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Annual Report

Research Institute of Innovative Technology for the Earth

30th Anniversary 1990 - 2020

Foreword

On the 30th Anniversary of RITE

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Feature

Key Technologies for Decarbonization

Overview and New Developments on CO_2 Separation and Recovery Technologies

R&D Activities

Topics

Outreach Activities

2019 Paper, Presentation and Publication

RITE Today 2020 Vol.15

Contents

On the 30th Anniversary of RITE

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At the RITE, we will celebrate our 30th anniversary this year. For me personally, the end of this March will mark the 10th anniversary of my appointment as Director-General of RITE, while last June saw my installation as Senior Vice President. I would like to take this opportunity to review the past years and consider the role of RITE.

We were authorized to be established in July 1990, followed by the opening of our office on August 1 of the same year. In 1993, the construction of our headquarters facility was completed where it is now located (Keihanna Science City). At the G7 summit held in Houston, Texas in the U.S., at the same time RITE was given the go-ahead for its founding, the Japanese government presented New Earth 21 as a long-term strategy to prevent global warming, which suggests that RITE has been established to implement New Earth 21. Incidentally, the name DNE21+, the global energy model developed and managed by the System Analysis Group, contains the acronym for New Earth 21 (NE21).

In New Earth 21, we were expected to play the role of doing research and development in fields difficult to be tackled in the private sector alone, such as separation/capture and treatment/disposal of generated GHGs, and expansion of sources of CO_2 absorption, including plants. For more than a decade after establishment, we were mainly committed to research and development projects commissioned by the New Energy and Industrial Technology Development Organization (NEDO), whose themes included various types of CO_2 storage (called “fixation” in those days), including ocean sequestration, desert greening, CO_2 capture and effective utilization, plus development of bioreactors, capture and recycling of CFCs, production of hydrogen, and development of biodegradable plastics. We proceeded with these research and development projects as joint research with universities or in cooperation with private companies. The research on ocean sequestration was suspended due to the London Convention, prohibiting disposal of CO_2 at sea. It was around that time, however, when the technology foundation regarding CO_2 capture, utilization, and storage (CCUS) and the bioresearch foundation were established.

In addition, we were also engaged in many other projects to promote technology development, surveys and research, as well as international interaction, with expenses shared between RITE and companies. One such survey and research project was one intended to explore how to implement the New Earth 21 strategy, and actually, I was involved in it. This was the beginning of our assessment of global warming mitigation, which is today known extensively both at home and abroad.

Since the beginning of this century, we have integrated and refined the research system at our headquarters, gradually reducing research operations commissioned to outside entities. During this time, our social recognition has greatly increased mainly through the underground storage of 10,000 tons of CO_2 in Nagaoka, and the development of the RITE bioprocess.

When looking back at efforts around the world to combat global warming, we find great progress achieved as if in step with the actions that we have taken over the last 30 years, indicated by the establishment of the Framework Convention on Climate Change adopted at the global summit in 1992, the effectuation of the Kyoto Protocol in 2005 after COP3 in 1997, and the conclusion of the Paris Agreement at COP21 in 2015 and its effectuation in 2016.

Last year, Japan submitted to the U.N. its Long-Term Strategy under the Paris Agreement, which indicates that it is necessary to realize a decarbonized society as early as possible in the second half of this century. The key for this lies in various forms of innovation, such as practical implementation of CCUS, including carbon recycling; production of biomass using microorganisms, and clean and mass utilization of such biomass as resources and fuels; and considerable reduction of energy demand in Society 5.0. RITE’s mission is gaining much more significance.

Key Technologies for Decarbonization: Overview and New Developments on CO_2 Separation and Recovery Technologies

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1. Introduction

Following the enforcement of the Paris Agreement, in order to work on energy conversion and decarbonization with the aim of reducing greenhouse gases by 80% toward 2050, it is necessary to advance the development of CO_2 separation and capture, effective use, and storage (CCUS) technology that can significantly reduce the release of CO_2 from emission sources into the atmosphere while promoting the reduction of CO_2, including the main use of renewable energy.

The cost of separating and capturing CO_2 is estimated to account for about 60% of the total CCS cost. On the other hand, carbon recycling (CCU approach) has been proposed in the carbon recycling technology roadmap formulated in June 2019. The CCU approach reduces CO_2 emissions into the atmosphere by using it as the raw material and fuel through mineralization, artificial photosynthesis, and methanation after separation and capture as a resource.

Since CO_2 separation and capture will be a common technology in this CCUS approach, it is important to reduce the costs.

2. Optimal capture methods for CO_2 sources[1), 2), 3)]

In the process of the separation and capture of CO_2, it is necessary to select the most appropriate method according to the physical properties of the pressure and concentration of CO_2 from the emission source (Fig. 1). Separation and recovery technologies include the following methods: a chemical absorption method and a physical absorption method where CO_2 is absorbed into a liquid, a solid absorption method where CO_2 is absorbed into an amine compound supported on a solid surface, a physical adsorption method where CO_2 is absorbed onto a solid surface, a membrane separation method, and a cryogenic separation method that liquefies gas mixtures at very low temperatures and separates mixtures using differences in boiling points. On the other hand, if the capture technology is classified by target gas for thermal power plants, steelworks blast furnaces, cement plants, and chemical plants as current large-scale CO_2 emission sources, then the technology can be broadly classified into post-combustion, which separates and captures CO_2 after combustion, and pre-combustion, which separates and captures CO_2 before combustion.

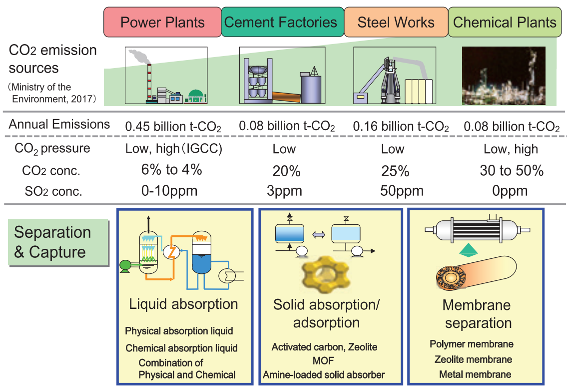

Fig. 1. CO_2 emission sources and CO_2 capture technologies

In post-combustion, CO_2 is separated and captured from flue gas generated from boilers at power plants usually at almost atmospheric pressure. Since the exhaust gas pressure is low, and the CO_2 concentration is low, chemical absorption using a liquid amine compound with high reactivity to CO_2, solid absorption using a solid surface supported on a solid surface, and cryogenic separation can be candidate technologies.

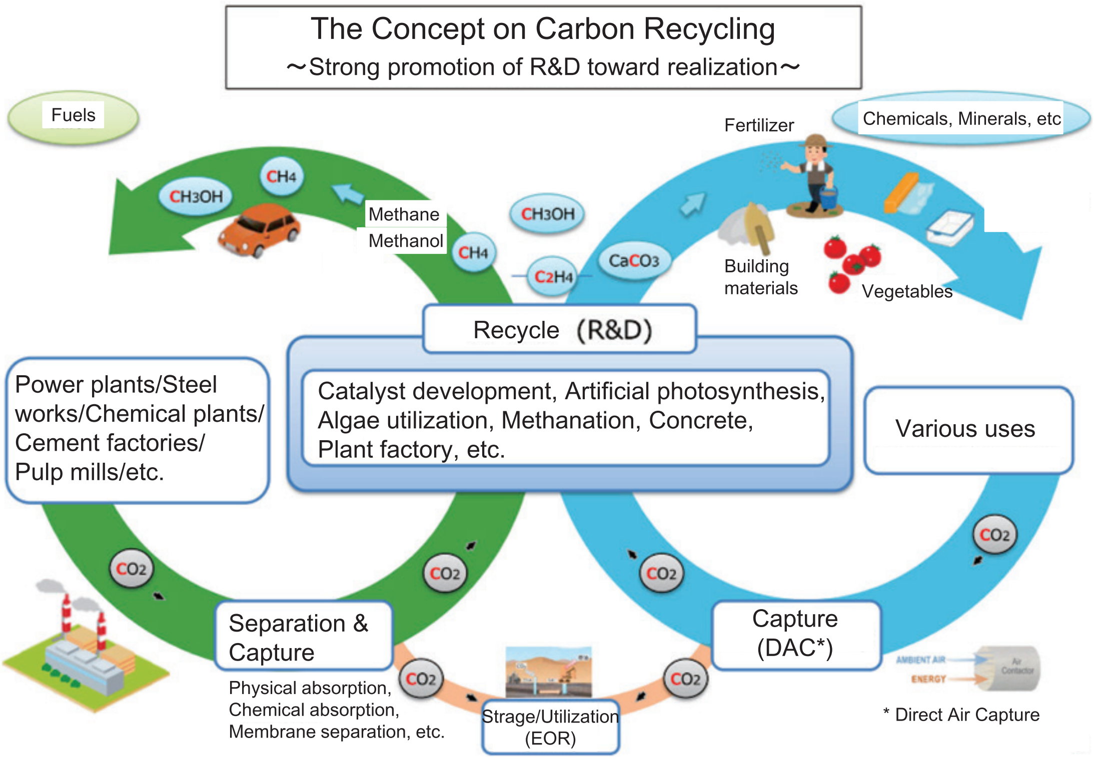

Fig. 2. Carbon recycling concept
https://www.enecho.meti.go.jp/category/others/carbon_recycling/pdf/concept_ja.pdf

The chemical absorption method and the solid absorption method are expected to be lower in cost than the cryogenic separation method, which requires CO_2 liquefaction.

In pre-combustion, CO_2 can be removed from steam reforming in chemical plants and from H_2, CO, and CO_2 generated from the partial oxidation of coal, such as the integrated coal gasification combined cycle (IGCC). Since the pressure of the above gases is generally high, the physical absorption method, physical adsorption method, and membrane separation method, which separate CO_2 by the pressure difference, are candidate technologies. In the case of separating and capturing CO_2 from high-pressure gas, the membrane separation method separates CO_2 simply by permeating gas resulting in potentially lower energy and lower costs than the physical absorption method and the physical adsorption method.

Based on the above summary, we will outline the current status and new developments in these technologies, focusing on the chemical absorption method where CO_2 is absorbed into a liquid, the solid absorption method using a solid surface, and the membrane separation method.

In addition, as shown in the carbon recycling concept diagram (Fig. 2), we will introduce technologies for capturing CO_2 from large-scale sources and technologies for directly capturing CO_2 from the atmosphere (DAC: Direct Air Capture).

3. Current Status and New Developments of CO_2 Capture Technologies

3.1. Chemical Absorption Method

In general, when a gas is dissolved in a liquid, a case involving a clear change in the chemical bond state is called chemical absorption, while a case without a chemical bond state is physical absorption. Since CO_2 is an acidic gas, it is chemically absorbed by the basic material (B). Because the absorption reaction is reversible, the CO_2 in the mixed gas can be selectively absorbed, and then the reverse reaction is caused by steam heating or other methods (Fig. 3).

$$B + CO_2 \rightleftarrows B\text{-}COO \quad (1)$$

Among the CO_2 capture methods using chemical absorption, the method using an aqueous amine solution is the most mature technology, which has been known since the early 20th century.

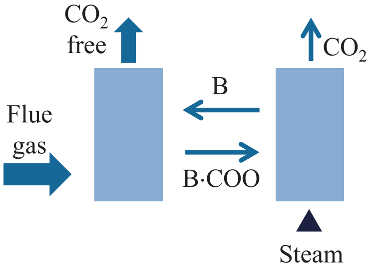

Fig. 3 CO_2 capture scheme by chemical absorption method

The combustion exhaust gas has a relatively low partial pressure of CO_2 and contains O_2 as a component. The exhaust gas also contains SO_X and NO_X as minor components. Thus, the difficulty of CO_2 capture from the gas is higher than that from syngas or natural gas. So, full-fledged CO_2 capture technology for post-combustion was only established in the 1980s.[4) This method, which uses monoethanolamine (MEA), has been a benchmark. As is well known, the MEA method presents the problems of high energy consumption during regeneration (reverse reaction of (1)), corrosivity, and oxidative degradation of MEA. Then, besides improving the MEA method, development, demonstration, and commercialization of processes using alternative amines have been actively pursued. In the field of CO_2 capture by the chemical absorption method, Japan is particularly active.

In the 1990s, Mitsubishi Heavy Industries, Ltd., and Kansai Electric Power Co., Ltd., jointly began development of the post-MEA method and developed the proprietary solvent KS-1 and KM CDR process. Then, they commercialized the capture of CO_2 as a raw material for urea production from the flue gas generated by chemical plants and other processes. The two companies have also applied their capture technology for enhanced oil recovery (EOR). The world's largest CO_2 capture process currently in operation is carried out with this KM CDR process with a capacity of approximately 5,000 tons of CO_2 per day.[5)]

In the 2000s, chemical absorption methods and other CO_2 capture methods were actively developed in Europe, the United States, Canada, and Australia. In Japan, Toshiba Corp. and IHI Corp. joined this field of development in earnest. After that, CCS was recognized as an effective global warming countermeasure technology, which accelerated the R&D of CCS technologies by industry, government, and academia. Unlike the industrial use of captured CO_2, CCS does not generate profits, so significant technological innovation is required to reduce the capture costs. The chemical absorption method using an aqueous amine solution has an inherent limit in reducing energy consumption. Therefore, other capture methods have been intensely studied. However, the achievements and maturity of the chemical absorption method are still greater than those of other methods.

In 2014, SaskPower launched the world's first commercial-scale CCS for coal-fired power (Unit #3, Boundary Dam Power Station, Saskatchewan, Canada). The capture process was based on an amine-based chemical absorption method (Cansolv, Shell). A total of about 2 MT was captured at about 3,000 tons of CO_2 per day by which EOR and geological storage were performed. The subsequent project (Shand study) is focusing on the feasibility of a next-generation CCS system using the KM CDR process.[6)] As mentioned earlier, the KM CDR process is already in operation at the world's largest capture facility. The commercial operation started in 2016 in a joint project by NRG Energy in the United States and JX Petroleum Corporation in Japan (Petra Nova project).[5)] In that time, among 21 large-scale CCS facilities in operation or under construction, the chemical absorption method was used in 11 facilities (amine: 8; potassium carbonate: 2), while the physical absorption method was used in eight facilities, the adsorption method and the membrane separation method were used one facility each, respectively.[7)] Incidentally, for a high-pressure gas containing H_2S, including natural gas, the physical absorption method is often used rather than the chemical absorption method.

RITE has been developing solvents for chemical absorption since the early 2000s to reduce the cost of CCS. In particular, the large-scale search for alternative amines that include existing amines as well as newly synthesized amines is unique in the world, and for that purpose, such new molecular design methods using computational chemistry have been introduced. The concept has contributed to the reduction in the energy required for CO_2 capture by the chemical absorption method.[8] In the project started in 2008 (COURSE 50), RITE developed a new chemical solvent in collaboration with Nippon Steel & Sumitomo Metal Corporation (Current Nippon Steel Corporation) for energy-saving CO_2 capture technology from blast furnace gas, which was adopted by ESCAP (an energy-saving CO_2 absorption process commercialized in 2014). The CO_2 captured from this process in steel-making and power plants in Japan is used in the food and chemical industries.[9]

The chemical absorption method has evolved steadily and has been put to practical use in CCS. In order to reduce the costs, the research and development aimed at improving processes, reducing renewable energy and improving the durability of solvents is still actively pursued. RITE is also conducting further research and development such as the application of the noble solvent to achieve the maximum reduction of separation energy.

3.2. Solid absorption method

The method of separating CO_2 by reacting with solid materials means the equipment is easy to operate, start up, and shut down, and the process does not require large amounts of waste liquid treatment. Therefore, if a chemically stable, high performance CO_2, absorbing material is developed, significant cost reductions can be expected.

The adsorption phenomena include weak physical adsorption from the van der Waals force and strong chemical adsorption from the chemical bonding. Zeolite and activated carbon are mainly used in the physical adsorption of CO_2, and in recent years, metal organic frameworks (MOF) have also attracted attention. On the other hand, alkali metal-supported activated carbon, silica modified with amines, hydrotalcite, calcium oxide, and lithium silicate have been used for chemisorption.[10)]

By changing the temperature and pressure to desorb the adsorbed CO_2, the adsorbent can be used repeatedly. Adsorbents used for special applications (such as manned space activities), such as lithium hydroxide and silver oxide, are difficult to regenerate at low temperatures and are sometimes discarded after being used once.

Adsorptive separation technology is being studied as part of a project to significantly reduce the CO_2 emanating from blast furnaces in Japan. The COURSE 50 (CO_2 Ultimate Reduction in Steelmaking process by innovative technologies for Cool Earth 50) project funded by the New Energy and Industrial Technology Development Organization (NEDO) is led by the Japan Iron and Steel Federation (JISF) in collaboration with six major steel and related companies, which has led to the development of environmentally benign steelmaking technologies, including CO_2 capture. JFE Steel Corporation developed a CO_2 adsorption and separation process by physical adsorption using zeolite. A bench scale test facility with a processing capacity of 3 tons of CO_2 per day was constructed, and the CO_2 separation performance from actual blast furnace gas was evaluated, and gas pretreatment methods and cost reduction methods were studied. The facility demonstrated that the purity and recovery of CO_2 by zeolites was > 90% and 80%, respectively, with capture energy (vacuum pump power) of 200 kWh/ton-CO_2, or less was achieved.[11] However, zeolites adsorb H_2O vapor more strongly than CO_2, so CO_2 capture in the presence of H_2O vapor using this adsorption method requires a dehumidification step that consumes large amounts of energy.

On the other hand, many reports have been published on amine-modified solid absorbents, such as silica supported on polyethylenimine as H_2O-resistant adsorbents. In the United States, the National Energy Technology Laboratory (NETL) of the United States Department of Energy (DOE) has been developing a solid sorbent material that supports amines on clay minerals.[12] The solid sorbent is a solid material where amine, a chemical absorbent, is supported on a porous surface (Fig. 4). Unlike the adsorption phenomenon where the substance accumulates at the interface between the two phases, this is called a solid sorbent because it involves the migration of CO_2 into the amine phase.

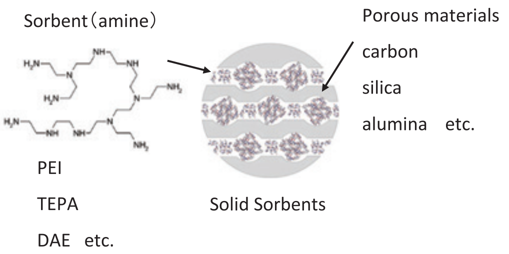

Fig. 4. Conceptual diagram of solid sorbents

By supporting the amine on the porous support, the energy loss (sensible heat and latent heat for heating water) required for CO_2 desorption is lower than in the scrubbing chemical absorption method used as an aqueous solution. In addition, the advantage is that the loss of the absorbing solution from evaporation in the regenerating step is small, and the corrosiveness of the device is low. It has been estimated that the energy requirement for CO_2, capture can be reduced to 1.8 GJ/t-CO_2, by applying a polyethylenimine (PEI) based solid sorbent for the moving bed or fluidized bed.[13)]

In the United States, various solid absorbents have been studied on a bench-to-pilot scale using DOE funds. In a pilot plant test (approximately 20 tons of CO_2 per day) using a commercially available polyamine conducted by ADA-ES Inc., recovery energy of 2.8 GJ/t-CO_2, was reported using steam at 120°C was reported using In addition, SRI Int'l conducted a bench plant test of a temperature swing adsorption (TSA) test using a circulating fluidized bed of about 200 kg per day. The CO_2 capture cost is reported to be $ 39.7/ton-CO_2 ($68/ton-$CO_2$ for the liquid absorbent).[14)] TDA Research's alkalized aluminum sorbent has also been tested on a pilot scale. The company developed an inexpensive alkalized alumina adsorbent with extremely low heat of reaction and a CO_2, capture process specifically designed for this adsorbent, a unique process for adsorption and regeneration under near-isothermal conditions. Pilot tests have been conducted at the National Carbon Capture Center (NCCC).

In addition, Shell is working with the Vienna University of Technology to develop a TSA process with solid absorbents for CO_2 capture from flue gas. So far, using a fluidized bed test device (50 kg/day), it has been confirmed that the CO_2, recovery rate is 90% and energy reduction is 40% compared to the MEA absorption solution method. From 2018, a pilot test of 1 ton of CO_2 per day has been promoted as the Vienna Green CO_2 project in Austria. (The target is biomass power generation.)

For materials other than amine-based materials, CO_2, capture technology using alkali metal carbonates is being studied by Korea Electric Power Corporation (KEPCO).[15)] A process to capture CO_2 in a TSA process using a fluidized bed with a material supporting potassium carbonate is being studied. Practical application tests have already been conducted on a scale of about 200 tons of CO_2 per day, equivalent to 10 MW. A 680-hour continuous test was performed with an 80% recovery rate. It was reported that the regeneration temperature of the sorbent was 140°C to 200°C and the energy recovered was 5 GJ/ton-CO_2.[16)]

In addition to the above, the application of solid sorbents to lower-concentration CO_2 emission sources, such as removal of CO_2 in enclosed spaces, such as indoors and space, and direct air capture (DAC) from air is also being considered (Fig. 5). Climeworks in Switzerland, a global pioneer in this technology, has commercialized a DAC device that uses an amine-loaded solid absorbent. Desorption is performed using the waste heat of an incinerator that can use waste heat at 100°C or higher, and it is assumed that the captured

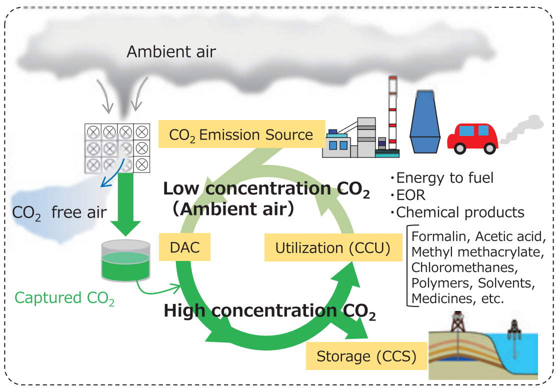

Fig. 5. Conceptual diagram of DAC

CO_2 will be supplied to a greenhouse to promote the growth of vegetables and fruits. If the capture unit is installed in three layers, a site of 20 m^2 is required, and the amount of CO_2 capture is 150 tons of CO_2 per year. In the United States, Carbon Engineering is conducting pilot testing, and several companies are studying DAC, but these systems have been shown to be extremely expensive as the state of the art. At the current state of the art, the size of the absorber is extremely large, so the cost of capture is estimated to be at least \$100/ton-CO_2. However, it is said that it does not require a large land area compared to biomass-based CCS.

RITE has been conducting research on the practical application of CO_2 capture technology from coal-fired power plants using solid sorbents in a project commissioned by the Ministry of Economy, Trade and Industry since FY 2010 (NEDO project from FY 2018). Until now, we have successfully developed a new solid sorbent that offers excellent CO_2 desorption performance and a high absorption capacity. Based on this technology, a solid sorbent has been manufactured at a scale of 10 m^3 and confirmed at 7.2 tons of CO_2 per day as the scale of recovery performance on a moving bed system bench scale apparatus of Kawasaki Heavy Industries, Ltd. Currently, R&D is underway to establish a higher performance solid sorbent system suitable for CO_2 separation and capture from coal-fired power plants by the 2020s. At the same time, the possibility is being studied of applying the process to lower-concentration CO_2 emission sources, such as capture from enclosed indoors spaces and the atmosphere.

3.3. Membrane separation

CO_2 separation by membranes is conducted by selective permeation of CO_2 from the pressure difference between the feed side and the permeate side of the membrane. Two major membrane separation mechanisms are 1) the molecular sieving mechanism and 2) the solution-diffusion mechanism (Fig. 6).

In the molecular sieving mechanism, small gas molecules smaller than the pore size of the membranes permeate selectively. On the other hand, in the solution-diffusion mechanism, the gas with an affinity for the membrane materials selectively permeates.

The advantages of membrane separation are the compact process (because of continuous operation without regeneration step) and, in the case of the high-pressure application, low cost and low energy required compared with other separation techniques. On the other hand, membrane separation is a relatively new technology, and R&D for CO_2 separation for CCS is delayed compared with absorption and adsorption. So far, the projects for membrane separation for CCS are limited to the relatively small scale from the laboratory to bench scale. Various novel membrane materials have been developed, such as polymeric membranes, inorganic membranes, organic/inorganic hybrid membranes, and facilitated transport membranes.[17)]

For post-combustion, since the feed gas is low-pressure gas, either the compressor or vacuum pump is needed, and it is difficult to reduce the separation cost and energy significantly compared with existing technologies. In post-combustion, it is more important to increase CO_2 permeance than to increase the separation factor for the reduction of separation cost and energy, since the high CO_2 permeance reduces the cost of the membrane. Numerous reports have been published on basic research in the development of membranes; however, there are few pilot-scale field tests on post-combustion. Since there is a limitation in the recovery rate and purity of the permeate using membrane separation alone, an increasing number of research studies have been conducted on the hybrid process composed of membrane separation and other separation techniques. Air Liquide is developing a hybrid process using cold membranes and liquefaction.[17)] Their process will concentrate CO_2 from 12% to more than 58% on the cold membrane and recover CO_2 at

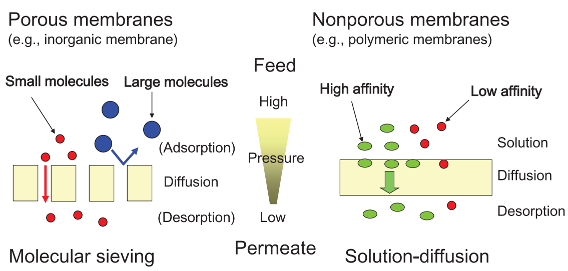

Fig. 5. Conceptual diagram of DAC

more than 95% using liquefaction. They have conducted bench scale field tests (6.5 tons of CO_2 per day) at NCCC.

TDA Research is developing a hybrid system composed of membranes (MTR) and adsorption (TDA Research) and will conduct field tests at CO_2 Technology Centre Mongstad (TCM) in Norway.[17)]

MTR is developing a hybrid system composed of membranes and liquefaction, and they have conducted field tests (20 tons of CO_2 per day) at NCCC.15 They plan to conduct pilot-scale field tests (200 tons of CO_2 per day) at the Wyoming Integrated Test Center (WITC).

