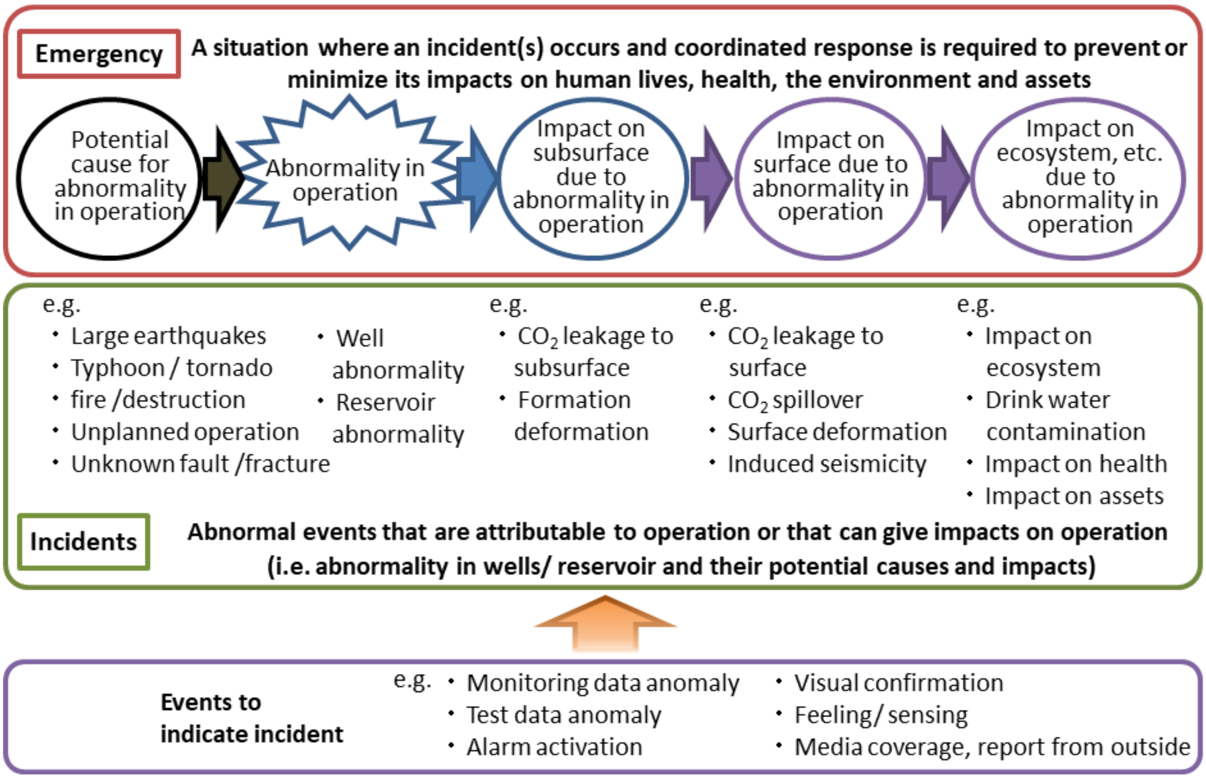

Fig. 5 Emergency Categories and Examples of Incidents

2.3.2. Practical Guidance for Geological CO_2 Storage

As a reference manual for developers and operators of CCS in Japan, our research group has been developing a Practical Guidance for Geological CO_2 Storage to summarize domestic and foreign case examples regarding to geological CO_2 storage.

The guidance consists of eight chapters based on the phases of geological CO_2 storage development and operation: Basic Plan; Site Selection; Site Characterization; Implementation Plan; Design and Construction; Operation and Management; Site Closure; and Post-closure Management. The Chapter 1 on Basic Plan was completed, available on our website in October 2021.

The aim of basic planning is to get understanding of a project from stakeholders by presenting its overview at a phase of project initiation. What to examine, plan and accomplish in the basic planning are diversified, ranging from technical aspects to economic, legal and social aspects. The Chapter 1 of the guidance shows all phases in the whole of project planning and outlines each of the phases.