In the case of pre-combustion, it is possible to separate CO_2 at low cost and energy, since the feed gas is high-pressure gas, and a vacuum pump is not needed for the membrane process. On the other hand, the membrane must be durable for high temperature and high pressure. In pre-combustion, the mixture of CO_2 and H_2 is separated. Since the molecular size of H_2 is smaller than that of CO_2, most membrane materials are H_2 selective, and with a few exceptions, R&D has been conducted using H_2 selective membranes.

In basic research, thermally stable materials (e.g., hollow fiber carbon membranes, organic/inorganic hybrid membranes containing palladium nanoparticles, and thermally stable glassy polymeric membranes) serve as the novel membrane materials. The MTR proposed hybrid process uses H_2 selective membranes (N_2 as sweep gas), liquefaction, and CO_2 selective membranes, and the company plans bench-scale field tests at NCCC. In addition, they are modifying the component parts of the membrane elements (e.g., spacers). [17)]

The Molecular Gate Membrane module Technology Research Association (MGMTRA; consists of RITE and a private company) is developing molecular gate membranes (novel CO_2 selective membranes) and membrane elements, mainly for pre-combustion, in the METI Project (FY 2011-2018) and the NEDO project (FY 2018-). Unlike conventional CO_2 selective membranes, molecular gate membranes show exceptionally high CO_2 separation over H_2. As a result, H_2 is kept at high pressure and can be introduced into the IGCC gas turbine without recompression. In practical applications, MGMTRA is developing membranes with a large membrane area using the continuous membrane-forming method and developing membrane elements.

4. Conclusion [1)]

Since CO_2 separation and capture will be a common technology in this CCUS approach, it is important to reduce the cost of CO_2 separation and capture.

In this report, we outlined CO_2 separation and capture technologies that are more suitable to post-combustion, which separates and captures CO_2 after combustion, and pre-combustion, which separates and captures CO_2 before combustion, separately.

In post-combustion, since the treated gas is at low pressure, chemical absorption and solid absorption using amine compounds of high reactivity to CO_2 are superior in cost. With the chemical absorption method, many systems have been developed in order to reduce the cost based on systems using monoethanolamine (MEA). Although each commercial CO_2 separation plant has been operated in the Boundary Dam Project, the Petra Nova Project, and the COURSE 50 Project, further cost reductions are needed to disseminate the practical use of CCS.

Significant cost reductions are expected for the solid-state absorption method, whose method makes it easy to operate, start up, and shut down the equipment and does not require large amounts of waste liquid treatment and water. In addition, the application of solid sorbents to lower-concentration CO_2 emission sources, such as removal of CO_2 in enclosed indoor and other spaces, and direct air capture (DAC) from air is also expected.

On the other hand, for pre-combustion, since the treated gas is usually high pressure, the separation membrane method that can also utilize affinity with CO_2 is considered the most advantageous with regard to cost. At present, membrane evaluations by real gas and the development of membrane systems are in progress.

In order to spread CCUS widely, promoting innovative technology development and proposing CO_2 separation and capture technology at lower energy and lower cost, as well as to implement measures to provide incentives to private companies and introduce regulations on CO_2 emission standards, feed-in tariffs, and carbon taxes, are considered necessary.

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Research and International Business Collaboration for the Social Innovation

1. Global environment and the economy

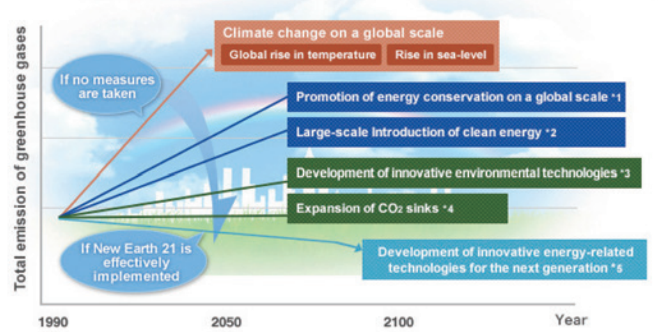
The Research and Coordination Group aims to i) searching for new research topics that enhance the research potential of RITE, proposing and implementing new research themes, ii) government support for the relation with international organizations such as IPCC (Intergovernmental Panel on Climate Change), ISO (International Standard Organization), 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.

1.1. Expectations for innovation

In 2019, Japan hosted the 14th Summit Meeting of the 20 Countries and Regions (G20 Summit) in Osaka. Here, the concept of a virtuous cycle of environment and growth and the innovation were discussed. The urgency of global initiatives including climate change, the importance of long-term strategies, and specific action initiatives was agreed for the first time throughout the G20 countries. RITE has been studied and promoted the R&D in the field of global environment technologies such as Hydrogen, CC(U)S, Carbon Recycling and Biotechnology.

1.2. Innovation and the mission of RITE

With the growing international debate on the issue of global warming, recognition of "balancing the global environment and the economy" has been increasing as a common goal for both industrialized and developing countries. In 1990, RITE was established under this mission, with the aim of realizing innovation through innovative environmental technology development (Fig. 1) to reduce costs and inefficiencies and promote sustainable growth. In the last 30 years and the future, RITE will continue its activities under the mission of R&D and the industrial use of R&D results with the growth of civil society and the economy.

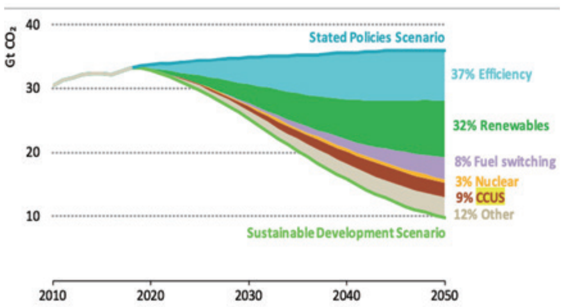


*1.Energy conservation movements in society, increased energy efficiency from equipment, more efficient power plants, improved mileage from automobiles
*2.Solar cells, fuel cells, nuclear energy
*3.CO_2 separation, capture and storage, bioenergy, biodegradable plastics
*4.Forestation and forest preservation, greening of arid land by genetically engineered plants
*5.Space-based solar power generation, nuclear fusion

Fig. 1 : The Role of RITE (Toward Economic Development and Global Environment)

2. Social systems for innovation: A social & commercial study for the implementation of CO_2 capture and storage technology

CCS (Carbon Dioxide Capture & Storage) technology, which separates and captures CO_2 from large-scale sources such as power plants and factories, and stores underground, is a negative emission technology. The planning, construction, and operation of 51 large-scale CCS projects (as of October 2019) are being promoted in the world. Every year approximately 40 million tons of CO_2 are stored. CCS technology has been expected as a "bridge technology" for a decarbonized society. IEA expected that the CO_2 reduction effect of CCS technology would be 9% by 2050 to reduce global temperature rise to less than 2℃ (Fig. 2).



CCUS: Carbon dioxide Capture, Utilization and Storage
Source: World Energy Outlook 2019(IEA)

Fig. 2: Estimated CO_2 reduction by CC(U)S technology

2.1. Commercialization of CCS

On the 5th Strategic Energy Plan (2018) as an important measure against climate change, Japan is steadily promoting R&D for the commercialization of CCS, collaborating with international organizations, and demonstrations. CCS system is a large-scale infrastructure deployed on the national land scale, and consists of (1) separation and capture of CO_2 sources, (2) transport to storage sites, injection and sequestration, and (3) safety and environmental monitoring. Therefore, it is essential for CCS to ensure technical perfection, lower business costs, and social acceptance.

2.2. Risk Reduction for Commercialization

It is essential to reduce various management uncertainties such as risks to safety and the environment, technology and commercial profits. It is also necessary to increase business experience in various aspects, such as private funding, participation of management entities, local acceptance and facility meintenance. In particular, (1) the impact on health, safety and the environment due to CO_2 leakage in separation and fixing, transportation, and storage, (2) responsibility after the abolition of storage wells and their costs, (3) business inheritance if CCS operator withdraws for any reason, (4) When a part of the CCS system stops due to a failure or the like, the impact on the upstream and downstream areas are important (Fig. 3).

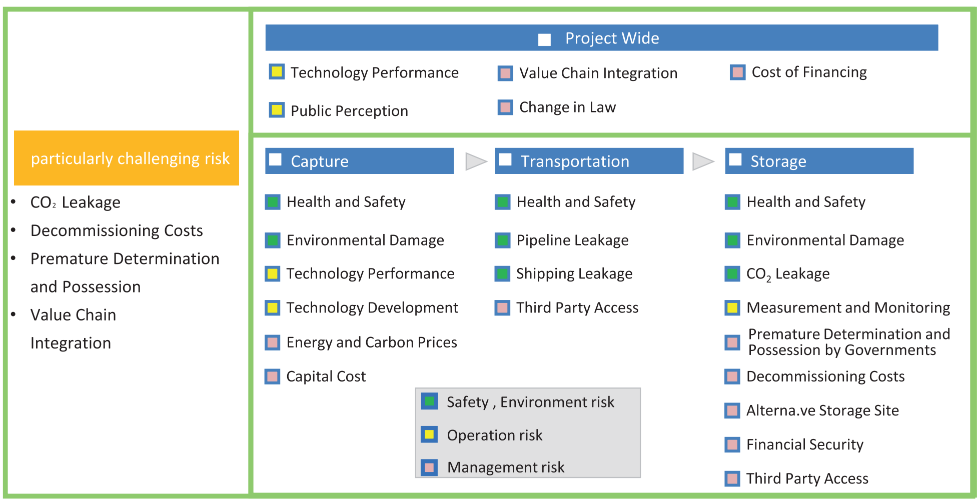


Fig. 3: Major risk categories in CCS prejects

The CCS business risks can be categorized into safety and operation area. If the risks and uncertainties are not negligible compared to the profits obtained from the CCS project, the participation of private enterprises and funds cannot be expected, and therefore, it is necessary to be owned and operated by the government. There is a possibility that the investment funds cannot be recovered and a possibility of having to take very long-term responsibility after the closure of the storage sites. This study suggests that many of these management risks require the development of social frameworks, including institutional aspects.

2.3. Leading projects for faster social implementation

This analysis includes an assumption of the amount of CCS in Japan in 2050. In order to estimate the CCS facility scale and investment amount, coal-fired power generation, which accounts for about half of the CO_2 emissions of the energy sector (540 million tCO_2 / year in 2013), was selected as a potential emission source. For estimation, three scenarios were set for CO_2 sequestration in 2050, high (250 million tCO_2 / year), middle (100 million tCO_2 / year), and low (0.2-0.3 billion tCO_2 / year).

2.4. CCS business models in Japan

In the business model study, CCS was assumed to be installed in existing coal-fired power generation plants. The CCS cost (the total cost of equipment and operation costs) was calculated. Consolication of collection facilities, transportation routes, and storage facilities is not considered, and CCS costs were compared about two cases pipeline and ship transportation.

Since the calculation was based on the CCS cost for each unit, the result was that the equipment configuration of the entire project had many redundant equipment and was inefficient. In the pipeline transportation, the transportation cost was large because the pipeline was set for each unit.

Achieving large CO_2 reduction targets in 2050, including zero emissions is a universal goal. For this purpose, it is effective to carry out easy-to-work projects (“low hanging fruits” projects) in parallel with technological development. This implementation is expected to increase the experience while achieving CCS cost reduction by the learning effects. The analysis concluded that starting from the lower case and aiming for the middle case introduction with 2020-30 as the run-up period is most effective (Fig. 4).

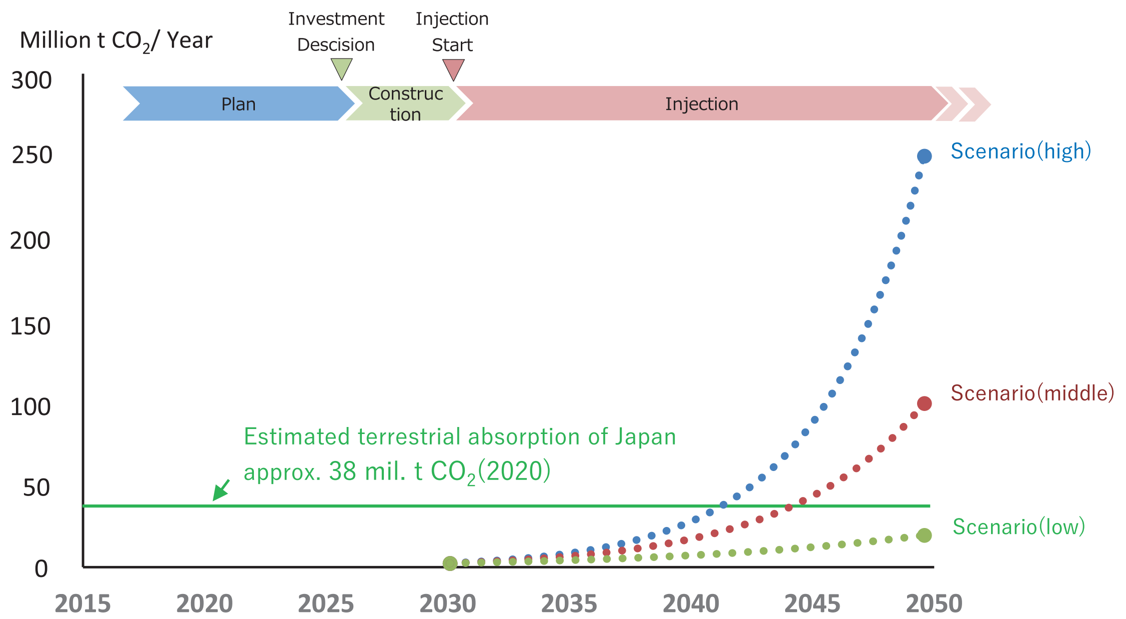


Fig. 4 : CCS Implementation Scenarios toward 2050

3. Promotion of international partnership

3.1. IPCC

IPCC (Intergovernmental Panel on Climate Change) has 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, the United Nations Environment Program (UNEP), and by the World Meteorological Organization (WMO).

IPCC examines scientific knowledge on global warming with three WGs, a global warming prediction (WG1), influence and adaptation (WG2), mitigation measures (WG3).

RITE plays the central role of domestic support secretariat of mitigation measures (WG 3) (Fig. 5). This outcome is to have a high influence on international negotiations because the scientific basis is also given to the policies of each country. IPCC published the special report 'Global Warming of 1.5℃', 'Climate Change and Land', 'The Ocean and Cryosphere in a Changing Climate' from 2018 to 2019. For 2022 'AR6 Synthesis Report' has been steadily prepared in the IPCC global researcher network. The report is expected to be a source of knowledge on climate change, its causes, potential impacts and response options.

3.2. ISO

ISO (International Standard Organization) is an organization composed of 162 standardization bodies of various countries. 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/TC265 (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. 6).

As of the end of 2019, eight standards related to the CCS field have been published from ISO/TC265, and seven are under development. Of the standards under development, two in the CO_2 collection and storage fields are being developed by Japan.

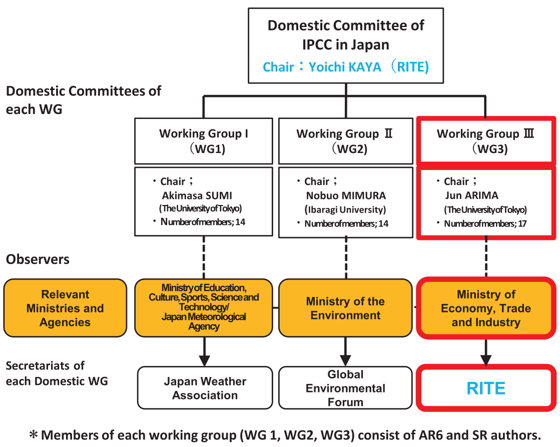


Fig. 5 : Committee Structure and RITE

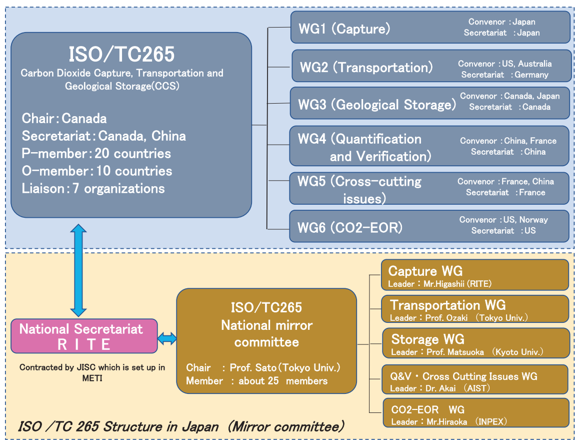


Fig. 6 : ISO/TC265 Structure

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 high and 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. In 2019, we held classes and workshops for a total of 397 students. 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. 7a).

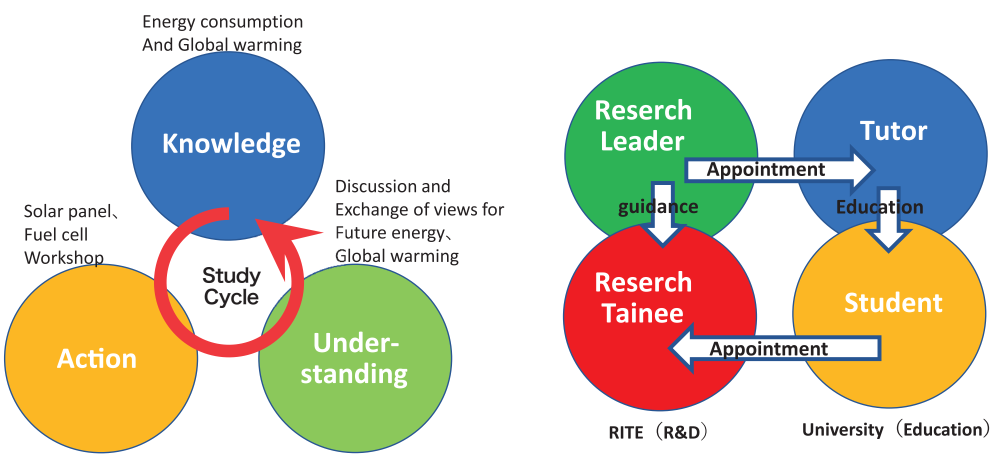
<University / Postgraduate student>

RITE is promoting collaboration of education with universities as part of human development supporting 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. 7b). 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.

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. As of the end of 2019, the patents owned by RITE are 119 domestic rights (12 of which are licensed to companies) and 54 foreign. RITE has established an IP management Committee and operates it with intellectual property experts (Fig. 8).

In order to develop academic research, it is important to create knowledge as a public property of the world by publishing research papers. In addition, we have patented inventions of researchers' creation and granted licenses to challenging enterprises. 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 research and development trends, RITE promotes intellectual property strategically.



(a) Elementary, middle and high school students

(b) University / Post graduate student

Fig. 7 : RITE and Environment Education (Primary, Middle and Higher Education)

5. Conclusion

The concern of the world is gathering up as measures against global warming by innovation. In IPCC 6th Evaluation Cycle (AR 6), where work has already begun, a new chapter called "Innovation, Technology Development, and Transfer" was established. i) Sustainable growth through innovation and achievement of the Paris Agreement, ii) Systems and policies to create innovation, iii) International partnership, iv) Environments to promote change and innovation, v) New destructive technologies, etc. RITE is to deepen the verification of this issue. This means that new perspectives such as compatibility of the wealth and the global environment are added by realizing a new society and life, rather than a accumulation of partial improvement by replacing old technology with new technology. The RITE mission is to conduct research on innovative technologies, as well as to promote international collaboration, address issues necessary for innovation such as human development, intellectual property development, industry collaboration contributing to the achievement of "a balance between the global environment and the economy".

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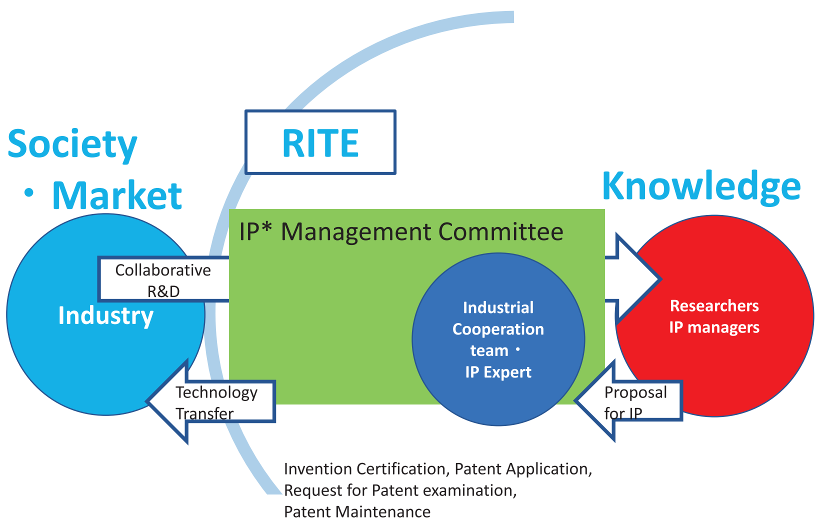

Fig. 8 : Strategic IP management and Industrial collaboration

Systems Analysis Group

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Takahiro Nagata, Associate Chief Researcher
Kenichi Wada, Senior Researcher
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Research Activities in Systems Analysis Group

The Systems Analysis Group aims to provide valuable information about response measures to global warming and energy issues through systemic approaches and analyses. We present here the outcomes of the analyses that our group has been conducting for future scenarios with regard to the countermeasure strategies for decarbonization based on systemic understanding of the current status.

1. Understanding of internal and external status

The Paris Agreement states that the long-term goal is to keep a global temperature rise well below 2℃ above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5℃, and therefore it aims to achieve net zero emission of global greenhouse gas in the second-half of this century. For the 1.5℃ target, the Special Report on Global Warming of 1.5℃ (SR15) of the International Panel on Climate Change (IPCC) indicates that the global CO_2 emissions will be required to be net zero around 2050[1). The IPCC Fifth Assessment Report (AR5)[2) showed a nearly linear relationship between cumulative CO_2 emissions and temperature change. Therefore, in order to stabilize temperature, global net CO_2 emissions are required to be nearly zero after the stabilization regardless of the temperature level. In recent years, the movement toward long-term net zero carbon emissions (decarbonization) is rising. In the Long-term Strategy under the Paris Agreement that the Japanese government formulated in 2019 proclaims a "decarbonized society" as the ultimate goal and aims to accomplish it ambitiously as early as possible in the second half of this century.

Meanwhile, the global temperature continues rising and so the global GHG emissions. Some of developed countries show decreasing trends of CO_2 emissions and electricity consumption despite their GDP growths, indicating the decoupling trend between the growths of the two. However, structurally the global emissions have never decreased, and especially the strong positive correlations have been observed between the world GDP and electricity consumption. Developed countries have been transferring energy intensive industries abroad and shifting to less energy intensive industries such as services. Our group has been working to grasp such trends through estimation of consumption-based CO_2 emissions and their factor analysis[3).

All of the world countries need to seek in cooperation to reduce emissions in light of the nature of the global warming. However, IPCC and other reports show extremely high costs required for the achievement of the 2/1.5℃ targets or nearly zero-emissions. SR15, for example, estimates 45-1050 US$/t$CO_2$ (the median is 130 US$/t$CO_2$) for 2℃ and 245-14300 US$/t$CO_2$ (the median is 2800 US$/t$CO_2$) for below 1.5℃ even in the case of uniform marginal abatement costs across countries[1). These high costs are not considered to be acceptable in the real world given the difficulty in international cooperation and the industry leakage.

In this circumstance, it is innovation that plays an important role as highlighted in the Long-term Strategy under the Paris Agreement. Yet, some desirable progresses are observed; substantial cost reduction of solar power and remarkable development of ICT, enabling low cost storage and processing of huge amounts of data. Such technological progresses and signaling social changes will possibly make new combinations to create technological and social innovations.

Large uncertainties still exist in climate change impacts, international politics etc. Innovations play important roles for sure, but all the technological attempts may not succeed. Conversely, technological innovations may take place unexpectedly. Required is the strategy of comprehensive risk management, aiming at long-term decarbonization.

2. Technological progress toward low/de-carbonization

Final energy needs to be supplied essentially by carbon free electricity or hydrogen for the decarbonization of energy system. Direct heating from solar thermal or bioenergy, and methane generated by methanation of captured carbon dioxide with CO_2-free hydrogen can be partially used. The captured carbon dioxide plays as a hydrogen carrier, and CO_2 emissions are practically reduced by replacing natural gas by carbon free hydrogen. Methanation has an advantage in utilizing the existing natural gas infrastructure. As shown in the IPCC reports [1, 4] and many other studies, the greater CO_2 emissions reduction requires the higher electrification rate.

Obviously decarbonization in electricity and hydrogen production with renewables, nuclear and CCS is necessary.

It is not realistic to eliminate hydrocarbons completely, so a certain amount of emissions can be tolerated even for net zero emissions. Negative emission technologies, such as afforestation, bioenergy plus CCS (BECCS), and direct air capture and storage (DACS) could be technological options and are well worth considering from the aspect of cost-effectiveness and others.

2.1. Renewable energy

Renewable energy has been recognized as one of the most important options in the decarbonization strategy for the prevention of global warming. When final energy is categorized as electricity and non-electricity, electricity can be decarbonized by increasing the portion of non-fossil electricity such as renewable and nuclear power.

Recently, the cost of renewable energy, especially wind power and solar power, has fallen rapidly in Japan and overseas. For example, in the United Arab Emirates, there have been examples of solar power projects at around ¥3/kWh. However, this renewable electricity is variable renewable energy (VRE). The massive introduction of this intermittent electricity needs additional costs for system stabilization, such as backup power supply, batteries, and hydrogen to ensure reliable electricity provision.

2.2. Hydrogen technology / CCUS

Hydrogen technologies also play an essential role in deep decarbonization. Coal/lignite gasification with CCS and water electrolysis by renewable electricity have been expected as the promising CO_2-free hydrogen production method. Figure 1 indicates that ultimately, hydrogen is also often converted into electricity by fuel cells. Hydrogen should be regarded as a complementary instrument in the dominant electrification trend toward decarbonization rather than an alternative to electricity.

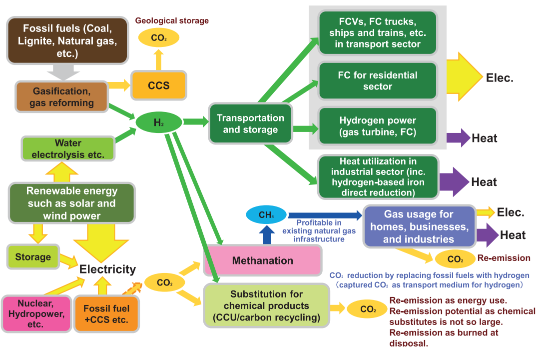

Figure 1 : Electricity and hydrogen system in decarbonization

2.3. Possibility of sharing economy induced by IoT progress

CASE (Connected, Autonomous, Sharing/Service, Electric) has become the major direction in the transportation sector. Therefore, new business models can be created by shifting from owning private cars toward Mobility as Service (MaaS). The occupancy rate of private cars is usually below 5%. Benefiting from the synergistic effect of these technologies, mobility services can be provided efficiently, at low cost, and without greatly impairing convenience. The deployment of fully autonomous vehicles can help to induce car-sharing and ride-sharing, which will increase vehicle utilization, reduce the number of vehicles. In this way, the use of steel and chemical products can be greatly reduced. Even if the initial investment is high, the electric vehicle (EV) can be economically feasible due to the increase in the occupancy rate. Particularly, in the end-use sector, energy is usually consumed more than the products and services that are really needed. Technological and social innovation can be expected through the development and deployment of technologies such as ICT and AI.

However, it should be noted that GHG emissions may also increase due to improved convenience.

3. Assessment by global energy and climate model

3.1. Model description

We make an assessment by using our global energy systems model (DNE21+: Dynamic New Earth 21+). The DNE21+ can make an assessment until 2100, with 54 regions (in which countries with a large area are divided into further small regions, making a total of 77 regions). Technologies not only in energy supply side but also in energy demand side are modeled in a bottom-up way, in which 400 technologies can be assessed. The model has been improved, especially while net zero emissions are required, a wider variety of options than ever before is being modeled in detail. For example, in 2019, as for international marine bunker sector, we modeled related technologies in the DNE21+, in which options of fuel switching to LNG and hydrogen-powered ships were considered. Also, methanation options were incorporated.

3.2. Assumption of Scenario Analysis

Assuming scenarios as shown in Table 1, evaluation of such mitigation targets as consistent with Paris 2°C Agreement and Japan's long-term target of -80% by year 2050 (assumption: -80% for G7 countries) of the global warming mitigation plan was conducted. In terms of the 2°C scenarios, two types of emission routes were analyzed: one was a probability >50% (equivalent to the 2DS of the IEA ETP scenario and the global GHG emissions were approx. -40% in 2050) and the other was a probability >66% (equivalent to the B2DS and the global GHG emissions were approx. -70% in 2050). Furthermore, scenarios which include the trends stated at the above section 2 were developed. Specifically, a case that photovoltaic power cost continues to fall, especially in the Middle East and North Africa, and a large potential supply would be possible at the cost of approx. ¥2-4/kWh in 2050 and the other case that autonomous vehicle implementation after 2030 which increases car-sharing and ride-shaning and decreases demands for steel and chemical products have been also evaluated. For the socioeconomic scenario, 'Middle of the Road' SSP2 of Shared Socioeconomic Pathways (SSPs) was used. The world population is expected to reach 9.2 billion in 2050 and the average growth rate of world GDP between 2000 and 2050 will be 2.4% / yr.

Table 1 : Model analysis scenarios

<table>
<tr><th>Scenario name</th><th>Global emission scenarios</th><th>G7 emission scenarios</th><th>Renewable costs (PV costs)</th><th>Share mobilities acceleration (Fully autonomous cars)</th></tr>
<tr><td>REF_1</td><td colspan="2">Baseline (without specific CO_2 emission constraints)</td><td>Mid. cost reduction</td><td>w.o. consideration</td></tr>
<tr><td>2DS-a_1</td><td rowspan="5">Below 2 °C (>50%): Corresponding to IEA ETP2017 [2DS]</td><td rowspan="2">[a] -80% in 2050</td><td>Mid. cost reduction</td><td rowspan="2">w.o. consideration</td></tr>
<tr><td>2DS-a_2</td><td>Low cost particularly in M-East & N. Africa</td></tr>
<tr><td>2DS-b_1</td><td rowspan="3">[b] Equal MAC among all nations (the least cost)</td><td>Mid. cost reduction</td><td rowspan="2">w.o. consideration</td></tr>
<tr><td>2DS-b_2</td><td rowspan="2">Low cost particularly in M-East & N. Africa</td></tr>
<tr><td>2DS-b_3</td><td>Share mobilities acceleration (Fully autonomous cars)</td></tr>
<tr><td>B2DS-b_1</td><td rowspan="3">Well below 2 °C (>66%): Corresponding to IEA ETP2017 [2DS]</td><td rowspan="3">[b] Equal MAC among all nations (the least cost)</td><td>Mid. cost reduction</td><td rowspan="2">w.o. consideration</td></tr>
<tr><td>B2DS-b_2</td><td rowspan="2">Low cost particularly in M-East & N. Africa</td></tr>
<tr><td>B2DS-b_3</td><td>Share mobilities acceleration (Fully autonomous cars)</td></tr>
</table>

Note: 2DS and B2DS are equivalent to the 2°C scenarios of the IEA ETP2017

3.3. Results of analysis

Table 2 and 3 show marginal abatement costs of CO_2 and reduction costs of CO_2 in 2050 by scenario. Large differences can be seen in global reduction costs even among the two 2℃ targets, i.e. >50% probability (2DS) and >66% probability (B2DS). For example, marginal abatement costs and CO_2 reduction costs in B2DS for b_1 and b_2 cases are estimated to be more than 3 times as large as those of 2DS. When assuming

-80% reduction in Japan in the 2DS scenario, reduction cost will increase significantly. Thus contribution to global reduction is required as well as increased reduction rate within Japan. In the lower renewable costs cases (a_2, b_2), especially in the Middle East, larger reduction of global mitigation costs can be found. In the mobility-sharing case (b_3), marginal abatement costs decrease significantly (in B2DS, 477 \$/tCO_2 for the b_2 case and 295 \$/tCO_2 for the b_3 case), and great benefit of net negative costs are estimated, thanks to the decrease in expense for owing automobiles in contrast to the non-mobility-sharing case, offsetting other costs for CO_2 emissions reduction.

Figure 2 depicts global CO_2 emissions by sector in each scenario. As the emissions reduction target becomes stringent, emission reduction takes place in the power sector (renewables, nuclear, and CCS, etc) first, then in CO_2 storage by afforestation, or diffusion of hybrid vehicle (HV) or plug-in hybrid vehicle (PHV) in the transport sector. Need for more stringent reduction may allow BECCS, CCS in the iron sector, and electric vehicle (EV) or fuel-cell vehicle (FCV) to become cost-efficient. For much more stringent reduction targets such as netzero emission or negative CO_2 emission, FCV trucks in the transport sector or methanation become cost-efficient. Emission reduction in the power sector is especially alleviated around 2050 in the mobility-sharing case (b_3).

Table 2 : CO_2 marginal abatement cost (\$/tCO_2)

	2DS-a_1	2DS-a_2	2DS-b_1	2DS-b_2	2DS-b_3	B2DS-b_1	B2DS-b_2	B2DS-b_3
Japan	552	512	161	157	132	528	477	295
Other nations	153	143						

Table 3 : CO_2 emission reduction cost (billion US\$/yr)

	2DS-a_1	2DS-a_2	2DS-b_1	2DS-b_2	2DS-b_3	B2DS-b_1	B2DS-b_2	B2DS-b_3
Japan	110	82	24	27	Negative	71	60	Negative
World total	2102	1654	1603	1296	Negative	5716	4164	Negative

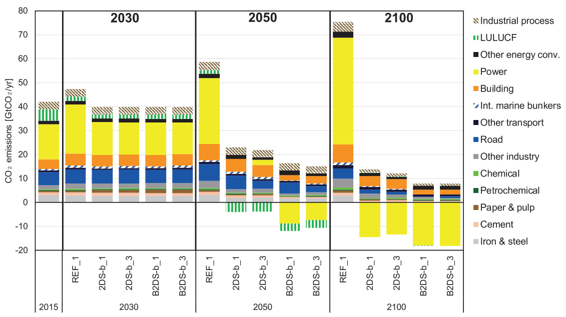

Figure 2 : Global CO_2 emission by sector

Figures 3 to 8 show global primary energy supply, global electricity generation, and final energy consumptions of the industry sector, the residential and commercial sector, the transport sector, and the international marine bunker (included in the transport sector), respectively.

Regarding the primary energy supply, it is estimated that almost all coal powers will be required to be equipped with CCS in 2100 in both 2DS and B2DS, and significant amounts of natural gas powers will be combined with CCS. Yet, a part of fossil fuel powers will remain without CCS, and to offset the emission, utilizing BECCS as a negative emission source will be economically more efficient to attain zero emission or negative emission. Further discussion is necessary to study whether such massive BECCS usage is possible realistically.

Global electricity generation will increase to a large extent. In the 2℃ scenario, cost-efficient measures are the expansion of natural gas toward 2030, and the expansion of renewables and nuclear, and CCS usage after 2050. In 2DS, cogeneration systems will play a more important role toward 2050. BECCS usage will increase in response to the requirement of zero CO_2 emission around 2100 in 2DS and around 2070 in B2DS. Especially in the lower renewable cost cases (a_2, b_2), it is shown that a part of PV power may become economically efficient when utilized for hydrogen production instead of the grid connection. In the mobility-sharing cases, a role of BECCS will decrease especially around 2050. In the lower PV cost scenarios, the share of PV power including for hydrogen production will increase significantly in 2100.

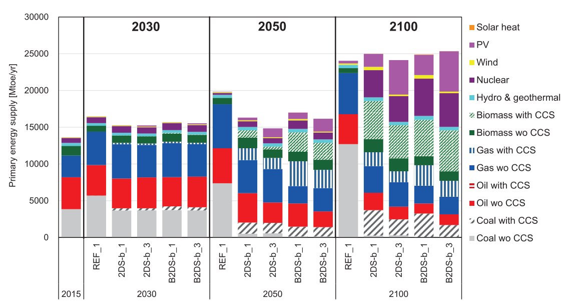

Figure 3 : Global primary energy supply

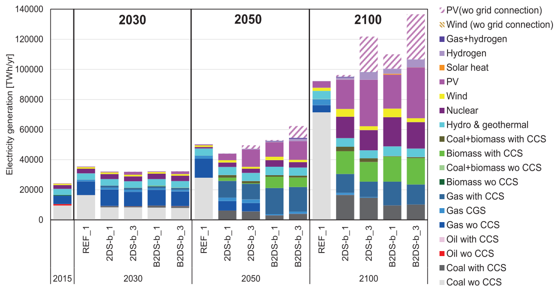

Figure 4 : Global electricity generation

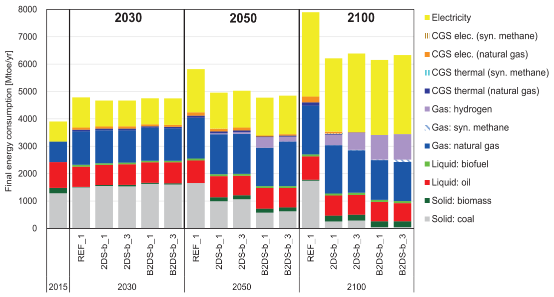

Figure 5 : Global final energy consumption in industry sector

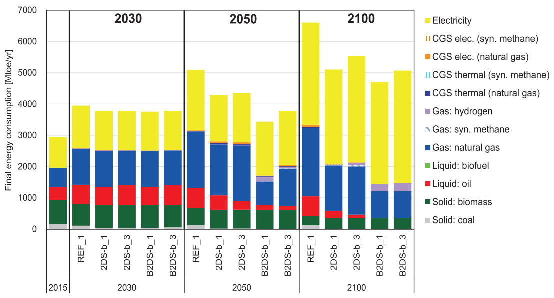

Figure 6 : Global final energy consumption in residential and commercial sector

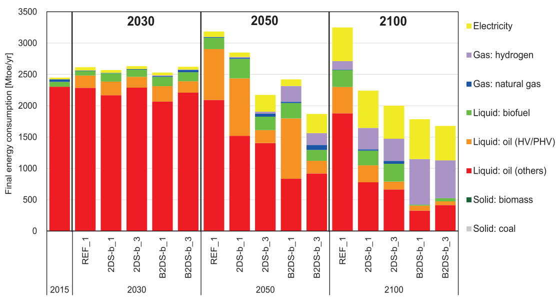

Figure 7 : Global final energy consumption in transport sector

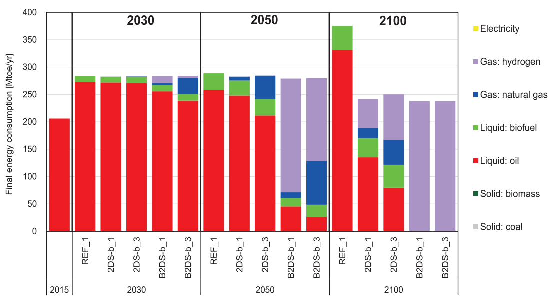

Figure 8 : Final energy consumption in international marine bunker

In the industrial sector, the share of electricity and gas will increase toward 2100. In the 2℃ scenario (2DS), in the latter half of the 21st century, there will be a shift from blast furnace-basic oxygen furnace to hydrogen direct reduction steelmaking in the steel sector. Under the 2DS, gas consumption for cement production will increase after the middle of the 21st century.

In the residential and commercial sector, the use of non-commercial biomass will decline gradually. Also, oil consumption will fall in the 2DS. On the other hand, electricity and gas consumption will increase. Since 2050, the use of hydrogen (and hydrogen methanation in some cases) will be partially seen in the 2DS.

In the 2DS, there will be seen an increase in EV, FCV and biofuel use in the transport sector. In particular, the use of hydrogen, including FC truck, will increase after 2050 in the B2DS. By the year 2100 of the B2DS, biofuel use will decrease. This is because the use of BECCS in the power sector is more cost-efficient and availability of biomass is limited. In the mobility-sharing scenario (b_3), it is shown that the oil consumption in 2050 may be significantly reduced compared to the other scenarios. In addition, the share of FCV and EV will increase due to the rise in operating rates. In the international marine bunker, biofuel and gas will be used around 2050. Hydrogen use would be cost-efficient after 2050 in the B2DS.

Figures 9 and 10 show the global CO_2 capture, utilization, storage balance, and hydrogen balance, respectively. Naturally, the amount of CO_2 captured will increase in the B2DS. In particular, the use of BECCS will increase toward the second half of the 21st century. The recovered CO_2 will be used in methanation and CCU; however, CO_2 storage in the aquifer will be overwhelmingly large.

For hydrogen production, gasification from coal and lignite with CCS will be cost-efficient under the standard cost case of PV. On the other hand, in the low-cost cases of PV (a_2, b_3), PV with water electrolysis will become cost-efficient. Hydrogen is used in a variety of ways, including power generation, hydrogen direct reduction steelmaking, transportation, and some for methanation.

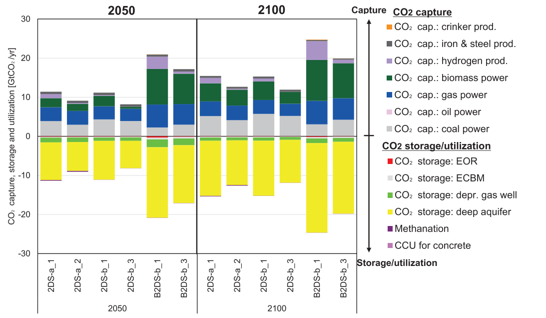

Figure 9 : Global CO_2 capture, utilization and storage

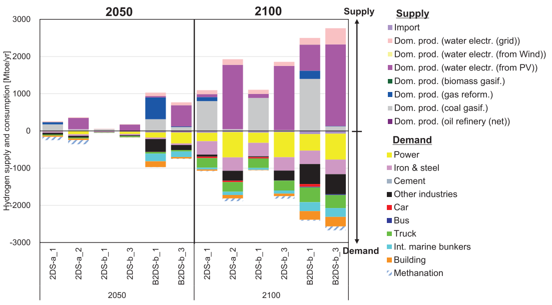

Figure 10 : Global hydrogen supply and consumption

4. Conclusion

The Paris Agreement has the long-term goals of 2℃, net zero emissions in the second-half of this century etc. In order to stabilize temperature, global net CO_2 emissions are required to be nearly zero. However, emission reduction cots are estimated very high for the 2℃ or the net zero emission target under the assumptions of gradual technology improvements, and the targets will be very difficult to achieve under such high emission reduction costs. Therefore, broad innovations will be necessary. The technological innovations using digital technologies etc. in the energy end-use sectors and the induced social innovations are really important.

There are large uncertainties in emission pathways only for the 2℃ target. In addition, international cooperation on climate change mitigation is also uncertain. A better risk management is required. The effectiveness of each technology for decarbonization varies according to the assumed emission reduction scenarios, technology outlook etc. Multiple technological options should be developed for the risk hedge under such large uncertainties.

For deep emission reductions, electrification ratio should increase basically. The decarbonization of electricity generation including hydrogen power will also be important. On the other hand, the cost reductions of hydrogen will be necessary for the large deployment. Recognizing the status of technology costs, it is important to expand its demands at the appropriate timing.

Large amounts of investment are required for the 2℃ target. Better environment for the investments and the policies improving predictability for the return of the investments will be also important.

Reference

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2) IPCC WG1 Fifth Assessment Report (2013)
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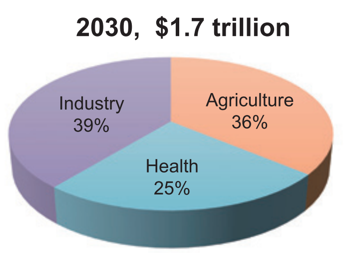
Development of Biorefinery Technology to Realize a Sustainable Society

1. Introduction

Biotechnology has made significant contributions to a wide range of fields. Owing to rapid advances in genome editing technology and synthetic biology, the fields benefiting include not only medicine, health, and agriculture, but also industry. Particularly in the past few years, the concept of "bio-economy," which aims to achieve economic growth while solving problems on a global scale by utilizing biotechnology and renewable biological resources, has been spreading to Asia, mainly in Europe and the United States. According to the Organization for Economic Co-operation and Development (OECD), "the biotechnology market in 2030 will expand to about 190 trillion yen in all member countries and the manufacturing sector will reach about 40%" (Fig. 1). It is said that all industries are bio-based. Under such circumstances, the government announced in June 2019 the Bio Strategy 2019 for the first time in 11 years; the overall goal is "Achieving the world's most advanced bioeconomy society in 2030."

Our group is promoting the development of biorefinery technology, which is the core technology of this bioeconomy, by using microorganisms. Biorefinery technology is used for producing biofuels and green chemicals using renewable resources (biomass) as raw materials. This section first provides an overview of the global situation in biofuel and green chemical production.



Source : The Bioeconomy to 2030. OECD(2009), NEDO

Fig. 1 : Economic contribution of biotechnology

Bio fuels

Bioethanol, a major biofuel, is produced from raw materials that include corn (in the U.S.) and sugarcane (in Brazil), and mixed with 10%–25% gasoline for use in automobile engines. The highest production and consumption of bioethanol is in the U.S., where corn is a major crop, with 15.9 billion gallons (60.1 million kL) of bioethanol produced in 2018, according to estimates provided by the U.S. Energy Information Administration. According to the report Agricultural Outlook 2018–2027, by OECD–FAO, 122 million kL of bioethanol were produced worldwide in 2018, with the U.S. accounting for approximately half of this production.

Cellulose ethanol, a second-generation biofuel whose raw material does not compete with food resources, is produced from agricultural wastes such as corn stover. The EPA (U.S.Environmental Protection Agency) target for the production of cellulosic biofuel in 2020 is 540 million gallons (2.0 million kL), based on RFS (Renewable Fuel Standard) rules. This is just over 5% of the RFS target set in 2007, and acceleration of commercialization is required in the future. RITE is developing a bioprocess that can efficiently utilize cellulosic biomass (see Chapter 2).

Regarding aviation fuel, the ICAO (International Civil Aviation Organization) decided at the 2010 General Assembly not to increase total greenhouse gas emissions after 2020. At the 2016 General Assembly, it was decided to introduce a greenhouse gas reduction system utilizing market mechanisms (GMBM: Global Market-Based Measures) after 2020. Based on this, the International Air Transport Association (IATA) has formulated a concrete action plan, including the use of biojet fuel and the use of emissions trading (Fig. 2). The GMBM is expected to launch in 2021. Along with these, biojet fuel has been widely spread mainly in Europe and the United States every year, and commercial flight has been continued as a sustainable aviation fuel (SAF) using cooking waste oil and the like. RITE also started technical cooperation for a private biojet fuel production project using biobutanol in 2018 (see topics).

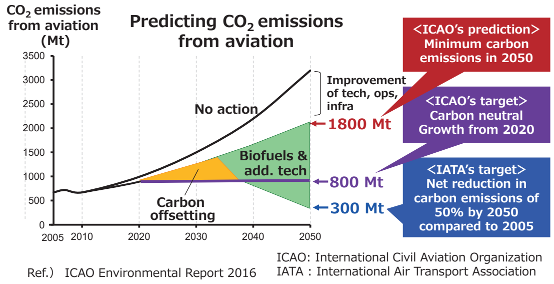


Fig.2 : Emissions reduction roadmap

For marine fuels, in 2018, the IMO (International Maritime Organization) adopted a greenhouse gas reduction strategy to reduce carbon emissions by more than 40% by 2030 compared to 2008 by 2008. Among them, as effective countermeasures, the introduction of alternative fuels has been mentioned in addition to the strengthening of fuel efficiency regulations already introduced and the improvement of operation efficiency (deceleration operation, route optimization, etc.). These are all candidates, and actual measures to be taken will be matters for further study and negotiations, and will be adopted as a reduction strategy (revised version) in 2023.

Green chemicals

In the past few years, the problem of environmental destruction owing to plastic bottles and disposable plastics has been highlighted as an international problem. In particular, microplastic pollution in the ocean is serious. The ban on waste plastic imports by China and Southeast Asian countries has had a significant impact on plastic recycling in Japan. Against this background, there are great expectations from bioplastics and biodegradable plastics made from biomass, which is a renewable resource. "Bio-Plastic (substitute for general-purpose plastics)" is one of the nine market areas in the "Bio-Strategy 2019," and the budget request for fiscal 2020 includes the "Plastic Effective Use Advanced Business" (business commissioned by the New Energy and Industrial Technology Development Organization [NEDO]).

2. Features of the RITE Bioprocess

Our group has established an innovative bioprocess "RITE bioprocess (growth-independent bioprocess)" based on a new technology concept. It has achieved great results in the development of technologies for producing green chemicals, such as biofuels, amino acids, and aromatic compounds exhibiting high efficiency; further, it has received high praise both in

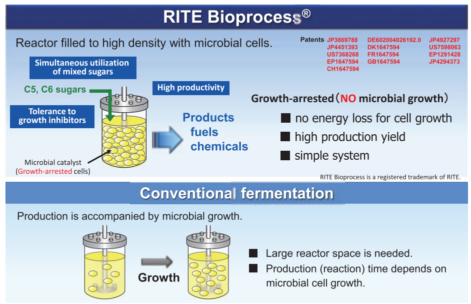


Fig. 3 : Features of the RITE Bioprocess

Japan and overseas.

This process involves cultivating a large amount of coryneform bacteria (smart cells), which are designed metabolically to efficiently produce the target substance; filling a reaction tank with high density of these cells; and, then, creating anaerobic conditions. Alternatively, the reaction is performed in a state where cell division is stopped by removing the factors essential for proliferation (Fig. 3). The key to high efficiency is to produce compounds in a state in which the growth of microorganisms is suppressed, and there is no need for nutrients or energy to achieve growth. As a result, microbial cells can be used as catalysts in the chemical process, and a bioprocess with high productivity, equal to or higher than that of a normal chemical process, can be realized. In addition, by improving the metabolic system of coryneform bacteria, C6 saccharides and C5 saccharides were completely used at the same time, enabling efficient use of cellulosic biomass. In addition, the process is highly resistant to fermentation inhibitors, such as furans, present in mixed sugars from the hydrolysis of cellulosic biomass (see RITE Today 2013-2017).

Currently, in addition to high-efficiency production of ethanol, L-lactic acid, D-lactic acid, amino acids, and so on, we are expanding our business to produce high-performance chemicals, such as butanol, jet fuel materials, and aromatic compounds (Fig. 4). In the following sections, we describe the recent progress made in our research into the production of biofuels and

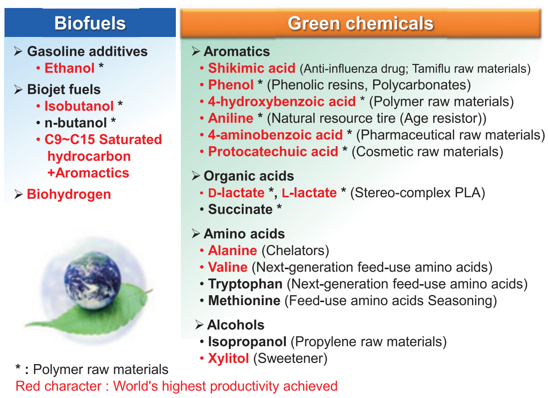


Fig. 4 : Examples of substances produced by RITE's biorefinery technology

green chemicals.

3. Biofuel production research and development

3.1. Biobutanol

Butanol is more suitable as a gasoline additive than ethanol owing to its physicochemical properties, including higher energy content, lower vapor pressure, and lower water solubility. It can also be used as the base material for the production of biojet fuel using conventional chemical reactions. Biojet fuel synthesized from biobutanol can be used in airplanes. Airlines and aircraft manufacturers have paid great attention to biojet fuel, whose importance has been recognized as being critical for reductions in CO_2 emissions by using plant-based materials as feedstock instead of petroleum. Biojet fuel synthesized from butanol is often referred to as "alcohol-to-jet" (ATJ) fuel. ATJ fuel has been approved by the American Society for Testing and Materials (ASTM) and is ready for use in commercial aircraft (http://www.gevo.com/).

We have developed a genetically engineered *C. glutamicum* that leads to highly efficient production of butanol. Further, we have been running a research project since 2015 to investigate cellulosic butanol production (see Topics in RITE Today, 2016); the project is funded by the Ministry of Economy, Trade and Industry (METI). The advantages of our production process include: (i) cellulosic biomass-derived mixed sugars can be used as feedstock, and (ii) production is fast and gives a high yield (Fig. 5).

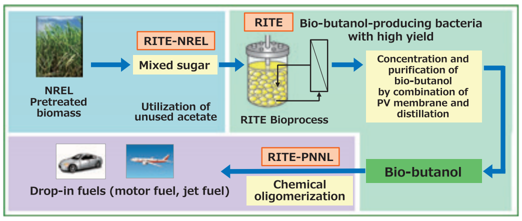


Fig. 5 : Production of biobutanol and biojet fuel by the RITE Bioprocess

Since butanol is highly toxic, we have developed a genetically engineered *Corynebacterium* strain that has high tolerance against its toxicity. The strain exhibited very high productivity in the RITE Bioprocess. We accelerated the research and development of biobutanol production from non-edible biomass by collaborating with the U.S. National Renewable Energy Laboratory (NREL).