The guidance summarizes relevant domestic and foreign legal and regulatory frameworks and clarifies timings of permission and authorization required. For economics, it presents an overview of project costs and breakdown costs of an oversea project. In addition, the document touches upon an overview of how to consider risk management and public outreach and public acceptance (PO/PA).

Chapter 2 to 8 describe each of the phases in detail, which will be published one by one. In order for them to be used overseas, their English versions are being compiled and will be publicly available.

2.3.3. Creation of Social Consensus for CCS Implementation (SLO)

Implementation of CCS in society needs social consensus. Our research group has therefore been developing methodology for the creation of social consensus (SLO).

What is essential in implementation of CCS is support from the local community. To get local support and consensus, it is critical to make well communications between local stakeholders and CCS developers/ operators. In overseas cases, it is recommended to start two-way communications at an early stage. The two-way communications is different from communications where a developer/ operator explains their project to the local unilaterally and requests them to accept it. It does mean that local people share their opinions, thoughts and concerns with the developer/ operator and as a result mutual understanding and mutual trust are built. There have been a number of proposed two-way communications methods. Our research group is examining how the developer/ operator should communicate with whom in the local community at each phase of a project. We are also analyzing economic ripple effects generated by the project to the local.

Consensus in society does not just mean simply that local people and general public accept CCS. In society there are diversified stakeholders from local residents and general public through investors and policymakers to the developer/operator. Different from many other non-CCS projects, CCS itself generates no profit so that consensus among investors, policymakers and the developer/ operator requires incentives as mechanisms to deliver business case. We are therefore examining incentives in other countries to design those suitable for Japan. We are also making analysis on costs of CCS projects. Through studies such as cost analysis for overseas projects, we are investigating breakdown of costs and their yearly changes.

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Inorganic Membranes Research Center

Members (As of Dec. 2021)

Shin-ichi Nakao, Director of the Center, Chief Researcher
Kumiko Konishi, Deputy-Director, Chief Researcher
Hidetoshi Kita, Chief Researcher
Masahiro Seshimo, Senior Researcher
Kazuyuki Kitamura, Senior Researcher
Makoto Ryoji, Senior Researcher
Fuminori Ito, Researcher
Lie Meng, Researcher
Hiromi Urai, Research Assistant
Yuko Nara, Research Assistant
Kazuaki Sasa, Research Assistant
Nobuaki Oono, Research Assistant
Chiyoko Shindo, Research Assistant
Akiyoshi Fujii, Research Assistant
Keiko Komono, Research Assistant

Research and Development of Innovative Environmental and Energy Technologies that Use Inorganic Membranes and Efforts for Practical Use and Industrialization

1. Introduction

The Paris Agreement began full-scale operation in 2020, and in October, 2050 Carbon Neutral was declared in Japan as well. In order to achieve this goal, it is necessary to effectively reduce greenhouse gas emissions and realize carbon recycling that utilizes CO_2 as a resource.

Inorganic membranes of silica, zeolite, and palladium have the features of excellent mechanical strength and heat and chemical resistance compared to polymer membranes. In addition, by using a membrane reactor that uses the inorganic membrane, energy consumption is significantly reduced compared to conventional packed-bed reactors that require separation and purification processes of distillation and adsorption. It also has the potential to simplify the process. Based on these excellent characters of inorganic membranes, as a technology that can realize an innovative production process, research is underway on the application of the membranes as an alternative to distillation and the effective use of captured CO_2. Furthermore, the development of hydrogen permselective membranes for CO_2-free and low-cost hydrogen production, which is indispensable for building a hydrogen society, is expected to be an innovative technology that greatly contributes to the reduction of greenhouse gas emissions.

The Inorganic Membrane Research Center (IMeRC) aims for the early practical use and industrialization of innovative environmental and energy-saving technologies using inorganic membranes. The organization is composed of two departments, the Research Department and the Industrial Cooperation Department, in order to promote activities with research and development and industrial collaboration.

In the Research Department, membrane reactors for carbon capture and utilization (CCU) are developed using silica, zeolite, and palladium membranes, which have unique characteristics, respectively. We mainly develop two-types of membrane reactors for synthesis of methanol and liquid hydrocarbon fuel via captured CO_2. In the case of liquid hydrocarbon fuel, CO_2 directly captured from the air is the raw material. In addition, we are also conducting research on hydrogen production by direct decomposition of methane for the purpose of CO_2-free and low-cost hydrogen production.