We have also been collaborating with the U.S. Pacific Northwest National Laboratories (PNNL) since 2017 by researching and developing the production of jet fuels by chemical oligomerization of biobutanol. This was based on a new idea that if acetic acid is included in mixed sugars from pre-treated biomass, it can be converted to ethanol by engineered *C. glutamicum* through the introduction of new genes. Therefore, the mixtures are utilized for bioproduction of butanol and ethanol, which can then be subjected to chemical oligomerization for jet fuels.

The distillation of biobutanol solution requires a large amount of energy. To reduce the amount of energy needed, we developed an energy-saving biobutanol-recovery process using a combination of distillation and pervaporation (PV); this resulted in energy savings up to 90% and achievement of the highest biobutanol productivity in the world.

In the future, we aim to use the results of this project to commercialize biobutanol by combining these elemental technologies and various types of know-how.

3.2. Green jet fuel

Petroleum-based jet fuels are mixtures of hydrocarbons that consist of n-paraffins, isoparaffins, cycloparaffins, and aromatic compounds with 9–15 carbon atoms. Jet fuel must meet strict standards with regard to its physical properties, such as a specified freezing point and density.

Isoparaffins have lower densities than cycloparaffins and aromatics, and, thus, the density of petroleum-based jet fuels varies according to the proportion of each type of hydrocarbon in a particular production area. Biojet fuels that have already been certified by ASTM are permitted for use when blended with petroleum-based jet fuels in a proportion of up to 50%. However, they mainly consist of isoparaffins having lower densities than petroleum-based jet fuels. If these biojet fuels were blended in a 50/50 mix with low-density jet fuels derived from crude oil from Africa or the Middle East, the resulting fuel would not be permissible as jet fuel because its density would not meet the jet-fuel standard. To avoid such nonconformity, the presence of cycloparaffins and aromatics is required in biojet fuels.

Thus, we are developing a novel green jet fuel that meets ASTM density standards on its own. Our new green jet fuel can be blended with any jet fuel up to the prescribed limit. Our strategy is to produce various kinds of branched and cyclic precursor compounds from non-food biomass using an energy-saving bioprocess, and then convert them to isoparaffins, cycloparaffins, and aromatics using a simple chemical reaction. A high volume of production of these precursor compounds by fermentation is usually extremely difficult owing to their hydrophobicity and toxicity to microorganisms. Thus, we are currently developing a novel versatile bioprocess—funded by METI since 2017—to enable a high volume of production of such toxic compounds with the simultaneous fermentation and detoxification technique (Fig. 6).

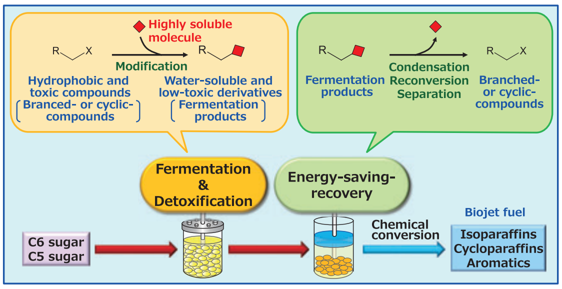


Fig. 6 : Production of a novel green jet fuel by a novel versatile bioprocess

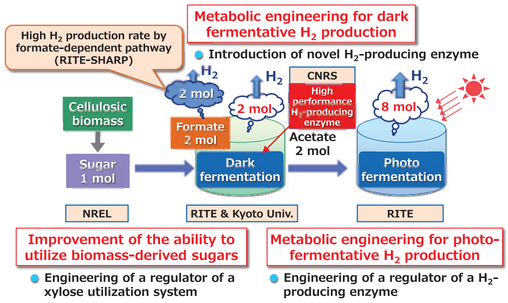


Fig.7 : Research and development to investigate highly efficient biohydrogen production from cellulosic biomass

3.3. Biohydrogen

Hydrogen, whose combustion generates only water, is considered the ultimate clean energy source. However, CO_2 emissions during the hydrogen production processes currently in use is a problematic issue; this is because fossil resources are used as the feedstock. The Basic Hydrogen Strategy drawn up at a meeting of the Ministerial Council on Renewable Energy, Hydrogen and Related Issues in 2017 states the importance of development of innovative CO_2-free hydrogen production technologies to realize a hydrogen society over the medium to long term; the aim is to do so by 2050, based on the goals set to develop commercial-scale hydrogen supply chains by 2030 or so.

Although bioprocesses have significant potential for CO_2-free hydrogen production, innovative improvements in technology are necessary to establish a cost-effective biohydrogen production process. In collaboration with the Sharp Corporation, our group has developed a biohydrogen production process. The hydrogen production rate of our process has achieved is two orders of magnitude higher than that of conventional fermentation processes. Based on this achievement, our group is now conducting an international collaborative research project that is supported by METI. The purpose of this project is to bring about major improvements in hydrogen yield by integrating dark fermentative and photo-fermentative hydrogen production processes. The latter process harnesses light energy, whereas the former does not (Fig. 7).

For this project, we are collaborating with Kyoto University, Japan, and the Center National de la Recherche Scientifique (CNRS) in France to advance metabolic engineering for dark fermentation; we achieved a high expression of a novel hydrogen-producing enzyme with an efficient reaction mechanism. Further, we engineered a regulator of a hydrogen-producing enzyme in a photosynthetic bacterium for photo-fermentation, and achieved constitutive high production of hydrogen; this result is highly favorable for industrial applications. Furthermore, we are collaborating with NREL to examine an improvement in the utilization of mixed sugars derived from cellulosic biomass (corn stover); we confirmed that engineering the regulator of a xylose utilization system is effective.

4. Development of technologies for the production of green chemicals

4.1. NEDO Smart Cell project

NEDO launched a project “Development of Production Techniques for Highly Functional Biomaterials Using Smart Cells of Plants and Other Organisms” (Smart Cell Project) in 2016. The concept “Smart cell” is defined as a finely designed and expression-controlled cell. Members of the project develop technologies to design the Smart Cell, and validate these Smart Cell design systems.

Our group has participated in this project since its inception. Our target is an aromatic compound, which has not been produced in high concentration by fermentation until now even though it has high value in industrial fields. It is presumed that the reasons are high toxicity of the target compound to microorganisms and high complexity of the metabolic pathways from glucose to the target. To solve these problems, we applied the Smart Cell design systems for creating a *C. glutamicum* overproducer strain of the target.

Our group contributed to the improvement of the Smart Cell design system by providing a large amount of experiment data. We also achieved a level of productivity that exceeded one of our final goals (Fig. 8). We are continuing the development of hyperproducers assisted by the Smart Cell design systems.

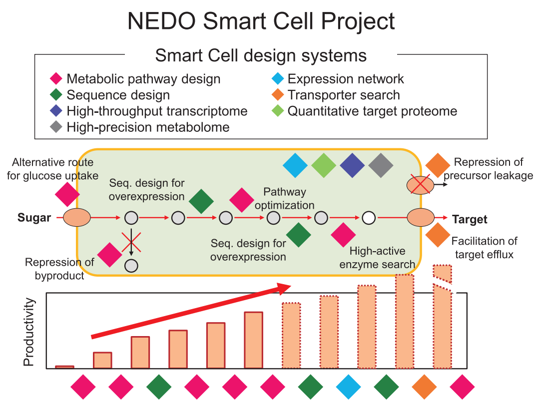


Fig.8 : Application of the Smart Cell design systems for improving productivity

4.2. SIP second period

The cross-ministerial Strategic Innovation promotion Program (SIP) promotes research and development in a seamless manner from the basic research stage to the final outcome by endeavoring to strengthen cooperation among industry, academia, and government in a way that goes beyond the existing framework of government ministries and traditional disciplines. The SIP has been promoting 11 themes since 2014 and 12 new themes since 2018 that address the most important social problems facing Japan. The theme "Technologies for smart bio-industry and agriculture" aims to realize a sustainable growing society that uses manufacturing technologies developed by integrating biotechnology and digital resources. RITE participated in the "Development of technologies for functional design and production of innovative biomaterials," one of the consortia focusing on this theme. This consortium consists of two groups: (i) the polymer group for designing polymers with marketable properties and predicting the function of polymers consisting of particular monomers, and (ii) the monomer group for designing biosynthetic pathway and enzymes for the monomers required for polymer synthesis. As a leader of the monomer group, RITE is evaluating enzyme candidates and enzyme modifications that it is predicted will be required for the synthesis of target monomers by the bioinformatics teams in the group. We have evaluated the prediction technologies using an enzyme for a diol synthesis as a target in 2019, and will improve the accuracy of the technologies by evaluating more enzymes.

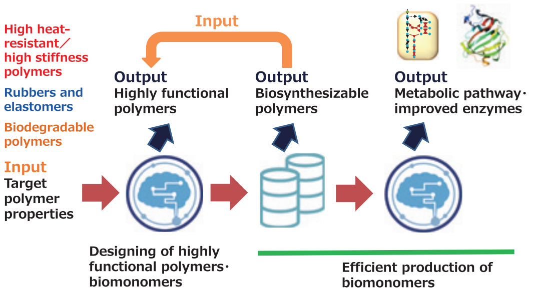


Fig.9 : Integrated designing and production technology system for biomaterials

4.3. Expanding production technologies for various aromatic chemicals

Aromatic compounds are important industrial chemicals used for polymer synthesis, and a diverse group of value-added chemicals that find applications in the pharmaceutical, nutraceutical, flavor, cosmetics, and food industries. While they are currently derived from petroleum or natural plant resources, their environmental friendly biotechnological production from renewable feedstocks is desirable from the viewpoint of creating 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, tryptophan), folate (vitamin B9), and coenzyme Q. All these compounds are derived from the shikimate pathway (Fig. 10). By employing the metabolically engineered *C. glutamicum*, we have successfully established a highly efficient bioprocess to produce the following aromatic compounds from non-food ligno-cellulosic feedstock: shikimate, a key building block of the anti-influenza drug Tamiflu; 4-aminobenzoate, which is used as a building block of a potentially useful functional polymer; and aromatic hydroxy acids, which have potential applications in the polymer, pharmaceutical, cosmetics, and food industries. Currently, we are seeking to develop new strains by introducing genes derived from versatile biological resources for the production of useful aromatic compounds that the wild-type *C. glutamicum* is unable to produce. The techniques developed in the Smart Cell Project, as described above, will help to accelerate strain development and improve strain productivity.

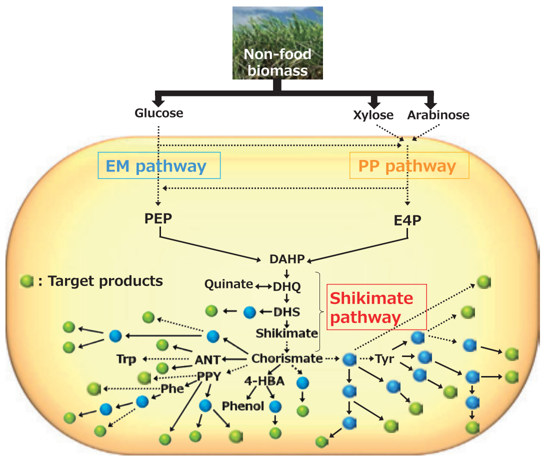


Fig.10 : Biosynthetic pathway for various aromatic compounds

5. Toward the industrialization of our technologies

5.1. Phenol/Aromatic compounds

Currently, commercial phenol can only be derived from petroleum. We have taken on the challenge—considered to be difficult—to develop the world's first manufacturing bioprocess for biomass-derived phenol; this aim is to aid global environmental conservation and greenhouse gas reduction.

In May 2014, Sumitomo Bakelite Co., Ltd. and RITE established Green Phenol Development Co., Ltd. (GPD) to accelerate the industrialization of our biomass-derived phenol-producing technology called the "Two-Stage Bioprocess". In April 2018, GPD changed its name to Green Chemicals Co., Ltd. (GCC).

At the ENEX2019 held at Tokyo from January 30 to February 1, 2019, three members from GCC and Sumitomo Bakelite Co., Ltd. attended an awards ceremony and gave lectures that were supported by NEDO (Fig. 11). The ceremony was held to recognize projects realizing outstanding achievements under NEDO's strategic innovation program for energy conservation technologies.

Because GCC's phenol-producing technology and knowledge are applicable to the production of various other aromatic compounds, the establishment of a bioprocess for each higher value-added chemical and the commercialization of products that meet customers' needs are in progress.

Fig.11 : Awards ceremony by NEDO

5.2. Amino acids

Normally, amino acid fermentation is carried out under aerobic conditions. Attaining high productivity requires aeration and agitation to be properly controlled; however, this is often difficult to achieve in large-scale fermenters because the oxygen concentration inside them is not homogeneous. To overcome this problem, we have developed a new, genetically modified *Corynebacterium* strain for amino acid production in the RITE Bioprocess that allows the production of amino acids to be carried out under anaerobic conditions. The technological hurdle for amino acid production under anaerobic conditions is to balance the redox reaction without oxygen as an electron acceptor. To this end, we introduced an artificial pathway for amino acid biosynthesis in microbial cells. Our group solved this technological hurdle and published its research accomplishments in an international journal in 2010 (Appl. Microbiol. Biotechnol. 87: 159–165) .

The Green Earth Institute Co., Ltd. (GEI) was established in 2011 for the industrialization of RITE Bioprocess. In 2011, RITE and GEI began collaborative research on amino acid production using the RITE Bioprocess, and developed technologies for: scaling up, growth of efficient production strains, and cost reduction. Our first target was to produce an amino acid, L-alanine, normally synthesized from a petrochemical product; however, our goal was to produce this amino acid from renewable resources, thereby reducing the life cycle carbon footprint. In 2016, we succeeded in demonstrating the feasibility of this production technique by using the commercial-scale facilities of our partner company, which was an important milestone for 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. As the result of an evaluation by the Food Safety Committee in August 2017, the safety of L-alanine, produced by our strain, for use as a food additive was confirmed; further, it was made commercially available as a food additive, besides its use for industrial applications. The L-alanine business is currently working on commercial production with both a domestic and foreign partner company. In addition, RITE succeeded in producing a strain with the world's highest production concentration and production efficiency of L-valine. Further, it has completed commercialization projects with GEI and overseas partners to achieve commercial production. We are now working on a joint research project for the production of other amino acids.

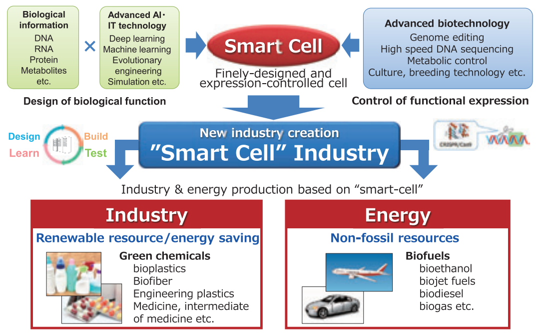
6. Closing remarks

Currently, more than 50 countries and regions around the world are developing bioeconomic strategies. Japan also set the goal of realizing a bio-economy society in its "Bio Strategy 2019." Three of the nine market areas in this strategy are related to our technology area; these are "high-performance biomaterials," "bioproduction systems," and the aforementioned "bioplastics." They are likely to be included in the government's list of items requiring priority development in the future.

In the area of biofuels, the government has set a goal of introducing 500,000 kL of bioethanol annually for five years, starting from 2018; however, it relies heavily on imports (mainly corn) that affect its raw material costs. It seeks to realize mass production, even as it meets the challenges of food competition and cost reduction by using waste non-edible biomass as a raw material.

In the field of biochemicals, several projects based on the fusion of information technology (digital), such as IoT and AI, and biotechnology, which have seen remarkable developments in recent years, are being led by the government, and RITE is also participating in them (see Chapter 4). In these projects, the biorefinery technology based on the smart cell described above is expected to play a major role as a core technology, and to have a large ripple effect on the industrial field (manufacturing), in addition to energy (Fig. 12).

In 2020, we will continue to develop innovative biorefinery production technologies centered on the cutting-edge biotechnology "Smart Cell" and contribute to the construction of a low-carbon society that is sustainable.



Source: International trends for realization of Bioeconomy & efforts being by Japan (METI) 25 Sept. 2018

Fig.12 : Fusion of industrial/energy fields changed by bio & digital

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Challenges Associated with the Advanced Industrialization of CO_2 Capture Technologies

1. Technologies for CO_2 capture

CO_2 capture and storage (CCS) involves the trapping of CO_2 (a greenhouse gas) from the emissions generated during fossil fuel combustion from such sources as electric power plants and factories and includes the subsequent sequestration of the captured CO_2 in geological formations. At present, the costs associated with capturing CO_2 from emission sources account for approximately 60% of the total CCS expenditures. Therefore, it is important to reduce the capture costs to allow for the practical application of CCS.

The Chemical Research Group studies 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 the 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 one such chemical absorbent with particular promise was selected for application in a commercial CO_2 capture plant owned by a private Japanese company; the second commercial plant started operations in July 2018.

On solid sorbent technology, we have also been developing sorbents for CO_2 capture to efficiently reduce energy consumption. Currently, the low-temperature regenerable solid sorbent that we developed is being evaluated for practical use. In lab-scale cyclic tests, our novel solid sorbent is capable of achieving 1.5 GJ/t-CO_2 in regeneration energy. In addition, we established a large-scale synthesis technology that can produce the solid sorbent at a scale of 10 m^3. Research on practical application is now underway in collaboration with a private company. In the near future, we will install a test facility to capture 40 t-CO_2/day at a coal power plant for practical application.

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 and membrane elements using a novel dendrimer/polymer hybrid membrane called the molecular gate membrane 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 membrane 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 are evaluating the separation performance and process compatibility of our membranes and membrane elements using coal gasification gas at the test sites in Japan and overseas in order to identify and then solve the technical problems of membranes and membrane elements. In addition, RITE joins the International Test Center Network (ITCN) and actively uses overseas networks towards the commercialization of CO_2 separation and recovery technology.

2. Chemical absorption method for CO_2 capture

CO_2 capture by chemical absorption is a prospective technology for the separation of CO_2 from gas mixtures. This technique consists of the thermal desorption of CO_2 following chemical absorption using an amine-based solvent. Since the cost-saving CO_2 Capture System (COCS) project (funded by the Ministry of Economy, Trade and Industry [METI]) started in 2004, RITE has been developing high-performance solvents for CO_2 capture mainly from blast furnace effluent gas in the steel industry to reduce separation energy and capture costs. The COURSE 50 project, which started in 2008, aims to reduce CO_2 emissions by 30% in the steel industry, where it is expected that CO_2 emissions can be reduced by 20% using the capture technology. Fig. 1 shows the flow of the development of chemical absorbers in RITE.

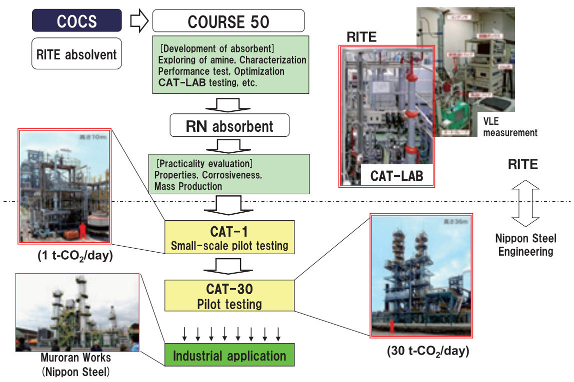

Fig. 1: Development of chemical absorbers in RITE

In the Phase I Step 1 of COURSE 50 (FY 2008–2012), RITE achieved the target CO_2 capture energy consumption value of 2.0 GJ/t-CO_2. In addition, significant new absorbents were developed for CO_2 desorption at less than 100℃. Beginning in FY 2013, Phase I Step 2 was initiated and ran until FY 2017. During this work, RITE and Nippon Steel Corporation continued to develop new absorbents that had the potential to deliver high performance, and we clarified the mechanism of performance development and related factors of a high-performance solvent. The latest R&D phase (Phase II Step 1) started in 2018. Based on previous milestones, we are exploring new non-aqueous solvents and developing methods for pelletizing absorption-promoting catalysts to achieve the target of 1.6 GJ/t-CO_2 (Fig. 2).

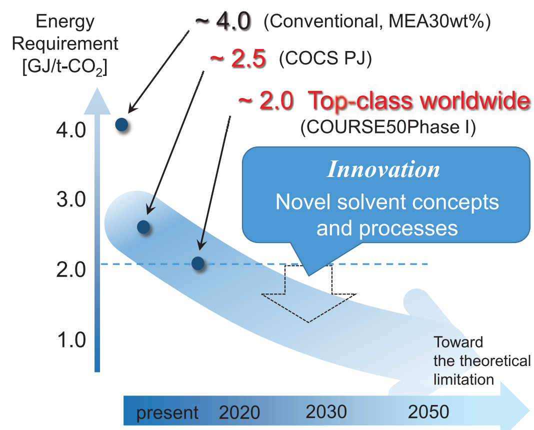

Fig. 2 : Challenge for higher performance solvents

Regarding practical technology development, one of the outstanding new absorbents was adopted for use in the commercial CCS plants (ESCAP) constructed by Nippon Steel Engineering Co., Ltd. The first such CCS plant began operating in 2014, and the second CCS plant began operating in 2018 (Fig. 3). The research results of RITE are contributing to the practical application of CO_2 capture in the industry.

#1@Muroran, Nippon Steel Cooperation	#2@Niihama, Sumitomo Joint Electric Powe
120 tons/day	143 tons/day
Hot stove	Coal fired power station
Industrial use	Production of feed additives

Fig. 3: Industrial application of COURSE 50 CO_2 capture technology

3. Solid sorbent method for CO_2 capture

RITE developed solid sorbents during a project aimed at the advancement of CO_2 capture technologies funded by METI from 2010 to 2014. Solid sorbents are composed of amine absorbents for chemical absorption and porous materials (Fig. 4). They have similar CO_2 adsorption characteristics with liquid amine absorbents. Furthermore, they make it possible to significantly reduce the energy consumed as sensible heat and evaporative latent heat during regeneration.

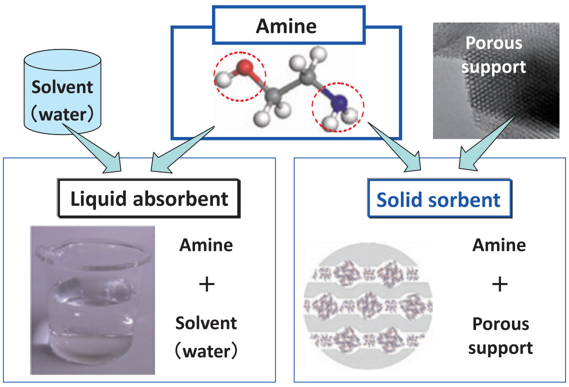

Fig. 4 : Amine solid sorbent

Novel amines synthesized by RITE have been employed for the developed solid sorbents. We had introduced a functional group of specific configuration to a commercially available amine compound, and then RITE successfully fabricated innovative high-performance solid sorbents capable of low-temperature regeneration with high adsorption capacities (Fig. 5). We obtained U.S. and Japanese patents for these solid sorbents.

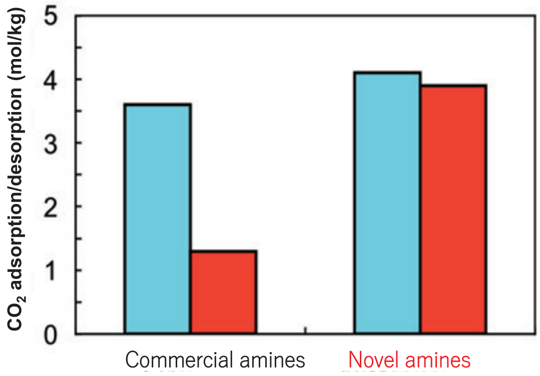

Fig. 5 : Improvement of solid sorbent performance by newly synthesized amine

The result of the process simulation based on the performance of the developed solid sorbents showed the potential of 1.5 GJ/t-CO_2 for separation and capture energy. When this CO_2 capture technology is applied to coal-fired power generation, the reduction in the power generation efficiency is expected to improve by about 2% compared to conventional chemical absorption technology (2.5 GJ/t-CO_2).

Under a project aimed at the advancement of CO_2 capture technologies (R&D of Advanced Solid Sorbents for Commercialization) funded by METI since FY 2015 (since FY 2018, transferred to NEDO), we are optimizing materials for practical use, optimizing and promoting the efficiency of solid solvent processes, and constructing simulation technology for the system, as well as working with Kawasaki Heavy Industries (KHI), Ltd., to develop a moving-bed bench-scale system for coal combustion exhaust gas.

So far, we have selected solid support with properties suitable to the moving-bed system. In addition, we have developed and optimized a method of synthesis for materials on a larger scale. As a result, we have almost established a mass method of synthesis with a view to scale-up (100 m^3 scale) the process.

The solid sorbents prepared by the established method (> 10 m^3) were evaluated by using a lab-scale fixed-bed test apparatus (Fig. 6). These tests were conducted by using the steam-aided vacuum swing adsorption (SA-VSA) process in which steam was supplied in a desorption process. The optimized operation process has shown that RITE solid sorbents are able to capture high-purity (> 99%) CO_2 from simulated flue gas (12% CO_2) at high yields (> 90%) under 60℃. In this case, energy consumption for regeneration steam at 60℃ was extremely low (1.1 GJ/t-CO_2), demonstrating that RITE solid sorbents had superior performance for CO_2 capture. In addition, as part of the process of optimization using a fixed-bed system, we have designed and constructed small bench scale test equipment of 0.1 t-CO_2/day and are currently studying scale-up issues.

Fig. 6 : Lab-scale fixed-bed apparatus for CO_2 capture test

Currently, the bench-scale combustion exhaust gas test is underway with the moving-bed system installed at KHI using RITE solid sorbents prepared by the established method. Thus far, we have achieved up to 7.2 t-CO_2/day as the scale of CO_2 capture

Coal flue gas contains about 5% O_2, and thus generally causes the problem of amine oxidative deterioration. Since the solid absorbent system developed in this project is a low-temperature regeneration process at about 60℃, it is expected to be advantageous in terms of oxidation resistance. Verification by lab-accelerated tests at approximately 100℃ with 20% O_2 confirmed that the newly synthesized amines developed in this project were significantly less degraded by oxidation than commercially available amines (Fig. 7). In addition, as a result of conducting an actual gas exposure test at a coal-fired power plant, we found suitable conditions under which the performance of this solid sorbent hardly deteriorated.

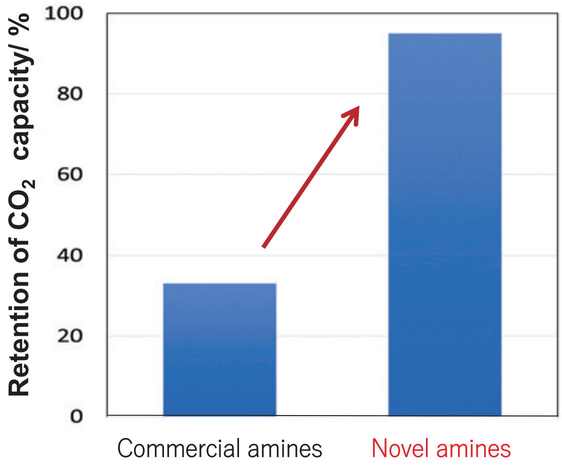

Fig. 7 : Oxidation degradation resistance of solid absorbent at 100 ℃ (O_2 (20%) / N_2 (80%) / H_2O (RH50%))

We plan to build a pilot-scale plant of 40 t-CO_2/day in a coal-fired power station, and a practical exhaust gas test will be carried out (announced in September 2017). We are working on an R&D roadmap to establish a solid sorbent system with much higher performance in the capture of CO_2 from coal fired power (Fig. 8).

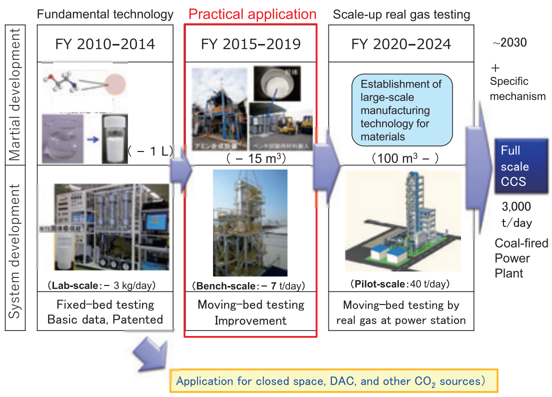

Fig. 8 : Project roadmap

The application of solid sorbents to lower-concentration CO_2 emission sources, including the removal of CO_2 in closed spaces indoors and spacecraft along with direct air capture (DAC) are being studied. We are also working with lower-concentration sources. We will continue to develop the solid sorbent system for further reduction of CO_2 separation energy and apply it to a variety of different emission sources with the modification according to each source and then promote practical use.

4. Membrane separation

CO_2 separation by membranes is conducted by selective permeation of CO_2 from the pressure difference between the feed side and the permeate side of the membrane. So, CO_2 capture with low cost and energy is expected by applying membrane processes to pre-combustion (Fig. 9). For this reason, we are currently developing novel CO_2 selective membrane modules that effectively separate CO_2 during the IGCC process.

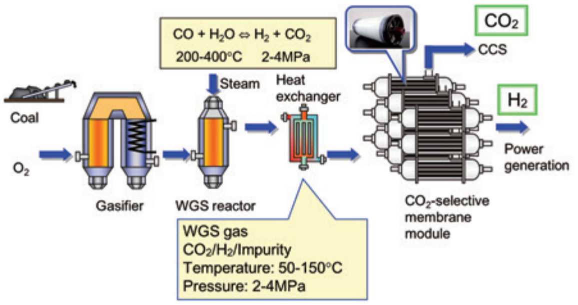

Fig. 9 : Schematic of the IGCC process with CO_2 capture by CO_2 selective membrane modules.

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. 10 presents a schematic that summarizes the working principles of a molecular gate membrane. Under humidified conditions, CO_2 reacts with the amino groups in the membrane to form either carbamate or bicarbonate, which then blocks the passage of H_2. Consequently, the amount of H_2 diffusing to the other side of the membrane is greatly reduced, and high concentrations of CO_2 can be obtained.

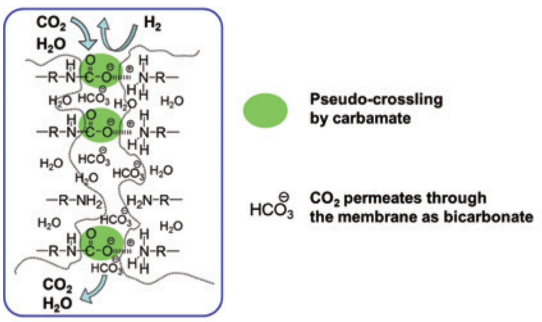

Fig. 10 : Schematic illustration of the working principles of the molecular gate membrane.

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. 11), and membrane separation systems.

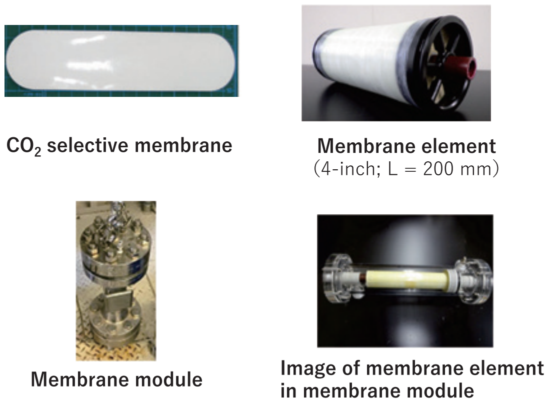

Fig. 11 : CO_2 selective membrane, membrane element, and membrane module.
Membrane element: The structure with a large membrane area composed of the membrane, support, and spacer.
Membrane module: The structure in which the membrane element is placed.

Based on the achievements of the project by the Ministry of Economy, Trade and Industry (METI), Japan, 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) in the current NEDO project, CO_2 Separation Membrane Module Practical Research and Development (FY 2018–), we are developing membranes with large membrane areas using a continuous membrane-forming method while developing the membrane elements. In addition, we started to conduct pre-combustion CO_2 capture tests of the membranes using real gas from the coal gasifier at the University of Kentucky Center for Applied Energy Research (UK-CAER) in the U.S., and we are planning to conduct CO_2 capture tests of the membrane elements at the test site in Japan, in 2020, to examine the separation performance and robustness of membranes and membrane elements.

To improve the CO_2 separation performance of the membranes using the continuous membrane-forming method, membrane preparation conditions were optimized to reduce membrane thickness, and the membranes were produced with the continuous membrane-forming method under optimized conditions. The separation performances of the membranes prepared from various conditions are shown in Fig. 12. It should be noted that helium (He) gas was used as alternative gas to H_2, for safety.

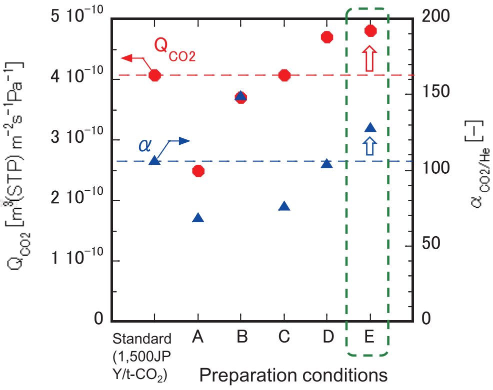

Fig. 12 : Separation performances of the membranes prepared from various conditions.
(QCO_2: CO_2 permeance, $\alpha CO_2/He$: CO_2/He selectivity)
(Condition E: optimized preparing condition)

CO_2 separation costs were evaluated using the experimental data in Fig. 12, and it was found that the cost target (1,500 JPY/t-CO_2) could be obtained by optimization of the preparation conditions.

In addition, we are conducting the development for the mass production of the membrane elements, and we are conducting research to improve the durability of the membrane elements. The membrane elements are stable under typical operating conditions (total pressure: 2.4 MPa) and cab be prepared by optimization of the permeate tube, spacers, and glues.

The CO_2 molecular gate membrane modules are being developed under a project recognized by the Carbon Sequestration Leadership Forum (CSLF), a ministerial-level international climate change initiative focused on the development of improved, cost-effective technologies for the separation and capture of CO_2 for transport and safe long-term storage.

5. Conclusion

In December 2015, the Paris Agreement was adopted at COP 21.* To meet the conditions of the agreement, it is essential to promote innovative ways to dramatically reduce emissions on a worldwide basis. In June 2019, 'Japan released the long-term strategy as a growth strategy based on the Paris Agreement' and 'the Integrated Innovation Strategy 2019', where it is shown that CCUS/Carbon Recycling is an important innovative technology that enables carbon neutrality in the world. In CCUS/carbon recycling, a combination of " reuse of separated and recovered CO_2 for fossil fuels and materials by treating CO_2 as a carbon resource (CCU)" and "storage of separated and recovered CO_2 underground (CCS)" is expected to have a significant CO_2 reduction effect.

Furthermore, it is 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 etc.

In general, it is crucial to promote the practical application of CCS by proposing optimized separation and recovery technologies for various CO_2 emission sources. It is also vital to establish new or improved technologies through scale-up studies and actual gas separation trials that closely mimic desired real-world applications. Furthermore, it is important to promote innovative technological development and to continually develop new energy-efficient, low-cost approaches to CCS.

*COP 21: 2015 United Nations Climate Change Conference

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Research and Development on Geological CO_2 Storage for Safe CCS Operation

1. Introduction

Deployment of commercial-scale demonstration projects is getting increase in the world. As more action on environmental issues is required, technological development for the safe storage of CO_2 will become more critical. In this regard, our CO_2 Storage Research Group as part of The Geological Carbon Dioxide Storage Technology Research Association has conducted one of the New Energy and Industrial Technology Development Organization (NEDO) projects called CCS Research Development/Demonstration Project: Research Development on CO_2 Storage Technology for Safe Implementation of CCS.

One of our developing technologies, called Distributed Fiber Optical Sensing (DFOS), is capable of acquiring spatially continuous recording. DFOS has facilitated low-cost multi-sensor systems that can capture temperature, pressure, strain and vibration by installing multiple fibers in a wellbore. We believe that this technology will play a significant role in commercial CCUS projects in North Dakota and the international project of assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE project) led by Norwegian Geotechnical Institute.

We have developed a management system for CO_2 storage (ATLS: Advanced TLS), which utilizes data from all monitoring systems and is applicable at a storage site in Japan, by collecting microseismic events from the ground motion data with frequent natural earthquakes and high environmental noise from human activity and processing data automatically in real time. We also intend to improve the level of public acceptance through information disclosure of test results to the public.

With regard to research on monitoring CO_2 leakage into the seawater, we have collected inter-annual data samples of various characteristics of the carbonate system in Osaka Bay. We will develop the relevant monitoring methods of the carbonate system by analyzing the data. This will contribute to developing the safest and more secured CO_2 storage with various aspects of research development and an appropriate form of information disclosure to the public.

We have also conducted a technological development of CO_2 microbubble injection test to create efficient CO_2 injection methods. Furthermore, we have implemented a pilot project in relation to the applicability of CO_2 microbubble injection.

Our group has also facilitated an international collaborative team to enable contribution to international frameworks, networking and collaborations to promote CCS technologies.

2. Major Research Themes and Outcomes

2.1. Development of Technique for Monitoring Formation Stability during CO_2 Injection Using Optical Fiber

Associated with CO_2 injection in the InSalah project site in Algeria, observed were ground uplift around injection wells and numerous microseismic events (below Magnitude 1). The locations of microseismic events were not limited to near the front of the CO_2 plume and pressure propagation. Formation deformations are considered to generate by rises in formation pressure. In geological CO_2 storage, it is therefore essential to monitor not only the location of CO_2 plume but also the area of pressure propagation. There are a number of technologies suitable for these monitoring, for example, the Distributed Fiber Optical Sensing (DFOS).

The DFOS system is capable of acquiring spatially continuous data and has been applied in various areas. DFOS can act as a multi-sensor system to capture temperatures, pressures, strains and vibrations simultaneously by installing multiple fibers together. The system is potentially much cheaper than a case where many sensors are installed. We tested multiple features of our DFOS systems in the field, two features are outlined below.

The first one is the distributed strain sensing (DSS) to measure minute geological strains caused by well drilling nearby. Fig.1 shows the changes of strains observed by the DSS system installed in two existing wells, 3 m (left in Fig.1) and 10 m (right in Fig.1) away from the new well. The figure shows that the DSS system, while drilling, successfully captured changes in strains caused by poroelastic deformations of the formations, the propagation of the strains, and differences in their attenuation trends which depend on the distance and direction of the propagation. Locally-varied deformation polarities and magnitudes along the wellbores are attributable to variation in strata's stiffness and permeability.

The second example is natural earthquake monitoring with the optical fibers installed in a wellbore. The optical fibers for vibration sensing are often used as receivers in the VSP (Vertical Seismic Profiles) technique in order to image geological features. The fibers also can be used as passive seismometers to monitor microseismicity around a well. In our test of long-term continuous monitoring, the system recorded numerous natural earthquakes. The record in Fig. 2 shows an example of a seismic event near the site (12 km in epicentral distance, 1.7 km in hypocenter depth, and Magnitude 1.3). In the accelerometer track (top in Fig. 2), P-waves and S-waves were clearly captured at around two sec. and six sec. In the optical fiber records (bottom in Fig. 2), waves from deep subsurface (the bottom of the record) were reflected at the ground surface (the top of the record), generating inverted V-shape signals. By analyzing the angles of V-shape signals, which depend on the propagation rates of waves, P-waves and S-waves can be easily distinguished in optical fiber records. These data also contain PS-converted waves generated by wave reflection at the surface and SP-converted waves generated at deep subsurface. These records can be used as input to the characterization of a seismic event detected and to an early warning system such as the ATLS.

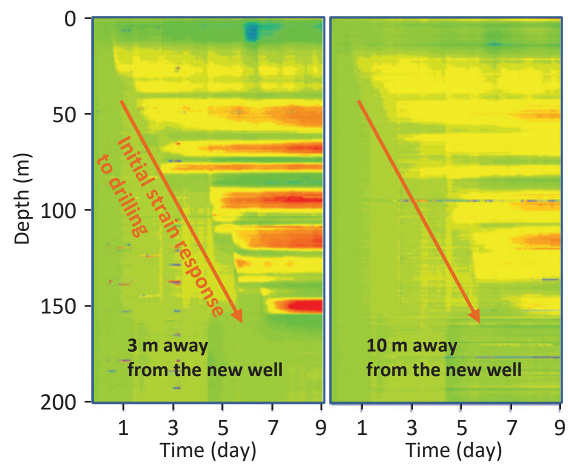

Fig.1 : Strain changes while drilling

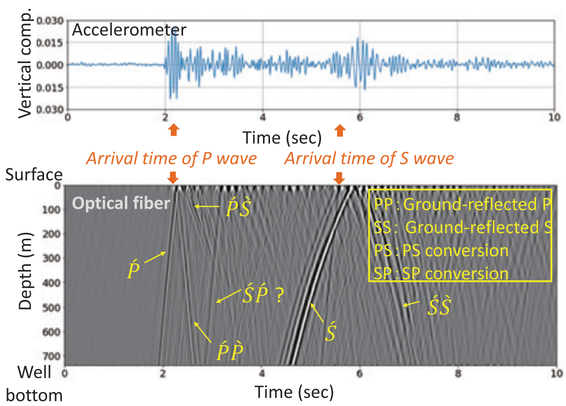

Fig. 2 : Record of a natural earthquake event

2.2. Development of Advanced Traffic Light System (ATLS) for the Safety Management of CO_2 Injection

In various fluid injection projects, there are concerns about earthquakes (felt seismicity) induced by increase of formation pressure. In waste water injection projects and enhanced geothermal systems (EGS), Traffic Light Systems (TLS) have, therefore, been used to manage operations to prevent the induced felt seismicity around sites. According to records with seismicity at CO_2 storage sites to date, microseismicity observed there have been limited to a magnitude of 1.1 or less. However, we should deeply consider the risk management about the possibility of the seismicity at a CO_2 storage site because the public concern to the earthquake is high.

Our group has been developing a management system for CO_2 storage (ATLS: Advanced TLS), which utilizes data from all monitoring systems and is suitable for storage sites in Japan (Fig.3). To be applicable in Japan, ATLS needs to have the capability to extract microseismic events from ground motion data that contain data of frequent natural earthquakes and high-level environmental noise derived from human activities, to determine the hypocenters of microseismic events, and to process data automatically in real time (Fig.4).

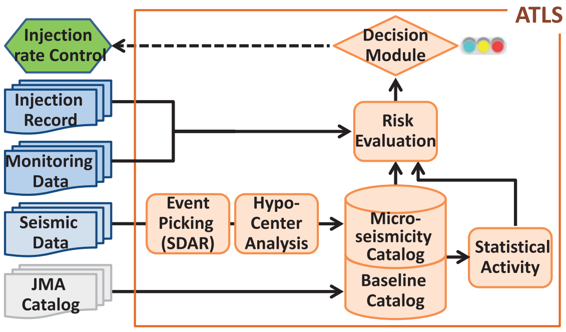

Fig.3 : Diagram of ATLS.

In order to distinguish microseismicity from natural earthquakes, ATLS automatically collects data in the seismological bulletin of Japan reported by the Japan Meteorological Agency and compares them with observed ground motions. To extract microseismic events from noisy data, a method was developed based on SDAR (Sequentially Discounting Auto Regressive model learning). As the function of hypocenter evaluation of microseismicity, "hypomh" was adopted, which is used to determine the authorized hypocenters of natural earthquakes in Japan. These functions were implemented in the ATLS codes, and the system was tested with data from the seismic observation system installed by at the Tomakomai demonstration site. The test successfully demonstrated that ATLS automatically performed signal processing and microseismic hypocenter analysis of data acquired for more than 1 year in the long-term continuous observation.

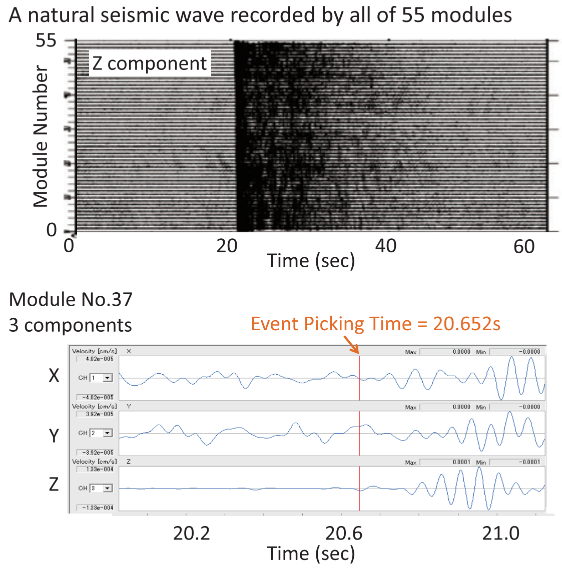

Fig.4 : Example of seismic wave observation by OBC

2.3. CO_2 Monitoring in the Marine Environment

Sub-seabed CO_2 storage is legally required to secure no CO_2 leakage into the seawater. The CO_2 monitoring activity for this purpose is also important socially from the viewpoint of securing safety and security for residents around a storage site. Our research group is aimed at developing appropriate detection methods of CO_2 leakage into the seawater.

The forms of CO_2 leakage into seawater are divided into the bubble phase and the dissolution phase. To detect bubble CO_2, we have been developing a methodology based on active acoustic sonar. For the dissolved CO_2, we have been demonstrating a methodology for judgement of CO_2 leakage, based on the seasonal data of the partial pressure of CO_2 (pCO_2) as an indicator of dissolved CO_2. Applied this method to the water composition data including those of carbonate relatives that had been accumulated from the Osaka Bay for several decades, we concluded that seasonal water sampling needs four to six years to obtain adequate background dataset. This is because water qualities are varied daily, seasonally and annually due to various factors such as biological and physical phenomena.

To understand seasonal variations and short-term variations in a season, we conducted continuous monitoring of pCO_2 and water quality in the Osaka Bay for more than one year from July 2018. The sensors were moored at two stations, which have different water body structures. One is the offshore of Kobe Port (Off KOBE) and the other is the offshore of Kansai Airport (Off KIX). The former station is located in the eastern area in the Bay, where water depth is shallow and water body has a tendency to be stratified by inflow of river water. The latter station faces the western area in the Bay, which is a deeper basin with a well-mixed water body due to tide current and mixing with the open ocean.

The observed seasonal changes of pCO_2 and dissolved oxygen saturation (DO%) are shown in Fig.5. At the both stations, pCO_2 were high in summer and low in winter. The trend is prominent at Off KOBE, where pCO_2 fell into a range of 200 – 300 μatm in winter and exceeded 1,000 μatm in summer. In addition, pCO_2 there had a large variation range of over several hundreds μatm in summer. On the other hand, pCO_2 at Off KIX show smaller seasonal changes: approximately 300 μatm in winter and approximately 600 μatm in summer. Different from pCO_2, DO% were high in winter and low in summer at the both stations. But the range of DO% was larger in summer as pCO_2 did. DO% were almost saturated at the both stations in winter but show different trends in summer: DO% at Off KIX were around 80% in summer, whereas DO% at Off KOBE were significantly lower than those in winter, which is occasionally close to zero.

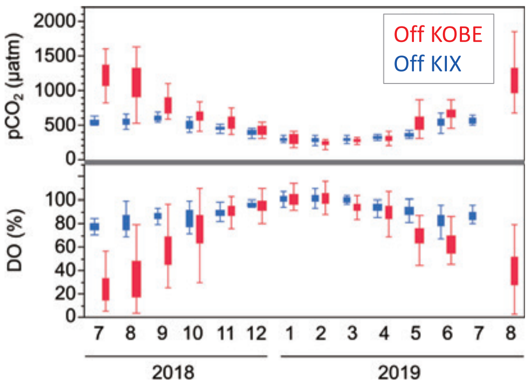

Fig.5 : Seasonal changes of pCO_2 and DO% (Bar indicates maximum and minimum. Box shows interquartile range.)

Plotting pCO_2 over DO% shows that they have an inverse correlation at the both stations (Fig.6). The relations are mostly attributable to biological activities such as photosynthesis by phytoplankton (CO_2 is consumed and O_2 is released) and aerobic respiration (O_2 is consumed and CO_2 is released). Due to these phenomena, DO% is low when pCO_2 is high and DO% is high when pCO_2 is low. When injected CO_2 leaks into seawater, DO% is expected to stay at the same level but pCO_2 should be increased, exceeding the inverse correlation curve based on the natural variations. We can use this to judge whether CO_2 is leaking so that it is important to understand the natural variations in the pCO_2 – DO% correlation. Analyzing the causes of variations is the next step. we plan to develop a methodology to define adequate criteria for the judgement of CO_2 leak. We are then aimed at establishing a frame work of marine monitoring for sub-seabed CO_2 storage.

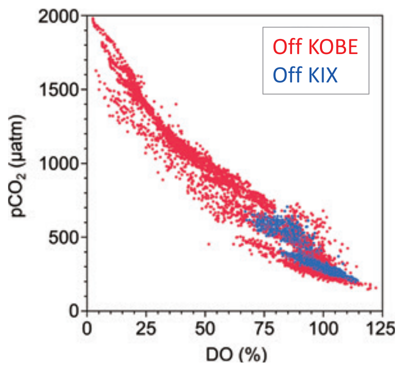

Fig.6 : Scatter plot of pCO_2 and DO%

2.4. Microbubble CO_2 Injection Test

Microbubble CO_2 injection is a technology to generate microbubble CO_2 by supplying CO_2 into a special filter and to inject the bubbles into pore space in formations. Using the microbubble technology, we have collaborated to improve CO_2 storage efficiency with Tokyo Gas and have obtained a patent "Device and Method for Sequestering a Substance" Patent No. 5399436). Its features have the potential of enabling us to maximize pore space utilization in geological CO_2 storage, to use low-permeability formations which have not been considered as a storage formation, and to enhance oil recovery rates.

On laboratory testing, we have evaluated the performance of microbubble CO_2 by generating the microbubbles with a circular porous filter and then injecting them into a cylindrical rock sample. In the field, we need to inject CO_2 into a tool hung in an injection well to generate microbubbles and to spray them in a 10 m or longer injection zone. The tool is an approx. 1.5m-long module unit, which is connectable with other units to be as long as the thickness of an injection zone.

In 2019, we, in collaboration with JAPEX, conducted a field test to examine level of storage efficiency at their Sarukawa oilfield in Akita (Fig. 7). The selected formation was a 900m-deep sand formation which bares oil. The oil is trapped in the formation with little natural flowing. We did a Haff and Puff test, injecting CO_2 and water at a ratio of 9:1 and then pumping formation fluid out.

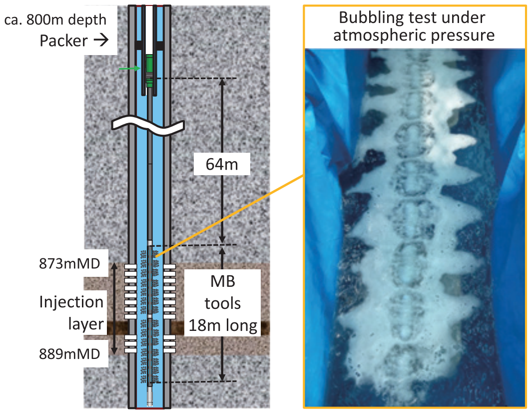

Fig.7 : Image of installed microbubble generator in a wellbore and microbubble generation test under the atmospheric condition

We injected 5.8 tonnes of CO_2 at a rate of about 0.6 tonnes per day for 10 days in a conventional manner without a microbubble generation tool. After a 2-day interval, we then collected subsurface fluid for consecutive five days. In total, 2.1 tonnes of CO_2 were collected from the reservoir, but no oil recovered. The ratio of CO_2 remained in the formation was 62%. We subsequently repeated the same process but with the microbubble tool, where we were able to inject 20 tonnes of CO_2 stably at a rate of 2 tonnes per day over 10 days. The storage efficiency for this time was 80% with 3.9 tonnes of CO_2 recovered and oil was also recovered. The results show that the microbubble CO_2 injection technique has the potential to improve efficiency of CO_2 injection, CO_2 storage and oil recovery in comparison with conventional ways.

This technology of ours draws attentions not only domestically but also internationally. In 2019, we sold the microbubble CO_2 generation tool to Junlun Petroleum Company, China, with whom RITE had concluded a license agreement for the use of our microbubble injection technology in the previous year. This was a first step toward the commercialization of the technology for CO_2-EOR in low-permeable oilfields. We are also planning the demonstration of this technology together with DFOS in the USA, concluded a memorandum of understanding on collaborative study on CO_2 geological storage and EOR with the University of North Dakota. We will test the microbubble CO_2 injection technology in various types of oil formations and to acquire data to investigate its applicability, effectiveness and also economics.