In the Industrial Collaboration Department, the Industrialization Strategy Council, which consists of 18 companies of inorganic membrane and porous-substrate manufacturers and user companies, aims to share the vision among manufacturers and user companies by planning joint research. Member companies have regular opportunities to share ideas and promote activities through study groups.

This paper introduces the main achievements and future prospects of the research division, such as CCU technology development and hydrogen production from methane, and the status of the activities of the Industrialization Strategy Council.

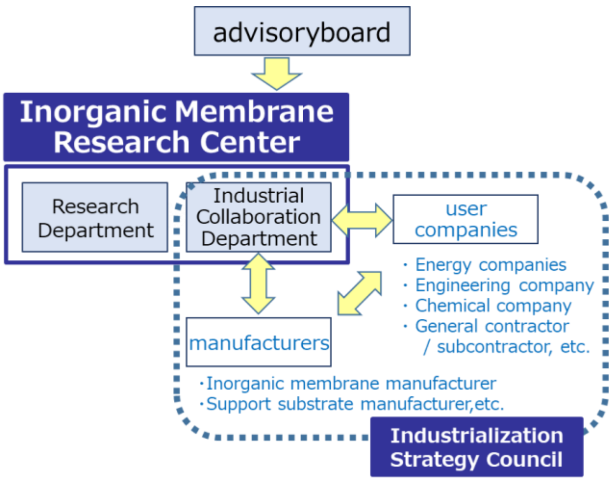

Fig. 1 Promotion system of IMReC

2. Development of CO_2-free hydrogen production technology from methane decomposition

To realize a society that relies on hydrogen, a method is required to produce hydrogen at low cost and in large quantities. With the focus on methane, which can be stably supplied for a long time because of the shale gas revolution, hydrogen and solid carbon are produced by pyrolysis, and hydrogen production costs can be reduced by selling the carbon. A membrane reactor, which is applied to that reaction, could produce hydrogen at low cost and save on energy consumption. In addition, the process has the advantage of not emitting carbon dioxide and is a technological development that contributes to a decarbonized society.

Adopted as a contract project of NEDO in FY 2019, the objective was follows: a) development of a high hydrogen permselective membrane with durability under high temperature conditions (>500°C), b) development of a catalyst that activates at relatively low reaction temperatures for the membrane reactor, and c) the development of membrane reactors consisting of a hydrogen separation membrane and a catalyst with a demonstration of their effectiveness. (Fig. 2)

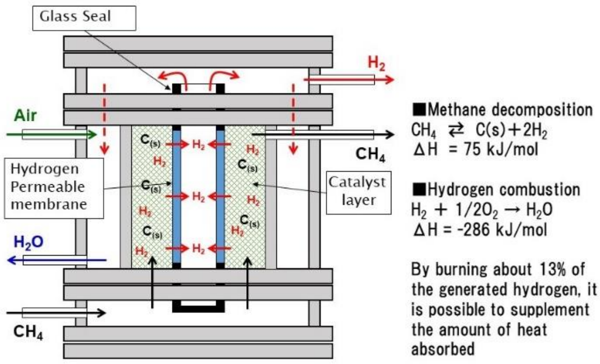

Fig. 2 Application of a membrane reactor to the hydrogen production process from methane decomposition

For the development of a hydrogen permselective membrane in a), silica and palladium membranes are candidates. We have succeeded in developing a hydrogen permselective membrane having high H_2 permeance and heat resistance at 723 K. Both of the silica and palladium membranes were showed over 5 x 10^{-7} mol m^{-2} s^{-1} Pa^{-1} of H_2 permeance, and 3,000 of H_2 selectivity. These results were exceeded the final goal of this project. In addition, $Ni/Fe/Al_2O_3$ as a catalyst for methane decomposition showed relatively high catalytic activity at 873 K.