2.5. International Collaboration and Review of CCS Development in the World

Our group facilitates an international collaborative team, which contributes to promoting CCS technologies through international collaboration with various international organizations (e.g. IEA-GHG) and frameworks, while researching the global trends of CCS development. Here, we summarize some of the highlights of international CCS development and frameworks during 2019.

(1) Global trends in CCS development

In terms of disseminating CCS technologies, building infrastructure sharing called "cluster" has been widely discussed as one of the key development areas across countries, especially in the EU.

In May 2019, The UK's Committee on Climate Change announced a report called *Net Zero-The UK's contribution to stopping global warming.* This report emphasizes that net zero emission in that country will need to be achieved by 2050 and CCS will play a significant role in the action. We would need at least one cluster to be operated by 2026, at least one and another four additional clusters would need to be operated. Furthermore, the UK in June 2019 passed *The Climate Change Act 2008 (2050 Target Amendment) Order 2019 :* a legally binding target of net-zero carbon emissions by 2050.

In Norway, there is also a full-scale industrial project currently being considered. The Norwegian full-scale CCS project is comprised of two capture projects: Heidelberg Norcem cement factory and Fortum Oslo Varme waste-to-energy plant. The project aims at capturing CO_2 from these two different sources, which will be transported by ship to an onshore terminal on the Norwegian west coast and from there transported by pipeline to an offshore storage complex under the North Sea (800,000 tonnes in total of CO_2 per year). After completing feasibility studies for CO_2 capture in 2018, the plants are presently compiling Front End Engineering Design (FEED) studies for the final investment decision, to be taken by the Norwegian Parliament in 2020/21.

Another key event of 2019 happened in October, when the parties of *the London Protocol agreed to allow provisional application of the 2009 amendment of Article 6 to the London Protocol* allowing for cross-border transport and export of CO_2 for geological storage in sub-seabed geological formations at the London Convention meeting held in London. As a result, this enables contracted countries to implement cross-border CCS projects and trading CO_2 for the purpose of geological storage. Such projects will also create opportunities for shared transport and storage infrastructures and regional hubs and clusters across countries, cost efficient and new business models.

In May, the Central Government of China (Ministry of Science and Technology) announced *Roadmap for Carbon Capture Utilization and Storage Technology Development in China (2019).* China aims at es-tab-lishing extensive deployment of large-scale CCUS and industrial clusters (80,000,000< tonnes of CO_2 per year) by 2050. Thus, China has actively initiated their legal system, infrastructure development, and technological development.

On August 8, 2019, a CO_2 injection system at the operating Gorgon natural gas facility on Barrow Island, called 'Gorgon project', was started, off the northwest coast of Western Australia. It aims at injecting between 3.4 and 4 million tonnes of CO_2 per year into a deep underground reservoir (saline aquifer beneath Barrow Island. The Gorgon Project is operated by Chevron Australia and is a joint venture of the Australian subsidiaries of Chevron, ExxonMobil, Shell, Osaka Gas, Tokyo Gas and JERA. JGC Corporation is also part of this project to support plan and construction of gas processing facilities (i.e. CO_2 capture plant).

(2) The global trends of CCS frameworks

CCS communities have implemented various activities to make a transition from large-scale CCS demonstration projects to commercialized CCS. It is also noteworthy that CCUS was covered by the G20 energy and environment ministerial meeting held in Karuizawa, Japan in June 2019, stimulated by recommendations publicized by RITE and C2ES (For details, see "Topics"). In its communiqué, the ministers recognize the potential of CCUS and the need for investment in and financing CCUS. In its action plan, they are committed to seek to enhance international cooperation on CCUS in relevant existing fora and to encourage CCUS research, development and deployment.

The CCUS initiative, which was launched at the Clean Energy Ministerial meeting (CEM) in May 2018, initiative will continue to strengthen the framework for public-private collaboration on CCUS throughout financial sectors and webinar to promote the technological deployment. In 2019, 'CEM CCUS Initiative countries' and the Oil and Gas Climate Initiative (OGCI) agreed to explore ways to collaborate to accelerate CCUS. This could create further promotion and development of CCUS.

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for CCS. The technical group of CSLF has emphasized a need for reviewing the past activities and future plans. *The CSLF Technology Roadmap 2017* addressed the global CO_2 reduction target by using CCS (at least 400 Mt CO_2 per year and/or permanent capture and storage of in total 1,800 Mt CO_2) by 2025, and four technical approaches to meet the target: CCS infrastructure development, sharing knowledge of large-scale demonstration projects, cost reduction, and a business model. Besides these, 'CO_2 utilization' has also been added under the new approach. The 2019 annual review noted that it would not be realistic to meet the 2025 target, based on the current status. It further mentioned that the target would be met, if extensive pub-lic-private partnership funds become available for building and expanding CCS infrastructures.

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

1. Introduction

Inorganic membranes, such as silica membranes and zeolite membranes, have the features of excellent heat resistance and environmental resistance, in addition to high separation performance, and are expected to be applicable to various applications. Compared to the conventional separation and purification methods of distillation and adsorption, inorganic membranes can save energy, and they are also being developed for CO_2 separation and purification, as well as for hydrogen separation and purification, which are indispensable for building a hydrogen society. Therefore, the use of the membranes is attracting a great deal of attention as an environmental and energy technology that contributes to the preservation of the global environment. However, practical application has so far been limited to alcohol dehydration. In the future, innovative environmental and energy technologies using inorganic membranes will be required for early commercialization and industrialization.

The Inorganic Membrane Research Center (IMeRC), established in April 2016, comprises two departments: the Research Department and the Industrial Cooperation Department. In the Research Department, hydrogen separation, purification, manufacturing, separation, and recovery are performed using silica membranes, zeolite membranes, and palladium membranes, each of which offers excellent characteristics. We are working on research in ways to more effectively use the CO_2 produced. In the Industrial Collaboration Department, the Industrialization Strategy Council, which consists of 17 companies of inorganic separator and support substrate manufacturers and user companies, aims to share the vision among manufacturers and user companies by planning joint research. Member companies meet regularly to promote activities through study groups.

In 2019 during the development of a membrane reactor for the dehydrogenation of methylcyclohexane (MCH) as an efficient hydrogen transport and storage technology, we proposed a module structure for mass production and commercialization to enhance the durability of the membrane reactor in actual operation. We examined the technology necessary for practical use. In addition, we commissioned a new project from the New Energy and Industrial Technology Development Organization (NEDO) to produce hydrogen from the direct decomposition of methane, and started studying the process.

As for CO_2 separation, capture, and utilization (CCU: Carbon Capture and Utilization), we developed a zeolite membrane with high selectivity for water, and applied it to a membrane reactor to enhance the conversion rate for methanol. We confirmed that could improve conversion about three times compared to conversion in the reactor. In addition, the Industrialization Strategy Council is in full swing with study group activities aimed at launching a nationally funded project. This paper describes the main achievements and future prospects of the Research Department in the development of membrane reactors for MCH dehydrogenation, hydrogen production from methane, and CCU technology development, as well as the activities of the Industrialization Strategy Council.

2. Development of Silica Membrane Reactors for a Hydrogen-Based Society

The development of efficient hydrogen transportation and storage methods is essential for building a hydrogen-based society. The proposed concept for an energy carrier is a promising method for concerting hydrogen into chemical hydrides that can be efficiently transported and stored, such as MCH and ammonia. Chemical hydrides are transported and stored to take out hydrogen at the place and time as required (Fig. 1).

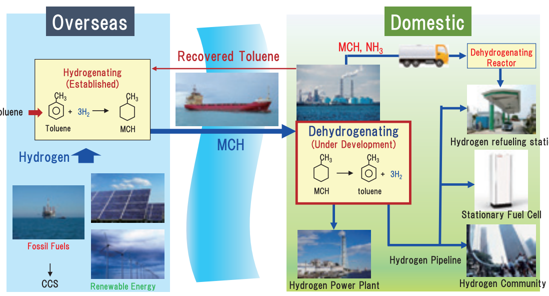


Fig. 1 : Energy Carrier

The technology for converting hydrogen to MCH or ammonia has already been established for mass production, but hydrogen extraction technology has not yet been developed as a definitive method.

The IMeRC develops membrane reactors using a silica membrane, which is prepared by counter-diffusion chemical vapor deposition (CVD) for the purpose of developing and commercializing efficient, stable production of pure hydrogen from MCH for small- to medium-sized customers, such as commercial establishments and office buildings.

The mechanism is illustrated in Fig. 2. When MCH is fed into a reaction at 300° C where a hydrogen separation membrane and a catalyst are set, MCH is dehydrated into toluene and hydrogen by an equilibrium reaction; however, only the generated hydrogen passes through the hydrogen separation membrane and is separated from the reaction field. Because the product is removed from the reaction field, the reaction shifts to the product side, which improves the conversion of hydrogen production. At the same time, the hydrogen passing through the separation membrane becomes high purity hydrogen with no toluene, so that hydrogen purification and improvement in reaction efficiency simultaneously proceed.

This work was funded by NEDO as part of the Advancement of Hydrogen Technologies and Utilization Project for the analysis and development of hydrogen as an energy carrier and the development of a dehydrogenation system using inorganic hydrogen separation membranes for organic chemical hydrides in collaboration with Chiyoda Corporation.

In the membrane reactor study, improvement in the reaction efficiency of the dehydrogenation reaction from the MCH using several silica membranes was achieved as a result of the development.

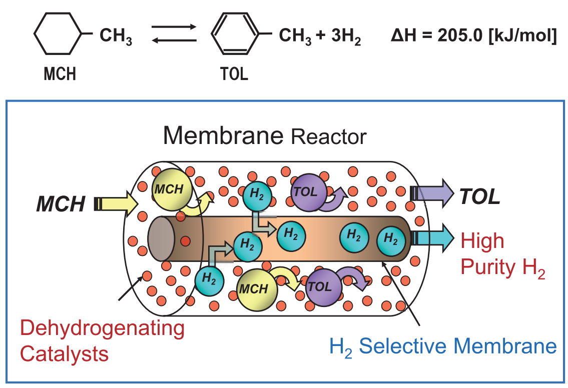


Fig. 2 : Diagram of a tubular single membrane reactor

In order to verify this phenomenon on an actual scale, we designed and fabricated a test apparatus composed of three 500 mmL silica membranes; as a result, the evaluation verified the remarkable equilibrium shift using 500 mmL silica membranes and the conversion rate of 95% or more, which was significantly higher than the equilibrium conversion rate of 42.1% (Fig. 3).

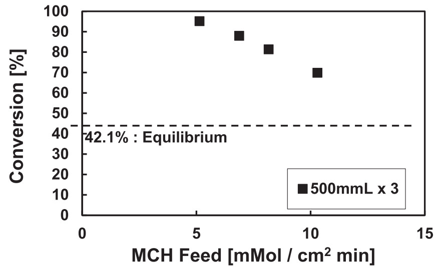


Fig. 3 : Operation result of the bench-scale membrane reactor

However, this study of the membrane reactor revealed the problem of sealing at the same time. In a membrane reactor, it is necessary to have airtight seals for the ceramic membranes with a metallic reactor, so rubber seals, such as O-rings, have been adopted. However, since the reaction field is exposed to organic solvents like MCH and toluene at high temperatures and high pressures, durability of the rubber seals was a problem. In addition, a conventional membrane reactor has a complicated structure with an independent reactor for each membrane and has the problem of requiring many person-hours for production and maintenance. The sealing structures were investigated, and a module structure was developed to address the problem of durability for pressure, temperature, and solvents; even at 300° C, it was easy to attach and detach the multiple integrated tubes from the reactor. The developed prototype module with this structure is shown in Fig. 4.

The first prototype silica module was made to bundle three silica membrane tubes using a glass binder to bond the ceramics to metal with different expansion coefficients, and airtightness was confirmed at 300° C and 500 kPa-G. On the other hand, when the number of tubes is increased, it becomes difficult to fasten with a ferrule.

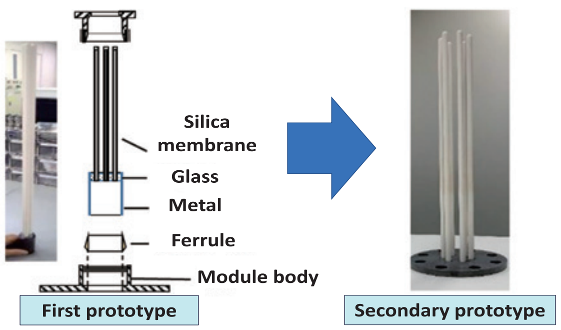


Fig. 4 : Silica membrane module using glass binder and reactor

Therefore, in the second prototype module, a flat metal and six membranes were joined, and the shape was made into a flange structure to maintain airtightness with a structure that could be easily removed.

The second prototype module was assembled in a test device as shown in Fig. 5, and the improvement effect from the heat transfer structure corresponding to the endothermic reaction of MCH was evaluated. The results are shown in Fig. 6. In addition to the conversion rate exceeding the equilibrium conversion rate, the heat supply from the outside was efficiently transmitted by installing a fin inside the reaction tube, and the conversion rate was further improved.

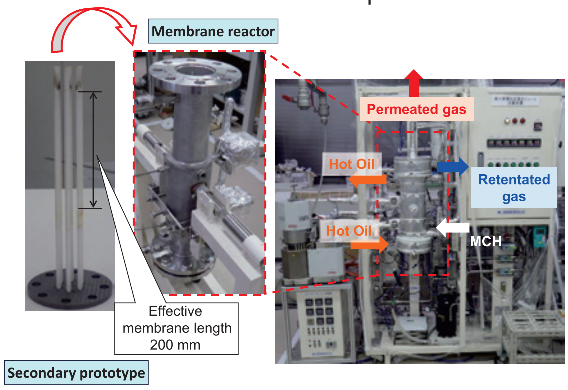


Fig. 5 : Membrane reactor for the silica module

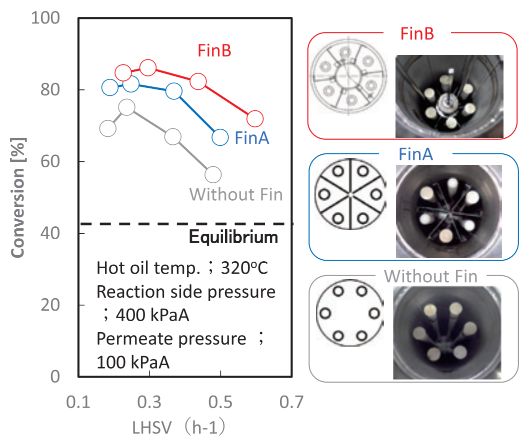


Fig. 6 : Evaluation results of the secondary prototype

A 1500-hour durability test was performed using a single-tube membrane reactor. The test results are shown in Fig. 7. Although there was a slight decrease in the hydrogen permeability due to the adhesion of the toluene film surface in the initial stage, stable operation was possible, and a reduction in the conversion after 15,000 hours from extrapolation was estimated at about 20%, which shows practical durability.

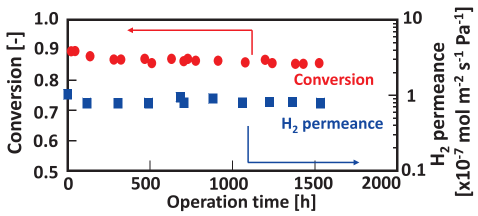


Fig. 7 : Durability test of single tube membrane reactor

Through these studies, RITE has demonstrated that hydrogen generation from MCH can be designed compactly in a membrane reactor using a high performance silica membrane on a bench scale.

3. Development of CO_2-free hydrogen production technology by methane decomposition

In order to build a hydrogen society, a method is required to produce hydrogen at low cost and in large quantities. Focusing on methane, which can be supplied stably for a long time from the shale gas revolution, hydrogen and solid carbon are produced by pyrolysis, and hydrogen production costs can be reduced by selling the carbon byproduct. We started to study the technology. Our goal was efficient, energy-saving hydrogen production by improving the conversion rate via a membrane reactor. 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 contracted project of NEDO in FY 2019, the objective was the (1) development of a selective hydrogen permeable membrane with a heat resistance of 500° C or higher required for methane decomposition, (2) development of a catalyst to efficiently decompose methane in a membrane reactor, and (3) the development of reactors and a demonstration of their effectiveness as the defined development items (Fig. 8).

For (1), silica membranes and palladium membranes are candidates for hydrogen separation membranes, and the guidelines for membrane formation are being narrowed down through experiments and literature surveys. For (2), we have narrowed down the types of catalysts based on a literature search and studied catalyst types that are close to equilibrium conversion at 600° C. For (3), the construction of the evaluation device has been completed and the evaluation has just started. In the future, we plan to demonstrate the effectiveness of the membrane reactor application.

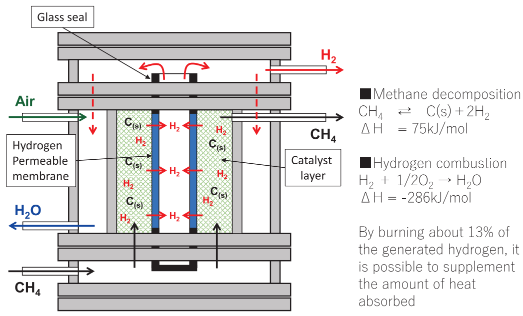


Fig. 8 : Application of membrane reactor to the hydrogen production process by methane decomposition

4. Development of CCU Technology

Since the fiscal year of 2018, RITE, JFE Steel Corporation, the Institute of Applied Energy (IAE), INPEX Corporation, and Hitachi Zosen Corporation have collaborated in the technological development of next generation thermal power generation, next generation thermal power development of power generation infrastructure technology, and the development of technology for effective use of CO_2 as a project of NEDO.

In this project, our goal was to establish promising future CCU (carbon capture and utilization) technologies in anticipation of fiscal year 2030 and beyond and to further grant industrial competitiveness to Japan's excellent clean coal technology (CCT). We plan to comprehensively evaluate CCU technologies for the effective use of CO_2 in the product manufacturing process and system with the aim of establishing CCU technology. At the Inorganic Membranes Research Center, a novel zeolite membrane for dehydration was successfully developed with relatively high durability under hydrothermal conditions. The zeolite membrane was applied to the membrane reactor for a methanol synthesis reaction. We demonstrated that the membrane reactor achieved high methanol production, which exceeded the thermodynamic equilibrium limitation (Fig. 9).

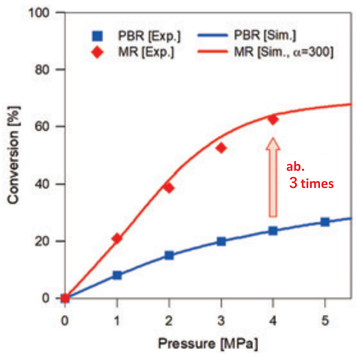


Fig. 9: Performance of membrane reactor for methanol synthesis

In addition, a methanol synthesis membrane reactor simulator was constructed, and the results showed good agreement with the experimental results. From the viewpoint of dehydration using inorganic membranes, our novel zeolite membrane has extremely high water permselective performance that can be applied to hydration processes such as water/methanol, ethanol or IPA binary mixtures. Prof. Kita (Yamaguchi University) is working on the development of inorganic carbon membranes, and Prof. Hasebe (Kyoto University) is working for the process development toward the same end.

5. Activities and efforts toward commercialization and industrialization

The Industry Collaboration Section of the IMeRC established the Industrialization Strategy Council on April 15, 2016. Our goal isto 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. To realize this goal, 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 a 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 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

As for Research Group activities, we have been conducting various studies at the following two research groups set up in November 2016:

a) CO_2 Separation Research Group

b) Common Base (Reliability Evaluation Method) Research Group

In fiscal 2019, we conducted in-depth surveys and studies through activities by both the Research Group and its subsidiary research workshop (each Research Group had three to four meetings, respectively, up-to the end of 2019), and they are preparing for projects aiming at practical application funded at government expense. The Common Base Research Group has started a preliminary test of accelerated deterioration for zeolite membranes. The plan is to start up a national funded project in 2021 by acquiring basic data on establishing long-term reliability. The CO_2 Separation Research Group has been conducting a study under the theme of "Applicability of inorganic membrane to natural gas separation with high CO_2 concentration."

In addition, exclusive technology seminars for council members are held three times each year in which the latest R&D trends, needs, and seeds are introduced in a total of nine lectures given by IMeRC advisory board members, member companies, and the IMeRC with active discussions among participants. At the same time, a site tour of the hydrogen production plant from used plastics was held at the Kawasaki Plant of Showa Denko KK and was well received by participants.

The participants are pleased to take part in the seminars, not only because they can acquire knowledge of inorganic membranes, which is useful in promoting the practical use and industrialization of the membranes, but also because they have the opportunity to interact with other frontline researchers from member companies and organizations.

In November 2019, a two-day training workshop was held at Gifu University. Lectures including an outline of Pd membranes and membrane reactors, Pd membrane separation technologies, and experiments on membrane formation methods and guidance on performance and evaluation methods for prepared membranes were provided at the workshop. The participants were able to acquire knowledge on the most advanced Pd membrane formation and evaluation experiment methods and to gain valuable experience. (Fig. 10)

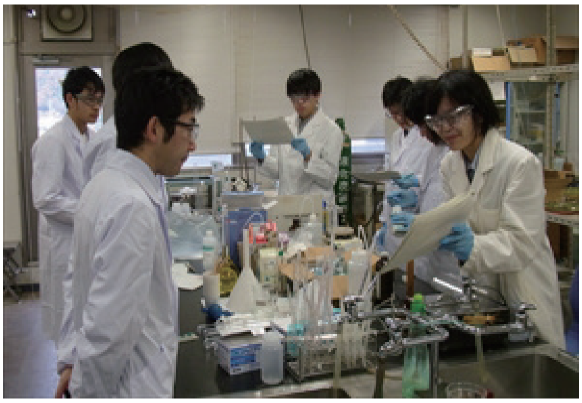


Fig. 10 : Exclusive training workshop for young researchers at Gifu University

We also conduct patent and literature surveys related to the seminar lectures and periodically provide council members with Needs and Seeds Technology Information, which has special comments from the IMeRC in the abstract.

In addition, we support the various activities of council members toward promoting the practical use and industrialization of inorganic membranes by providing a summary of the remarkable lectures at the international conference on inorganic membranes with RITE comments.

6. In conclusion

In 2019, we focused on practical application technology for dehydrogenation from MCH using hydrogen separation membranes, which the IMeRC has been working on since its establishment. In addition, we started a new hydrogen production project from methane, which is funded by NEDO, and steadily achieved results in research and development using CO_2 more effectively. On the other hand, the activities toward practical application and Industrialization for realization of R & D results are also in full swing, as the IMeRC it can be said that the foundation is solidifying. Going forward, we will work diligently to become the core organization that leads the development and commercialization of inorganic membranes worldwide.

Research & Coordination Group

IPCC Symposium "To Think about Measures for Mitigation of Global Warming"

- Special Report on the impacts of Global Warming of 1.5℃ (SR1.5) and 6th Assessment Report (AR6) -

The Ministry of Economy, Trade and Industry (METI) and RITE hold an IPCC symposium, inviting Dr. Jim Skea, co-chair of IPCC Working Group III that assesses certain options for mitigating climate change through limiting or preventing greenhouse gas emissions. Dr. Skea delivered keynote lecture on the overview of SR1.5, and the important points and issues to be addressed in the AR6, as well as the procedure for writing and reviewing of the IPCC reports. Moreover, Dr. Keigo Akimoto and Dr. Kanako Tanaka delivered speeches, respectively, on the subjects of the emission pathways and mitigation costs for achieving below 1.5℃ and the impacts of low energy demand scenarios and the expectations to industry sector seen from IPCC reports. In addition, a panel discussion on expectations, issues regarding IPCC and how to tackle global warming was held by Dr. Skea and some Japanese experts with many questions and comments from participants in the hall.

Date: 6 March 2019
Venue: Hall B, Toranomon Hills Forum (Tokyo)
Organization: METI
Co-organization: RITE
Number of participants: 269
Program:

- Keynote lecture "Building on the IPCC Reports: Plans for the Working Group III Sixth Assessment Report" Jim Skea (Co-chair of IPCC Working Group III)
- Lecture-1 "The emission pathways and mitigation costs for achieving below 1.5℃ and the impacts of low energy demand scenarios" Keigo Akimoto (RITE)
- Lecture-2 "Expectations to industry sector seen from IPCC reports" Kanako Tanaka (Japan Science and Technology Agency)
- Panel Discussion
  "Expectations, issues regarding IPCC and how to tackle global warming"
  Moderator, Mitsutsune Yamaguchi (RITE)
  Panelists, Jim Skea (IPCC), Keigo Akimoto (RITE), Kanako Tanaka (Japan Science and Technology Agency), Hiroyuki Tezuka (Keidanren), Yoshiki Yamagata (National Institute for Environmental Studies)

Research & Coordination Group

Symposium in Kansai on Global Warming Mitigation Technology for Future Society

RITE holds the annual Innovative Environment Technology Symposium in Tokyo as a platform to report our latest research results. To welcome more participants from Kansai, we organized this event in Osaka, following last year.

This time, we had Mr. Motohiko Nishimura from Kawasaki Heavy Industries, Ltd. deliver a special lecture. Under the theme of "Technical demonstration starting in 2020: Initiatives by Kawasaki Heavy Industries toward the establishment of international hydrogen supply chains," he presented the necessity of hydrogen energy and the company's global hydrogen supply chain projects. It was an easy-to-understand lecture which was supported by video and CG, with the introduction of their cutting-edge technology and other topics.

We hosted a poster session this year for the first time, which invoked an active exchange of opinions among participants and our researchers. Through a questionnaire, we received many comments from participants saying that the event was very informative and helpful. The event served as a wonderful opportunity for people in Kansai to learn about RITE's research and development activities.