We calculated the hydrogen production efficiency and CO_2 emissions using a membrane reactor for methane decomposition. As shown in Fig. 3, high hydrogen production efficiency and low CO_2 emissions were obtained compared with the conventional packed bed reactor (PBR). Compared with the CO_2 emissions from the methane steam reforming (SRM), which is a general hydrogen production method, CO_2 emissions from SRM are 0.95 kg-CO_2/Nm^3-H_2, whereas methane decomposition using the membrane reactor is 0.2 kg-CO_2/Nm^3-H_2. The CO_2 emissions from this membrane reactor can be suppressed to about 1/5.

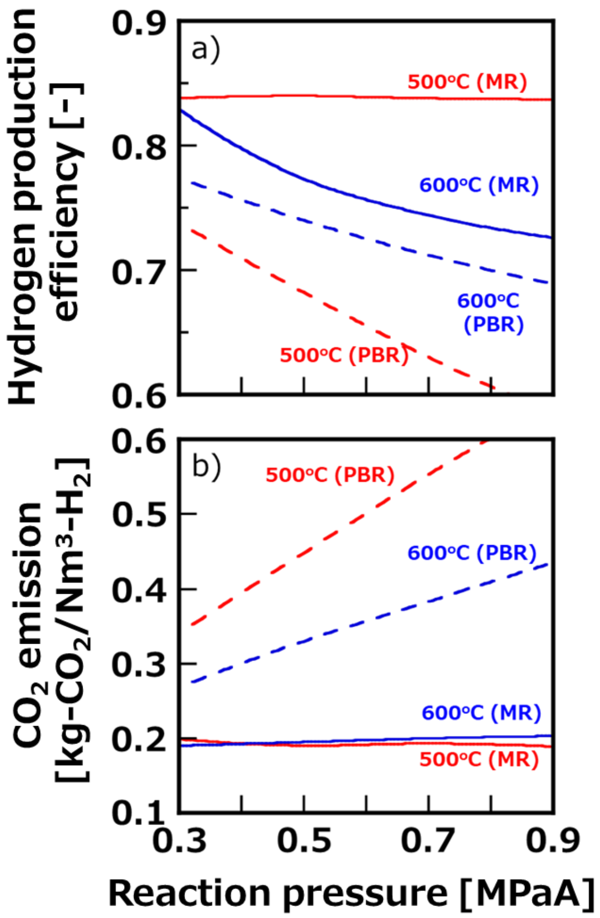

Fig. 3 Calculation results of effect to apply the membrane reactor for methane decomposition.
a) Hydrogen production efficiency, b) CO_2 emission.

Fig. 4 shows results of the membrane reactor tests using palladium and silica membranes as hydrogen permselective membranes. A broken line in this figure shows methane conversion using the packed bed reactor, and a solid line shows the maximum methane conversion theoretically obtained using the membrane reactor. From these results, methane conversion using the membrane reactor showed 0.8 (palladium membrane), and 0.7 (silica membrane) at 873 K as the reaction temperature and 0.4 MPa as the reaction pressure. Compared to a packed bed reactor, both membrane reactors obtained higher methane conversion. On the other hand, in the case of a reaction temperature of 773 K, methane conversion using a membrane reactor was approximately the same as when using a packed bed reactor. It is assumed that the Ni/Fe/Al_2O_3 catalyst showed low catalytic activity at 773 K. Thus, these results propose that the development of a catalyst having higher catalytic activity in lower reaction temperatures is indispensable. This is one of the major issues in the development of membrane reactors using inorganic membranes and is not limited to methane decomposition. In the future, the research and development of a membrane reactor should be promoted by integrating catalyst development and membrane development.

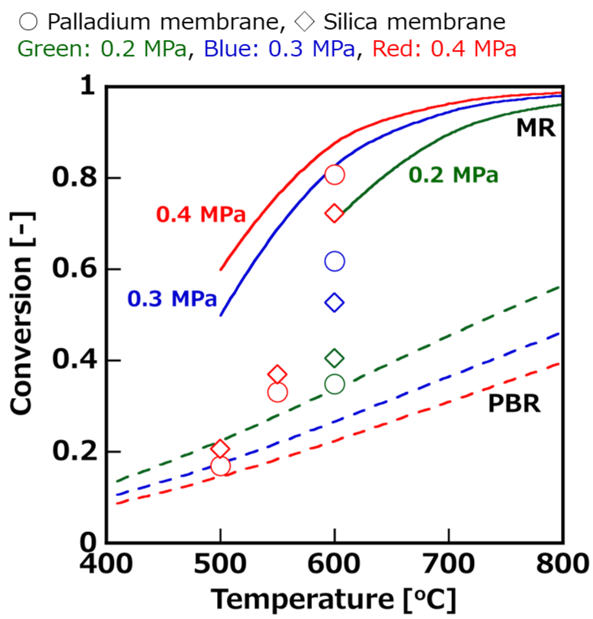

Fig. 4 Effect of methane conversion increasing using membrane reactor.

3. CO_2 utilization technologies in RITE

Recently, CO_2 utilization technologies have been actively researched and developed in countries around the world, including the EU, as being effective in reducing CO_2 emissions. On the other hand, in the hydrogenation of CO_2, water is generated by the reaction, which decreases the reaction rate. In addition, most reactions are exothermic, and the removal of the reaction heat is one of the problems. In order to solve these problems, highly efficient, energy-saving CO_2 utilization technology has been developed at the Inorganic Membranes Research Center using a membrane reactor.

3.1. Development of effective methanol synthesis from CO_2 hydrogenation

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.

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

CO_2 emission reduction potential can be expected at about 100 million tons/year (assuming demand methanol production of 50 million tons/year) when methanol production process will change to that via CO_2 as the raw material. Thus, highly efficient methanol synthesis processes from CO_2 have been required. If the produced water is removed from the methanol synthesis reaction system, it can be improved to a one-pass yield with synthesized methanol at a relatively mild condition of lower reaction pressure and temperature. The membrane reactor with the water permselective membrane is expected to be one of the highly efficient methanol production processes.

At the RITE Inorganic Membranes Research Center, we successfully developed a novel hydrophilic zeolite membrane, which has higher hydrothermal stability and water/methanol permselectivity 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 at a reaction temperature of 473 K and a reaction pressure of 4 MPa.

In near future, we will improve dehydration zeolite membrane performance, and produce a membrane having a higher effective membrane area. A new project for that purpose was adopted in 2021.

3.2. Development of liquid hydrocarbon fuel synthesis technology using CO_2 as a raw material captured from the air

Liquid hydrocarbon fuels by recycling CO_2 through the existing infrastructures for transportation and storage have a lower cost than new fuels, so they should be established to achieve carbon neutrality. The NEDO project Moonshot Research & Development Program was adopted in collaboration with Kanazawa University and the RITE Chemical Research Group in 2020. At the IMeRC, we accepted the challenge of developing the technology to convert the captured CO_2 into liquid hydrocarbon fuel by FT (Fischer-Tropsch) synthesis (Fig. 5). Similar to methanol synthesis, the water produced from the reaction causes catalyst deactivation and a reaction rate reduction in FT synthesis. Another problem is the difficult reaction control for liquid fuel because the product followed the ASF (Anderson-Schulz-Flory) distribution.