Date: 26 September 2019
Venue: Osaka Science & Technology Center (OSTEC)
Number of participants: 182
Program:

- Special lecture: Technical demonstration starting in 2020: Initiatives by Kawasaki Heavy Industries toward the establishment of international hydrogen supply chains
  Motohiko Nishimura, Associate Officer, General Manager, Hydrogen Project Development Center, Corporate Technology Div., Kawasaki Heavy Industries, Ltd.
- The global energy system of long-term decarbonization -The role of hydrogen and electricity-
  Keigo Akimoto, Group Leader, Systems Analysis Group
- Development of biorefinery technology to realize a sustainable society
  Masayuki Inui, Group Leader, Molecular Microbiology and Biotechnology Group
- Development status and future prospects toward the practical use of CO_2 capture technology
  Katsunori Yogo, Associate Chief Researcher, Chemical Research Group
- Initiatives for the development of safety control technology, aimed at the practical use of underground CO_2 storage
  Ziqiu Xue, Group Leader, CO_2 Storage Research Group
- Initiatives toward the practical use of inorganic membranes to realize a hydrogen-based society
  Yuichiro Yamaguchi, Deputy-Director, Inorganic Membranes Research Center

Research & Coordination Group

Innovative Environmental Technology Symposium 2019

~Taking on challenges toward a low-carbon society~

RITE hosts this symposium every year as a platform to report our latest research results. This year, as a guest speaker, we invited Mr. Tomoyoshi Yahagi, Deputy Director-General for Environmental Affairs at the Ministry of Economy, Trade and Industry (METI), who had just returned from COP25. He gave a summary of the negotiations at COP25, activities at the Japan Pavilion, and the trend of climate change policies in other countries. As the keynote lecture, Dr. Yamaji, Senior Vice-President/Director-General of RITE, talked about recent trends in energy and environmental innovation, as well as the importance of drastic innovation in technologies related to energy and the prevention of global warming to promote the shift to a zero CO_2 emission society. Representatives from each Group and Center at RITE gave lectures about their latest research results and future prospects. At the poster session, active discussions took place between participants and researchers. The event attracted almost 500 participants, indicating people's growing interest in environmental issues.

Date: 18 December 2019
Venue: Ito hall, The University of Tokyo
Number of participants: 491
Program:

- Guest Speech: About COP25
  Tomoyoshi Yahagi, Deputy Director-General for Environmental Affairs, METI
- Keynote Speech: Stimulating innovation to realize a low-carbon society
  Kenji Yamaji, Senior Vice President/Director-General
- Evaluating energy system transition towards decarbonized society
  Keigo Akimoto, Group Leader, Systems Analysis Group
- Research on the practical use of CO_2 capture technology and future prospects
  Shin-ichi Nakao, Group Leader, Chemical Research Group
- Initiatives for the development of safety control technology, aimed at the practical use of underground CO_2 storage
  Ziqiu Xue, Group Leader, CO_2 Storage Research Group
- Development of green bioprocess for the realization of decarbonized society
  Masayuki Inui, Group Leader, Molecular Microbiology and Biotechnology Group
- Initiatives toward the development of inorganic membranes for practical application and the realization of a low-carbon society
  Shin-ichi Nakao, Director, Inorganic Membranes Research Center

Systems Analysis Group

Winning of 2018 Masaji Yoshikawa Memorial Prize for Fusion Energy Excellence Prize

Dr. Gi, Researcher (current Senior Researcher) of the Systems Analysis Group, has been awarded the 2018 Masaji Yoshikawa Memorial Prize for Fusion Energy Excellence Prize of Fusion Energy Forum of Japan (FEFJ).

The prize aims to manifest excellent achievements performed worldwide by young people in fundamental investigation, research and technology development activities for realization of fusion energy, and the excellence prize is given to the work recognized as especially outstanding.

Dr. Gi was awarded the excellence prize for his research paper "Energy scenarios analysis for long-term fusion energy development strategy", in which he analyzed the market potential of fusion energy up to 2100 with energy system models considering global environmental issues and the characteristics of each region in the world. It clarified that fusion energy could have significant market potential in some regions where competitive power generation costs were achieved and indicated its technology development goals along with mechanisms determined by energy market trends. This result shows the value and potential of fusion energy in the new global energy market after the Paris Agreement and is expected to be a reference for the future research and development of fusion energy and the improvement of its social acceptance.

The award ceremony was held in the 12th Plenary Meeting of FEFJ at Tohoku University on 13th February of 2019, where a certificate and incentive were bestowed on Dr. Gi.

Systems Analysis Group

FY2018 ALPS International Symposium

Challenges to harmonized achievement of economic growth and long-term deep emissions reduction

The Paris Agreement entered into force in November 2016, establishing a new international framework in which almost all nations should make efforts to reduce GHG emissions and each country has submitted its own GHG emission reduction targets for 2030 (or 2025). Also, discussions on long-term GHG reduction beyond 2050 are becoming active facing submission of its low emissions development plan. Under recognition of various risks of climate change, ALPS International Symposium was held to disseminate the research achievements of the project. Lectures were presented by eminent specialists from the various viewpoints such as the possibility of future low demand scenarios due to technological and social innovations.

Date 19th February 2019
Venue Toranomon Hills Forum (Tokyo)
Organized by RITE
Co-organized by METI
Number of participants 278
Program

- Policy trends of Japan and the world, and scenarios of long-range strategy for deep CO_2 emissions reduction
  Kenji Yamaji, Director-General, RITE
- Disruptive technologies and sustainable lifestyles toward net-zero emissions
  Nebojsa Nakicenovic, Deputy Director General/Deputy CEO, IIASA
- Assessing company climate policy risk —a scientific foundation for companies, investors, and others—
  Steven Rose, Senior Research Economist & Technical Executive, Energy and Environmental Analysis Research Group, EPRI
- Insights on electricity transitions from the World Energy Outlook 2018
  Yasmine Arsalane, Senior Energy Analyst, World Energy Outlook, IEA
- Are we entering a new golden age of energy productivity improvement?
  Koji Nomura, Professor, Keio Economic Observatory, Keio University
- General purpose technology and global warming
  Taishi Sugiyama, Research Director, The Canon Institute for Global Studies
- Deep emission reduction for transportation sector
  Jari Kauppila, Head of Quantitative Policy Analysis and Foresight, International Transport Forum, OECD
- Alternative strategies for sustainable development and deep decarbonization —Renewed focus on end-use, efficiency, granularity, and digitalization—
  Arnulf Grübler, Acting Program Director, Transitions to New Technologies, IIASA
- Innovations of products, services and social systems, and their impacts on climate change mitigation measures
  Keigo Akimoto, Group Leader, Systems Analysis Group, RITE

Systems Analysis Group

International Workshop on Energy Demand

To make strides toward decarbonization from the perspective of 2050 and beyond, a virtuous cycle of environment and growth and as well as paradigm shift which promotes business-driven technological innovation are required. Although IPCC published a special report of 1.5℃ in 2018, its quantitative and comprehensive analysis have not been sufficient yet. In order to actualize the virtuous cycle, it is extremely important for global research communities to deeply discuss energy demand scenarios and find a future direction.

Therefore, RITE and the International Institute for Applied Systems Analysis (IIASA) held a workshop to examine opportunities and issues of the low energy demand society with modelers, social scientists, economists, engineers and practitioners in various fields.

At the workshop, various initiatives to reduce energy demand were introduced, such as lower energy consumption office buildings, car-sharing simulations at the city level, and quantification evaluation using international integrated models. The importance of taking energy demand from a service perspective, controlling not only greenhouse gas emissions, but also a wider range of SDGs and working with policy makers has been also indicated.

Date 11-13th November 2019
Venue IIASA (Laxenburg, Austria)
Organized by RITE, IIASA
Co-organized by METI
Number of participants 57 (19 countries)

Systems Analysis Group

COP25 Side Event Global Climate Change Policy

The RITE side events at COP25 in Spain were held both in Japan Pavilion and UNFCCC side event room, to disseminate achievements of joint research with RFF, covering scientific comparative evaluation of Nationally Determined Contributions (NDCs) and their impacts on economy and international competitiveness.

After an introduction by Dr. Kopp of RFF, Dr. Akimoto presented RITE's comparative analyses of marginal abatement costs (MACs) of NDCs across nations and their economic impacts, arguing that coordination of NDCs through reviewing process is crucial because large differences in MACs may hinder efficient emissions reduction. He also pointed that innovation both in energy supply side and demand side is necessary towards 2℃ target and deeper emissions reduction, due to the difficulty of realizing international coordination with assumed high carbon prices.

Speakers including Prof. Aldy (Harvard Univ.), Dr. Verdolini (EIEE), Dr. Parrado (EIEE), and Prof. Arima (the University of Tokyo) pointed out the need for increasing transparency of climate change policy through NDC evaluations, as well as the importance of innovation contributing to the reduction of mitigation costs.

Date 11th December 2019
Venue COP25 Japan Pavilion
Organized by RITE
Co-organized by RFF

Date 12th December 2019
Venue COP25 UNFCCC side event
Organized by RITE, RFF

Molecular Microbiology and Biotechnology Group

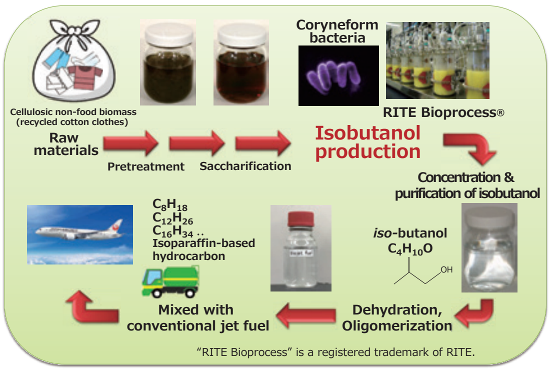
Collaboration with the JAL biojet fuel flight project

Aviation is responsible for 2% of worldwide anthropogenic CO_2 emissions. Because it is difficult to replace jet fuel with electricity, biojet fuel made from non-food biomass as a raw material is expected to contribute to solving the global warming problem without causing food shortages. Given these circumstances, RITE began technical cooperation with the Japan Airlines Co., Ltd. (JAL) project "Let's fly with 100,000 used clothes!" in October 2018.

This project aims to produce biojet fuel from used clothes collected from across the country by JAL and JEPLAN, INC. Ltd. The Green Earth Institute Co., Ltd., which was established in 2011 for the industrialization of RITE Bioprocess, is participating in this project and is responsible for: the production of isobutanol from the cotton fibers in used clothes, and producing biojet fuel that conforms to the international standard ASTM D7566 Annex 5.

Corynebacterium glutamicum R, which was developed by RITE, is a key component in the production of isobutanol. It is possible to use the RITE Bioprocess® to efficiently produce isobutanol from sugars after the saccharification of used cotton fibers, which is an innovative bioprocess invented by RITE.

Despite the various challenges of scaling up from the lab level to the business level, this project aims to operate in 2020 Japan's first chartered flight running on this biojet fuel.



Molecular Microbiology and Biotechnology Group

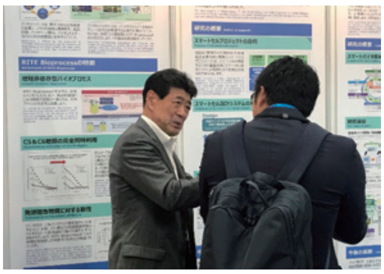
BioJapan 2019

The World Business Forum's "BioJapan 2019" was held at PACIFICO Yokohama on October 9-11, 2019, along with Regenerative Medicine JAPAN 2019. Many companies, government agencies, universities, and so on from Japan and overseas participated; the number of exhibitors was 974 (879 in 2019) and the number of visitors was 17,512 (16,309 in 2018), both being the largest ever.

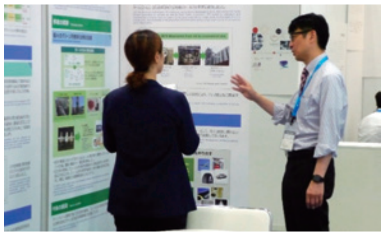
RITE had a joint booth at the exhibition in collaboration with Green Chemicals Co., Ltd. (GCC).

In the booth, we introduced our key technologies, as well as our current projects funded by METI and NEDO. We also explained the activities of Green Earth Institute Co., Ltd. (GEI) by giving examples of the commercial uses of the RITE Bioprocess, and technologies for producing green-aromatic compounds, together with our introduction to GCC. We displayed the following posters in the exhibition booth.

1) New trends in biotechnological production or green-aromatic compounds
2) RITE Core Technology: Biorefinery
3) Smart Cell Project
4) Development of technologies for functional design and production or innovative biomaterials
5) R&D of Biofuels (Bio-butanol／Bio-hydrogen)
6) R&D for a novel bioprocess to produce 100% green jet fuel
7) Green Chemicals Co., Ltd. (GCC)
8) Green Earth Institute Co., Ltd. (GEI)
9) Collaboration with the JAL biojet fuel flight project

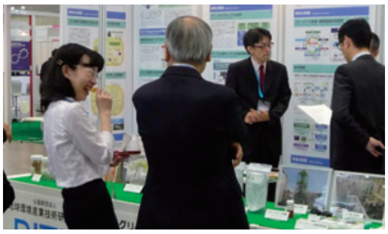


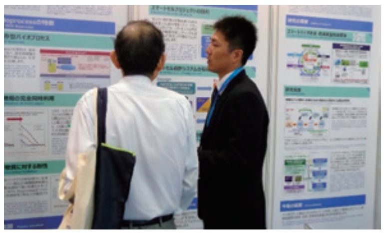
We also had exhibits that included various samples and pictures, such as several types of non-food biomass; amino acids, including L-alanine and L-valine, which are commercial products made by GEI using the RITE Bioprocess; GEI's ethanol for cosmetics; and green phenolic moldings from GCC.

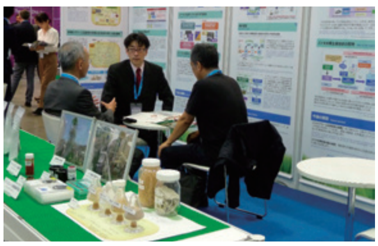


Nearly 120 people from various industries, universities, and governments came to the RITE/GCC booth during the three-day exhibition, and they eagerly asked questions to the RITE researcher, who gave explanations. This made us realize the great expectations from biorefinery as a technology.

We would like to extend our appreciation to all those who attended this event and visited our booth.







Chemical Research Group

Fifth Post Combustion Capture Conference (PCCC-5)

RITE hosted the fifth Post Combustion Capture Conference (PCCC-5) in Kyoto on 17 –19 September 2019. PCCC is organized by IEAGHG (IEA Greenhouse Gas R&D Programme) every two years, and past conferences were held in UAE, Norway, Canada, and the United States. This time, around 140 participants from 19 countries gathered with great success.

Technical sessions with 74 oral presentations and 11 poster presentations prompted lively discussions by experts from Japan and abroad. Plenary and keynote presentations from Japan were good opportunities to show off the competitiveness of the PCC technical field.

RITE also described the latest achievements in chemical absorption, solid sorbents, and membrane separation. In addition, a site visit to the Kansai Electric Power / Mitsubishi Heavy Industries Engineering (Osaka City) and Kawasaki Heavy Industries (Akashi City) was held the day after the conference.

We would like to thank all visitors for the success of PCCC-5.

Date: 17–19 September 2019
Venue: Hotel Granvia Kyoto (Kyoto, Japan)
Host: IEAGHG, RITE
Sponsors: IHI, KHI, Toshiba, MHI Eng. CO2CRC, DOE, Southern Company/NCCC
Sessions: Demonstration, Technologies, Modelling, Environment, Industries, Cost, etc.

CO_2 Storage Research Group

International CCUS Roundtable and Recommendations for G20 in Japan

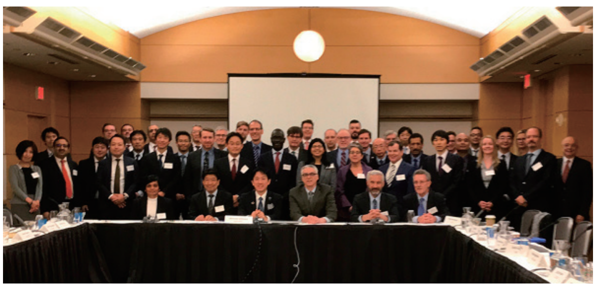
Since Japan planned to host the G20 meetings in June 2019, RITE, prior to them, hosted an international Carbon dioxide Capture, Utilization and Storage (CCUS) roundtable and developed based on dis-cus-sions there to publicize recommendations to G20.

RITE, in conjunction with a US think tank the Center for Climate and Energy Solutions (C2ES) and funded by the Ministry of Economy, Trade and Industry (METI), organized the roundtable in Washington DC in the USA on 13－14 February 2019. The meeting was attended by more than 60 from governments, major companies in the energy and financial sectors, international organizations and NGOs in 11 countries, including Japan's Parliamentary Vice-Minister of Economy, Trade and Industry, a US senator and US Under Secretary of Energy. The participants discussed longitudinal perspectives, the state of CCUS and opportunities for international collaboration, policies, financing, and knowledge sharing and international collaboration, and then explored recommendations for strengthening international collaboration to accelerate the deployment of CCUS at the G20 summit in Japan.

The final recommendations were released in March 2019, namely.

- to highlight the importance and benefits of CCUS and to call for stronger action to advance the deployment of CCUS in the communiqués of the energy and environ-ment ministerial meeting and the summit,
- to develop joint action plans on CCUS and to integrate CCUS in national action plans to be developed by individual G20 members, and
- to promote carbon recycling.

In the communiqué of the G20 Karuizawa energy and environment ministerial meeting, the ministers recognize the potential of CCUS and the need for investment in and financing CCUS. In its action plan, they are committed to seek to enhance international cooperation on CCUS in relevant existing fora and to encourage CCUS research, development and deployment. CCUS is also referred to in six national action plans out of 16 submitted to the G20. We can say that our recommendations were by and large incorporated and we believe that RITE contributed to the success of the Japan-hosted G20 meetings.



Source: METI web site, (https://www.meti.go.jp/press/2018/02/20190215006/20190215006.html)

CO_2 Storage Research Group

CCS Technical Workshop 2020

The commercialization of CCS technology requires not only technical development but also social and economic improvements in economics, public awareness, and incentives for the private sector. The CCS Technical Workshop 2020 provided an opportunity of learning initiatives for the commercialization of CO_2 geological storage and CO_2-enhanced oil recovery (CO_2-EOR) in the United States and Norway. The workshop was concluded with update on research and development in the Geological Carbon Dioxide Storage Technology Research Association, Japan.

Date: 23 January 2020

Venue: Toranomon Hills Forum (Tokyo)

Organizer: The Geological Carbon Dioxide Storage Technology Research Association

Co-organization: The Ministry of Economy, Trade and industry (METI) / the New Energy and Industrial Technology Development Organization (NEDO)

Number of Participants: 378

Program:

Talk1-1: Scaling up to industrial CCUS projects: A regional perspective, North Dakota, USA
John Hamling, Assistant director for Integrated Projects, Energy & Environmental Research Center (EERC), University of North Dakota, USA

Talk1-2:Red Trail Energy (RTE) Carbon Capture and Storage (CCS) Project
Dustin Willett, Chief operating officer, RTE, North Dakota, USA

Talk2:Creating value from CO_2 monitoring
Prof. Sally Benson, Co-director, Precourt Institute for Energy Professor, Energy Resources Engineering Department, Stanford University, USA

Talk3: CarbonSAFE Illinois
Steven Whittaker, Director, Energy & Minerals, Illinois State Geological Survey University of Illinois, USA

Talk4: CO_2 storage technology and pathway to global scale-up
Philip Ringrose, Specialist, Reservoir Geoscience, Equinor ASA Adjunct Professor, NTNU, Norway

Talk5:Efforts to develop safety management technology in Geological Carbon Dioxide Storage Technology Research Association
Ziqiu Xue, General Manager, Technical division, Geological Carbon Dioxide Storage Technology Research Association

Inorganic Membranes Research Center

Inorganic Membrane Environment and Energy Technology Symposium to Explore the Future

In this symposium, under the theme of carbon recycling, universities, companies, and general foundations gave lectures on the latest trends in hydrogen production technology and CO_2 separation and recovery technology and their efforts for practical use. The latest research results of the Inorganic Membranes Research Center (IMeRC) and the activities of the Industrialization Strategy Council were also introduced.

We received favorable comments from visitors, such as "I was able to see the potential for new innovation by combining elemental technologies of CO_2 separation, methanation, and membrane reactors using inorganic membranes. The content was very suggestive of the potential for CCU and carbon recycling."

Program :

・Keynote Lecture: Expectations and prospects for energy and environmental innovation, Kenji Yamaji, Senior Vice President RITE

・Lecture ①: Hydrogen, hydrocarbons and CO_2 related solid catalyst processes and possibility for membrane applications, Yasushi Sekine, Professor, Waseda University

・Lecture ②: Research and development on integration between methanation and CO_2 capture, Koyo Norinaga, Professor, Nagoya University

・Lecture ③: Power to Gas for low carbon Society; the role of methanation, Yoshiaki Shibata, Manager, New and Renewable Energy Group,

・Lecture ④: JGC's effort for CO_2 separation process using DDR-type zeolite membrane, Nobuyasu Chikamatsu, Group Leader, JGC Corporation Oil & Gas Project Company Technology Innovation Center

・Activity report: Recent research in Inorganic Membranes Research Center and future development, Shin-ichi Nakao, Director, IMReC, RITE

In order to introduce the recent achievements of our research and development and also to promote the collaboration among industry, government and academia, RITE is providing the most advanced information for mitigating global warming through symposiums and various media.

In addition, we actively engage in environmental education activities on global warming issue targeting students from elementary school to high school mainly in the Keihanna district where RITE is located.

Symposiums

Date	Symposium Description	Related Dept.
16 Jan. 2019	**CCS Technical Workshop 2019** ・Venue：Toranomon Hills Forum ・Organizer：Geological Carbon Dioxide Storage Technology Research Association (GCS) ・Number of participants：362	CO_2 Storage Research Group
18 Jan. 2019	**8th Symposium for Innovative CO_2 Membrane Separation Technology** ・Venue：Ito Hall ・Organizer：Molecular Gate Membrane module Technology Research Association (MGMTRA) ・Number of participants：179	Chemical Research Group
19 Feb. 2019	**FY2018 ALPS International Symposium** ・Venue：Toranomon Hills Forum ・Organizer：RITE ・Number of participants：278	Systems Analysis Group
6 Mar. 2019	**IPCC Symposium "To Think about Measures for Mitigation of Global Warming"** ・Venue：Toranomon Hills Forum ・Organizer：Ministry of Economy, Trade and Industry ・Co-Organizer：RITE ・Number of participants：269	Research & Coordination Group
26 Sep. 2019	**Symposium in Kansai on Global Warming Mitigation Technology for Future Society** ・Venue：Osaka Science & Technology Center ・Organizer：RITE ・Number of participants：182	Research & Coordination Group
7 Nov. 2019	**Inorganic Membrane Environment and Energy Technology Symposium to Explore the Future** ・Venue：Ito Hall ・Organizer：RITE ・Number of participants：191	Inorganic Membranes Research Center
18 Dec. 2018	**Innovative Environmental Technology Symposium 2019** ・Venue：Ito Hall ・Organizer：RITE ・Number of participants：491	Research & Coordination Group
20 Jan. 2020	**Symposium for Innovative CO_2 Separation Technology** ・Venue：Ito Hall ・Organizer：RITE, Molecular Gate Membrane module Technology Research Association (MGMTRA) ・Number of participants：294	Chemical Research Group
23 Jan. 2020	**CCS Technical Workshop 2020** ・Venue：Toranomon Hills Forum ・Organizer：Geological Carbon Dioxide Storage Technology Research Association (GCS) ・Number of participants：378	CO_2 Storage Research Group

Exhibitions

Dates	Event Description	Related Dept.
25 Sep. 2019	**International Conference on Carbon Recycling 2019** Venue：Hotel New Otani Tokyo Organizer：Ministry of Economy, Trade and Industry New Energy and Industrial Technology Development Organization	Molecular Microbiology and Biotechnology Group, Chemical Research Group
9-11 Oct. 2019	**BioJapan 2019** Venue：Pacifico Yokohama Organizer：BioJapan Organizing Committee,JTB Communication Design, Inc.	Molecular Microbiology and Biotechnology Group

Press Releases

Date	Title
11 Jan. 2019	Announcement of FY2018 ALPS International Symposium
6 Feb. 2019	Announcement of IPCC Symposium "To Think about Measures for Mitigation of Global Warming"
13 Feb. 2019	Announcement of International Roundtable: Strengthening Collaboration on Carbon Capture, Utilization and Storage (CCUS) in Washington, D.C.
28 Mar. 2019	Recommendations to Strengthen International Collaboration on CCUS to G20 governments
2 Jul. 2019	Announcement of Symposium in Kansai on Global Warming Mitigation Technology for Future Society
12 Sep. 2019	Announcement of Inorganic Membrane Environment and Energy Technology Symposium to Explore the Future
23 Oct. 2019	Announcement of Symposium for Innovative CO_2 Separation Technology
28 Oct. 2019	Announcement of Innovative Environmental Technology Symposium 2019
3 Dec. 2019	Announcement of CCS Technical Workshop 2020
23 Dec. 2019	Announcement of IPCC Symposium "Measures for Mitigating Climate Change that We Should Take Now"

Environmental Education

◇Facility Visit Program and Lecture

Date	Participants	Number of participants
21 Jan.	Seikaminami Junior High School	4
31 Jan.	Kizugawadai Elementary School	31
19 Apr.	TOKIWA Inc.	63
30 May	Seisho High School	39
21 Jun.	Ritsumeikan Senior High School	24
12 Jul.	Tezukayama Junior High School	23
31 Jul.	Nishimaizuru High School	6
7 Aug.	Nara Prefectural Super Science High School Students	16
21 Aug.	Nishiyamatogakuen Junior High School	24
19 Sep.	Naragakuen Tomigaoka Junior High School	15
2 Oct.	Izumo Senior High School	40
11 Oct.	MASUDA Senior High School	20
15 Nov.	Seikanishi Junior High School	6

◇Workshop and Exhibition

Date	Title	Number of participants
26 Jan.	KEIHANNA Science Festival 2019	102
Jul. – Aug.	Craft and Science Experiment to Learn about the Future Energy	-

Directors

Original Paper

	Title	Researchers	Journal
1	Towards net zero CO_2 emissions without relying on massive carbon dioxide removal	Y. Kaya, M. Yamaguchi, O. Geden	Sustainability Science, Vol.14, pp.1739–1743, 2019

Oral Presentation (Domestic Academic Society)

	Title	Researchers	Forum
1	Exploring ultimate objective of climate strategies through reviewing role of IPCC	Mitsutsune Yamaguchi	Society for Environmental Economics and Policy Studies (SEEPS) 2019 Annual Conference, Sep. 28, 2019