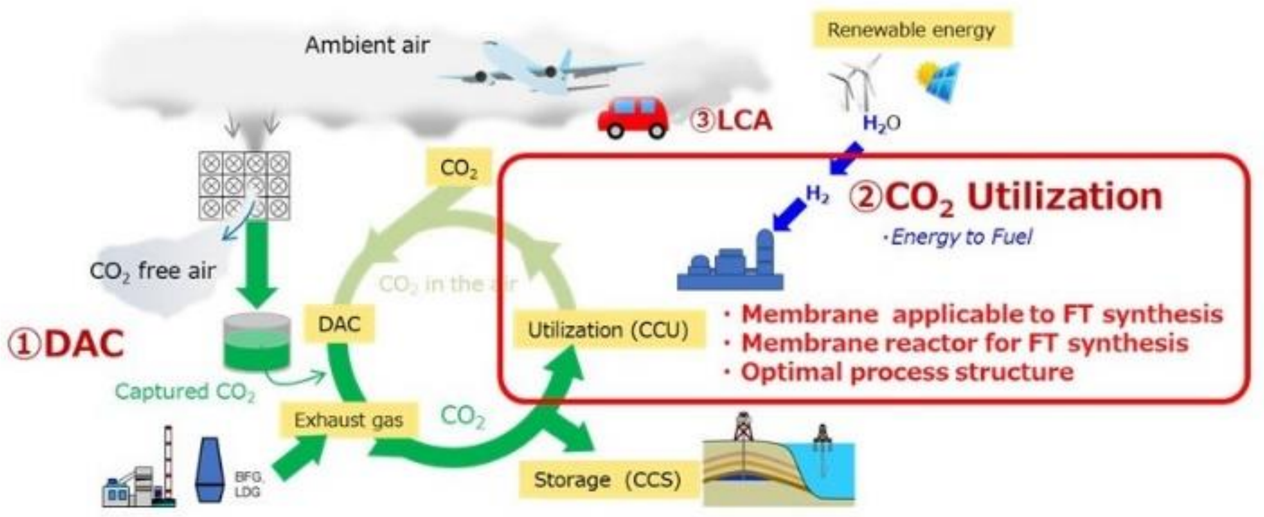

Fig. 5 Overview of the Moonshot project at RITE

Therefore, in this project, we will develop high efficiency, energy-saving CO_2 utilization technology from the CO_2 captured from the air as the raw material for the membrane reactor. Research and development items are as follows.

a) Development of membranes applicable to FT synthesis
b) Development of a membrane reactor for FT synthesis
c) Search for the optimal process structure

The target membranes are hydrophilic membranes and hydrogen permselective membranes. Catalyst deactivation can be suppressed if the generated water can be removed from the reaction side by using a hydrophilic membrane, such as zeolite. Furthermore, the reaction can be controlled by supplying H_2 to the reaction field via hydrogen permselective membranes, such as silica and palladium. We succeeded in developing the Si-rich LTA-type zeolite membrane with improved hydrothermal stability compared to the conventional LTA-type zeolite membrane. We are also involved in the development of silica membranes with excellent hydrogen permselectivity.

The membrane reactor for FT synthesis was designed and will be put into operation. A simulation model was constructed prior to the experiments, and it was confirmed that the membrane reactor can obtain a higher CO_2 conversion rate than the conventional catalyst-packed bed reactor.

In the future, we will make the best use of the knowledge we acquired and strongly promote the development of inorganic membranes and membrane reactors applicable to FT synthesis. We then intend to unravel the science of inorganic membranes that we have left unattended.

4. 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 using 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 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, membrane-related companies, etc. on the latest R & D trends and introduction of needs, seeds, practical development cases of membranes, and lively questions, answer. In addition, we conduct patent and literature searches related to the content of the lecture, and regularly provide members with needs seeds information with comments from the IMeRC in the summary.

5. In conclusion

In November 2021, the Inorganic Membrane Environment and Energy Technology Symposium to Explore the Future was held online for the first time in two years with the attendance of 389 people. At this symposium, under the theme of carbon recycling, universities and companies gave lectures on the latest trends in CO_2 separation / recovery / effective utilization, carbon cycle technology and efforts toward practical application. We introduced the latest research results of the IMeRC and the efforts of the Industrialization Strategy Council.

The audience commented that they were able to deepen their understanding of carbon recycling, as well as understand the specific efforts toward practical use and the effectiveness of inorganic membranes in separation technology.

The need for innovative environmental and energy technology development that contributes to decarbonization is increasing toward 2050 carbon neutrality. As the IMeRC, we would like to deepen basic and applied research that makes the best use of the advantages of inorganic membranes, and accelerate the movement toward social implementation

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
- Inorganic Membranes Research Center

Other Activities

◆Environmental Education

Date	Participants	Number of partici-pants
7 Jan.	Teachers of Kyoto Prefectural Joyo High School	9
30 Jul.	Kyoto Prefectural Nishimaizuru High School	9
21 Oct.	Society of Physics and Chemistry Education, Kyoto	16
22 Nov.	Nara Prefectural Narakita Senior High School	20

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Research Institute of Innovative Technology for the Earth

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

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