Systems Analysis Group

Original Paper

	Title	Researchers	Journal
1	An analysis on changes in risks of high temperature and precipitation days due to climate change in global major urban areas	A. Hayashi, M. Kii	Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management), Issue 74, No. 5, I 379-I 387, Jan. 10, 2019
2	Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges	Masahiro Sugiyama, Shinichiro Fujimori, Kenichi Wada, Seiya Endo, Yasumasa Fujii, Ryoichi Komiyama, Etsushi Kato, Atushi Kurosawa, Yuhji Matsuo, Ken Oshiro, Fuminori Sano, Hiroto Shiraki	Energy, Volume 167, pp 1120-1131, Jan. 1, 2019
3	A model-based analysis on energy systems transition for climate change mitigation and ambient particulate matter 2.5 concentration reduction	K. Gi, F. Sano, A. Hayashi, K. Akimoto	Mitigation and Adaptation Strategies for Global Change, Volume 24, Issue 2, pp. 181-204, Feb. 1, 2019
4	The role of methane in future climate strategies: mitigation potentials and climate impacts	H. Mathijs, D. van Vuuren, B. L. Bodirsky, J. Chateau, O. D.-Lasserve, L. Drouet, O. Fricko, S. Fujimori, D. Gernaat, T. Hanaoka, J. Hilaire, K. Keramidas, G. Luderer, M. C. Moura, F. Sano, S. Smith, K. Wada	Climatic Change, May 24, 2019
5	Taking some heat off the NDCs ? The limited potential of additional short-lived climate forcers' mitigation	H. Mathijs, O. Fricko, J. Hilaire, D. van Vuuren, L. Drouet, O. D.-Lasserve, S. Fujimori, K. Keramidas, Z. Klimont, G. Luderer, L. A. Reis, K. Riahi, F. Sano, S. Smith	Climatic Change, June 17, 2019
6	Mid-century emission pathways in Japan associated with the global 2℃ goal: national and global models' assessments based on carbon budgets	K. Oshiro, K. Gi, S. Fujimori, H. L. van Soest, C. Bertram, J. Despres, T. Masui, P. Rochedo, M. Roelfsema, Z. Vrontisi	Climatic Change, July 20, 2019
7	An analysis of Japan's long-term energy systems reflecting fusion energy development roadmap by using a global energy systems model	K. Gi, F. Sano, K. Akimoto, R. Hiwatari, K. Tobita	Journal of Japan Society of Energy and Resources, Sep. 10, 2019

Other Paper

	Title	Researchers	Forum
1	Significance and challenges of technologies for CCS and CCU under the Paris Agreement	K. Akimoto	Monthly publication of Japan Society of Mechanical Engineers, Feb. 2019
2	Overview of IPCC Special Report on Global warming of 1.5℃ and its Implications	K. Akimoto, K. Gi	Energy and Resources, July 1, 2019
3	Prospect for global warming and energy policy: The direction of the company response based on the trends for both domestic and overseas.	K. Akimoto	"Environmental Management" Monthly Issue October, Oct. 1, 2019

Oral Presentation (International Academic Society)

	Title	Researchers	Forum
1	The strategy of delivering CCS projects: Lessons from three-decade pilot and demonstration experience	N. Wang, K. Akimoto	MIT Applied Energy Symposium 2019, May 24, 2019, USA
2	Analysis of Energy Intensity of Basic Materials Industry in Japan	J. Oda, K. Akimoto	42nd IAEE International Conference, June 1, 2019, Canada
3	Bottom-up development of service demand scenarios by consideration of heterogeneous actors and transparent reflection of a narrative of future socioeconomic change: A case study of passenger travel demand in Japan	K. Gi, F. Sano, K. Akimoto	38th International Energy Workshop, June 6, 2019, France

Systems Analysis Group

	Title	Researchers	Forum
4	Evaluations on consumption-based CO_2 emissions in Europe	T. Homma	The 16th IAEE European Conference, Aug. 27, 2019, Slovenia
5	Current policies and issues, and strategies in the future on energy and climate change response	K. Akimoto	10th International Symposium of Advanced Energy Science: Beyond the Decade of Zero Emission Energy, Sep. 4, 2019, Japan
6	Development of energy demand scenarios taking sharing economy evolution into account based on SSPs and its alleviating effect on emissions reductions efforts	K. Akimoto, F. Sano, J. Oda, K. Gi, H. Kanaboshi, T. Nagata	Scenarios Forum2019, Mar. 11-13, 2019, USA
7	Conditions and mechanism behind co-benefits of CO_2 emissions reduction and ambient PM2.5 concentration reduction in China and India	K. Gi, F. Sano, A. Hayashi, K. Akimoto	Twelfth Annual Meeting of the IAMC, Dec. 2, 2019, Japan
8	Japan's emission pathways in the context of the 2℃ goals and their implications for the mid-century strategy	K. Oshiro, S. Fujimori, K. Gi, H. van Soest, C. Bertram , J. Després, T. Masui, P. Rochedo, M. Roelfsema, Z. Vrontisi	Twelfth Annual Meeting of the IAMC, Dec. 3, 2019, Japan

Oral Presentation (Domestic Academic Society)

	Title	Researchers	Magazine, Newspaper, etc.
1	Mobility Demand in Japan: An Analysis of Current Structure by Reconstruction of National Statistics and Development of Futures Scenarios	K. Gi, F. Sano, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
2	Analysis on decoupling between economic growth and CO_2 emissions, based on evaluations of consumption-based CO_2 emissions	T. Homma, J. Oda, S. Chen, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
3	An Analysis on Climate Change Mitigation Considering Relationship among Petroleum-related Products by Using a Global GHG Mitigation Assessment Model	H. Kanaboshi, F. Sano, K. Akimoto, M. Nagashima	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
4	The role of financial sector in addressing climate change: Study on the impact of fossil fuel divestment	M. Nagashima, K. Akimoto, F. Sano	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
5	The Chinese CO_2 emission: The Impact of Business Cycle and Structural Break	N. Wang, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
6	Analysis on the contribution of natural gas as medium and long term global warming countermeasure	T. Nagata, F. Sano, T. Homma, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 29, 2019
7	An Analysis of Japan's Fusion Energy Development Scenarios	K. Gi, F. Sano, K. Akimoto, R. Hiwatari, K. Tobita	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
8	Analysis of Energy Intensity of Major Materials Industry in Japan	J. Oda, T. Homma, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
9	Analyses of Price Volatility in Deregulated Electricity Market and Its Effect on Global Warming Policy	Y. Nakano, J. Oda, F. Sano, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
10	A Study on Opportunities for Reducing GHG Emissions Relating to Supply and Demand Processes for Food Considering Progress of Information Technologies and the Like	A. Hayashi, T. Homma, F. Sano, N. Nakamura, K. Akimoto	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
11	An Analysis on the Global Warming Risk Management by CO_2 Direct Air Capture	Y. Arino, K. Akimoto, F. Sano, N. Nakamura	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
12	Support for implementing climate technology activities under the UNFCCC	K. Wada	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
13	An evaluation of climate change mitigation under the socioeconomic scenarios considering diffusion of sharing economy	F. Sano, K. Akimoto, K. Gi	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
14	Implicit discount rate for investment and its consideration in Energy Economics Model	K. Akimoto, M. Nagashima, F. Sano,	The 35th Conference on Energy, Economy, and Environment, Jan. 30, 2019
15	Revisiting CCS Deployment: Empirical analysis of three-decade global pilot and demonstration project	N. Wang, K. Akimoto	The 38th Annual Meeting of Japan Society of Energy and Resources,, Aug. 6, 2019
16	Comprehensive analysis on energy and global warming induced sharing economy by technology innovation	K. Akimoto, F. Sano, K. Gi, J. Oda, T. Nagata, H. Kanaboshi	The 38th Annual Meeting of Japan Society of Energy and Resources, Aug. 6, 2019
17	Estimation of passenger travel demand on various energy models	K. Gi, K. Akimoto,	The 38th Annual Meeting of Japan Society of Energy and Resources, Aug. 6, 2019
18	Current long-term energy policy on climate change	K. Akimoto	Japan Institute of Energy, Aug. 8, 2019

Systems Analysis Group

	Title	Researchers	Magazine, Newspaper, etc.
19	Energy model on passenger travel section toward the analysis of long-term scenario	K. Gi	Symposium on arrangement of information and perspective and method for long-term strategy reducing greenhouse gas emission, Aug. 21, 2019

Other Oral Presentation and Non-Journal Publication

	Title	Researchers	Magazine, Newspaper, etc.
1	The 5th Strategic Energy Plan	K. Akimoto	Lectures for the Center for Development of Power supply regions, Jan. 11, 2019
2	Present status of researches on climate change mitigation	F. Sano	Joint research workshop of Tougou C/D and SI-CAT, Jan. 15, 2019
3	Chapter 5"Sustainable Development, Poverty Eradication and Reducing Inequalities"	K. Gi	2018 special lecture on energy, Japan Society of Energy and Resources, Jan. 18, 2019
4	The 5th Strategic Energy Plan	K. Akimoto	Workshop for the Electric Power Council for a Low Carbon Society, Jan. 23, 2019
5	A review of electricity supply and demand structure of 2030 in Basic Energy Plan	K. Akimoto	Symbio community forum, Jan. 28, 2019
6	Analysis of the role of CCS in long-term CO_2 emission reductionby integrated assessment model	J. Oda	I2CNER International Workshop (CO_2 Capture and Utilization), Feb. 1, 2019
7	Opportunities for achieving low energy demand society through innovations, the quantitative analyses of their impact on climate change mitigation, and future issues to be tackled	K. Akimoto	Energy Transitions Working Group (ETWG) Meeting for G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, Feb. 12, 2019
8	Analyses on energy and climate change-related issues and future strategies	K. Akimoto	Research Committee on Natural Resources and Energy, the House of Councillors, National Diet of Japan, Feb. 13, 2019
9	Innovations of products, services and social systems, and their impacts on climate change mitigation measures	K. Akimoto	ALPS International Symposium, Feb. 19, 2019
10	System cost evaluation of diversifying power source -hidden costs and policy issues-	K. Akimoto	The 26th Power Talk, Japan Energy Association, Feb. 21, 2019
11	The emission pathways and mitigation costs for achieving below 1.5℃ and the impacts of low energy demand scenarios	K. Akimoto	IPCC Symposium, Mar. 6, 2019
12	Global warming in progress and energy issues	K. Akimoto	Energy lecture meeting in Hokugenkon, Mar. 19, 2019
13	Current status of renewable energies usage, and Efforts towards Global warming issues	K. Akimoto	Present and Future of Nuclear, Mar. 20, 2019
14	Activity status and outlook of technology mechanism	K. Wada	The 82nd TECUSE Study Meeting, Apr. 17, 2019
15	How to read IPCC special report: an unintended bias	K. Akimoto	IEEI web article, Apr. 19, 2019
16	Current condition of energy and global warming mitigation, and pathways towards deep CO_2 emissions reduction	K. Akimoto	Lecture meeting at Meisho Eco Club, Nagoya Chamber of Commerce & Industry, Apr. 24, 2019
17	Conditions surrounding climate change and the future of energy and global warming countermeasures and issues	K. Akimoto	The 29th energy symposium, Environmental and energy research conference of 3 labor association in Chugoku district, June 1, 2019
18	Impacts of realization of low-energy demand society due to technology development in IoT or AI on the long-term target under the Paris Agreement	K. Akimoto	Open Symposium of Science Council of Japan "Roles and issues of innovation for long-term, deep emissions reductions of GHG", June 6, 2019
19	Effects of global warming mitigation measures induced by sharing economy	K. Akimoto	Green Forum 2, June 27, 2019
20	Global warming and energy problem – Solution to complex economics and policies	K Akimoto	General Meeting of Yokohama Electrical Engineering and Computer Science, July 13, 2019
21	Global energy system comparison review under Paris Agreement toward 2050	K. Akimoto	Society of Automotive Engineer of Japan, Inc., Sep. 25, 2019
22	The global energy system of long-term decarbonization-The role of hydrogen and electricity-	K. Akimoto	Symposium for Global warming Solutions to Support Our Future Society in Kansai, Sep. 26, 2019

Systems Analysis Group

	Title	Researchers	Magazine, Newspaper, etc.
23	The economic analysis of the fusion power considering global warming response	K. Akimoto	Ministry of Education, Culture, Sports, Science and Technology, Oct. 08, 2019
24	Impacts of IT and AI on Energy Consumption and CO_2 Emission Reductions	K. Akimoto	ICEF, 6th Annual Meeting, Oct. 10, 2019
25	Analysis on climate change - Challenges and solutions for integrated cost minimization analysis-	K. Akimoto	Research Report at The Institute of Energy Economics, Japan, Oct.15, 2019
26	Japan's long-term strategy to achieve Paris Agreement	K. Akimoto	2019 Energy Lecture at Kyushu District Conversazione on energy problem, Oct. 25, 2019
27	Toward the sustainable development: Long-term vision for climate change and short-and-medium term behavior considering actual restrictions	K. Akimoto	The Iron and Steel Institute of Japan, Oct. 28, 2019
28	The reduction of greenhouse gas emissions for long-term goal of Paris Agreements	K. Akimoto	13th YGN young researcher study meeting at Atomic Energy Society of Japan,Decarbonization, innovation, the role of nuclear power, Nov. 1, 2019
29	The keys of virtuous circle according to technological innovation	K. Akimoto	Morning Edition of The Nikkei, Nov. 7, 2019
30	Global warming and energy	K. Akimoto	Seminar to Enjoy Learning about Unusual Weather and Environmental Problem, Nov. 9, 2019
31	Opportunities and Challenges, and Impacts of Low Energy Demand Society	K. Akimoto	Joint IIASA-RITE International Workshop: Towards Improved Understanding, Concepts, Policies and Models of Energy Demand, Nov. 11, 2019
32	Preliminary Modeling Analyses on Global Impacts of Sharing Mobility Beyond Transportation Sector	K. Gi	Joint IIASA-RITE International Workshop: Towards Improved Understanding, Concepts, Policies and Models of Energy Demand, Nov. 13, 2019
33	Evaluations on International Competitiveness of NDCs and the Implications of Long-term Deep Emission Reductions	K. Akimoto	Japan Pavilion of Side Event at COP25, Dec. 12, 2019, Spain
34	Evaluations on International Competitiveness of NDCs and the Role of Technological and Social Innovations toward the Paris Long-term Goals	K. Akimoto	Official Side Event of the UN Climate Change Conference at COP25, Dec. 12, 2019, Spain
35	Evaluating energy system transition towards decarbonized society	K. Akimoto	Innovative Environmental Technology Symposium 2019, Dec. 18, 2019

Molecular Microbiology and Biotechnology Group

Original Paper

	Title	Researchers	Journal
1	Enhanced production of D-lactate from mixed sugars in *Corynebacterium glutamicum* by overexpression of glycolytic genes encoding phosphofructokinase and triosephosphate isomerase	Y. Tsuge, N. Kato, S. Yamamoto, M. Suda, M. Inui	Journal of Bioscience and Bioengineering, Vol.127, pp.288-293, 2019
2	Introduction of glyoxylate bypass increases hydrogen gas yield from acetate and L-glutamate in *Rhodobacter sphaeroides*	T. Shimizu, H. Teramoto, M. Inui	Applied and Environmental Microbiology, Vol.85, e01873-18, 2019
3	Carbohydrate-binding property of a cell wall integrity and stress response component (WSC) domain of an alcohol oxidase from the rice blast pathogen *Pyricularia oryzae*	S. Oide, Y. Tanaka, A. Watanabe, M. Inui	Enzyme and Microbial Technology, Vol.125, pp.13-20, 2019
4	Metabolic engineering of *Corynebacterium glutamicum* for hyperproduction of polymer-grade L- and D-lactic acid	Y. Tsuge, N. Kato, S. Yamamoto, M. Suda, T. Jojima, M. Inui	Applied Microbiology and Biotechnology, Vol.103, pp.3381-3391, 2019
5	Development of biorefinery technology for bioeconomy	K. Toyoda, M. Inui	Journal of environmental conservation engineering, Vol.562, pp.141-145, 2019
6	Bioenergy and Biorefinery	S.O. Han, M. Inui, Y.S. Jin	Biotechnology Journal, Vol.14, e1900160, 2019
7	Development of bioproduction technology for aromatic compounds	Y. Kitade, M. Inui	Japan Plastics, Vol.107, pp.20-23, 2019

Molecular Microbiology and Biotechnology Group

	Title	Researchers	Journal
8	Engineering the transcriptional activator NifA for the construction of *Rhodobacter sphaeroides* strains that produce hydrogen gas constitutively	T. Shimizu, H. Teramoto, M. Inui	Applied Microbiology and Biotechnology, Vol.103, pp.9739-9749, 2019
9	Development of bio-based overproduction technology for aromatic compounds	Y. Kitade, M. Inui	Adhesion technology, Vol.136, pp.22-26, 2019
10	Isobutanol production in *Corynebacterium glutamicum*: suppressed succinate by-production by *pckA* inactivation and enhanced productivity *via* the Entner–Doudoroff pathway	S. Hasegawa, T. Jojima, M. Suda, M. Inui	Metabolic Engineering, (in press)

Oral Presentation (International Academic Society)

	Title	Researchers	Forum
1	Identification of the regulon of the ECF sigma factor SigE in *Corynebacterium glutamicum*	Koichi Toyoda, Masayuki Inui	FEMS2019 8th Congress of European microbiologists, Jul. 7-11, 2019
2	The regulon of the ECF sigma factor SigE in *Corynebacterium glutamicum*	Koichi Toyoda, Masayuki Inui	14th international symposium on the genetics of industrial microorganisms (GIM2019), Sep. 8-11, 2019

Oral Presentation (Domestic Academic Society)

	Title	Researchers	Forum
1	Improvement of H_2 yield from acetate by engineering of *nifA* and disruption of the Calvin cycle in *Rhodobacter sphaeroides*	Tetsu Shimizu, Haruhiko Teramoto, Masayuki Inui	The 2019 Annual Meeting of The Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 24-27, 2019
2	Regulation of RNase III expression in *Corynebacterium glutamicum*	Masato Sawa, Yuya Tanaka, Masayuki Inui	The 2019 Annual Meeting of The Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 24-27, 2019
3	Development of a CRISPR-Cas9-based genome engineering tool for *Corynebacterium glutamicum*	Hikaru Ozawa, Takeshi Kubota, Masako Suda, Masayuki Inui	The 2019 Annual Meeting of The Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 24-27, 2019
4	Analysis of transcriptional regulation mechanism of asparagine catabolic operon in *Corynebacterium glutamicum*	Riki Sugaya, Koichi Toyoda, Masako Suda, Kazumi Hiraga, Masayuki Inui	The 2019 Annual Meeting of The Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 24-27, 2019
5	Identification of the regulon of the ECF sigma factor SigE in *Corynebacterium glutamicum*	Koichi Toyoda, Masayuki Inui	The 71th Annual Meeting of the Society of Biotechnology of Japan, Sep. 16-18, 2019

Other Oral Presentation and Non-Journal Publication

	Title	Researchers	Magazine, Newspaper, etc.
1	Development of green bioprocess toward realizing a carbon recycling society	Masayuki Inui	Symposium of The 6th Society of Biotechnology of Japan, May 24, 2019
2	Development of green bioprocesses for the realization of bioeconomy	Masayuki Inui	19-2 Polymer Frontier 21, The Society of Polymer Science, Japan, Jun. 11, 2019
3	R&D for a novel bioprocess to produce 100% green jet fuel	Masayuki Inui	Symposium of The 71th Annual Meeting of the Society of Biotechnology of Japan, Sep. 18, 2019
4	Development of biorefinery technology to realize a sustainable society	Masayuki Inui	Symposium in Kansai on Global Warming Mitigation Technology for Future Society, Sep. 26, 2019
5	The emerging green bioprocess technology to attain a carbon-free society	Masayuki Inui	Innovation for Cool Earth Forum (ICEF) 6th Annual Meeting, Oct. 9, 2019
6	Development of biorefinery production technology to attain a sustainable society	Takeshi Kubota	BioJapan 2019 Exhibitor presentation, Oct. 10, 2019
7	Present development status and future prospects of biochemical production technology	Masayuki Inui	Biomass Seminar, Tokyo Tech Alumni Association, Oct. 18, 2019
8	Development of biorefinery production technology for the realization of decarbonized society	Masayuki Inui	New Energy Div., The Japan Petroleum Institute, Nov. 21, 2019
9	Development of green bioprocess for the realization of decarbonized society	Masayuki Inui	Innovative Environmental Technology Symposium 2019, Dec. 18, 2019
10	Feature "Flying on bio jet fuel !"	-	Ashita no Tsubasa ("Wings of tomorrow") (Japan Airlines Co., Ltd.), Spr. 2019
11	FLY INTO TOMORROW "SDGs -JAL initiatives-/73rd Flying on bio jet fuel !"	-	SKYWARD (Japan Airlines Co., Ltd.), Vol.5, 2019

Molecular Microbiology and Biotechnology Group

	Title	Researchers	Magazine, Newspaper, etc.
12	Symposium of The 6th Society of Biotechnology of Japan	-	Seibutsu-kogaku Kaishi, Vo.97, No.8, 2019

Chemical Research Group

Original Paper

	Title	Researchers	Journal
1	Development of high-performance polymer membranes for CO_2 separation by combining functionalities of polyvinyl alcohol (PVA) and sodium polyacrylate (PAANa)	Fuminori Ito, Yuriko Nishiyama, Shuhong Duan, Hidetaka Yamada	Journal of Polymer Research Vol.26, 106 (2019)
2	Ab Initio Study of CO_2 Capture Mechanisus in Aqueous 2-Amino-2-methyl-1-propanol:Electronic and Steric Effects of Methyl Substituents on the stability of Carbamate	Hidetaka Yamada, Firoz A. Chowdhury, Shin Yamamoto, Kazuya Goto	Industrial & Engineering Chmistry Research Vol.58 Issue8 pp. 3549-3554, 2019
3	Oxidative Degradation of Tetraethylenepentamine-Impregnated Silica Sorbents for CO_2 Capture	Quyen T. Vu, Hidetaka Yamada, Katsunori Yogo	Energy Fuels Vol.33 Issue4 pp. 3370-3379, 2019
4	Preparation of Biodegradable Polymer Nanospheres Containing Manganese Porphyrin (Mn-Porphyrin)	Fuminori Ito, Hidetaka Yamada, Kiyoshi Kanamura, Hiroyoshi Kawakami	Journal of Inorganic and Organometallic Polymers and MaterialsVol.29, 3, pp 1010–1018, 2019
5	Enhancement Mechanism of the CO_2 Adsorption–Desorption Efficiency of Silica-Supported Tetraethylenepentamine by Chemical Modification of Amino Groups	Hidetaka Yamada, Firoz A. Chowdhury, Junpei Fujiki, Katsunori Yogo	ACS Sustainable Chemistry & EngineeringVol.7 Issue10 pp. 9062-9726 May 20, 2019
6	Bottom-Up Synthesis of Defect-Free Mixed-Matrix Membranes by Using Polymer-Grafted Metal–Organic Polyhedra	Nobuhiko Hosono, Wenbo Guo, Kenichiro Omoto, Hidetaka Yamada, Susumu Kitagawa	Chemistry LettersVol.48 No.6 pp. 597–600, 2019"
7	Water adsorption on nitrogen-doped carbons for adsorption heat pump/desiccant cooling: Experimental and density functional theory calculation studies	Junpei Fujiki, Katsunori Yogo	Applied Surface Science, Vol. 492, 30 October 2019, pp. 776-784
8	Examination of selection and combination of water-absorbing agent to blend with polyvinyl alcohol (PVA) in preparing CO_2 separation membrane with high performance	Fuminori Ito, Yuriko Nishiyama, Shuhong Duan, Hidetaka Yamada	Macromolecular Research(online) Nov. 22, 2019
9	Effect of Carbonic Anhydrase on CO_2 Separation Performance of Thin Poly(amidoamine) Dendrimer/ Poly(ethylene glycol) Hybrid Membranes	Shuhong Duan, Teruhiko Kai, Shin-ichi Nakao	Membranes 9(12), 167, 2019

Oral Presentation (International Academic Society)

	Title	Researchers	Forum
1	Experimental and DFT Calculation Studies on Water Vapor Adsorption on Nitrogen-Doped Carbons	Junpei Fujiki, Katsunori Yogo	FOA2019（13th International Conference on Fundamentals of Adsorption）, May 26-31, 2019
2	Development of Amine-based Solvents for CO_2 Capture from Blast Furnace Gas	Kazuya Goto, Firoz. A. Chowdhury, Hidetaka Yamada, Shin Yamamoto, Yoichi Matsuzaki, Masami Onoda	World Hydrogen Technologies Convention(WHTC)2019, Tokyo, Japan, Jun. 2-7, 2019
3	Simulation of Amine-Based CO_2 Capture Using Transtion State Theory	Hidetaka Yamada	17th International Conference on Carbon Dioxide Utilization - ICCDU 2019, Aachen, Germany, Jun. 23-27, 2019
4	Effect of Membrane Thickness and Carbonic Anhydrase on CO_2 Separation Properties of Poly(amidoamine) Dendrimer/Poly(ethylene glycol) Hybrid Membranes	Shuhong Duan, Teruhiko Kai, Shin-ichi Nakao	"The 12th Conference of the Aseanian Membrane Society (AMS 12), Jeju, Korea July 2-5, 2019"
5	Development of CO_2 Molecular Gate Membranes for CO_2 Capture	Teruhiko Kai	"The 12th Conference of the Aseanian Membrane Society (AMS 12), Jeju, KoreaJuly 2-5, 2019"
6	CO_2 Separation and Capture System with Polyamine-Supported Solid Absorbent	Shin Yamamoto, Hidetaka Yamada, Katsunori Yogo	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019
7	Molecular Mechanism of Liquid-Liquid Phase Separation in the Amine-CO_2-H_2O System	Hidetaka Yamada, Ryohei Numaguchi, Firoz A. Chowdhury, Shin Yamamoto, Yoichi Matsuzaki, Kazuya Goto	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019

Chemical Research Group

	Title	Researchers	Forum
8	Development of CO_2 Capture Technology with Solid Sorbent Utilizing Low-Temperature Steam: Progress in Bench-Scale Demonstration	Shohei Nishibe, Katsuhiro Yoshizawa, Okumura Takeshi, Ryohei Numaguchi, Kazuo Tanaka, Hidetada Yamada, Shin Yamamoto, Tomohiro Kinosita, Katsunori Yogo	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019
9	Oxidative Degradation of Polyamine-Containing CO_2 Adsorbents	Quyen T. Vu, Hidetaka Yamada, Katsunori Yogo	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019
10	Development of amine-based non-aqueous absorbent for post-combustion CO_2 capture	Firoz A. Chowdhury, Kazuya Goto, Hidetaka Yamada, Shin Yamamoto, Yoichi Matsuzaki	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019
11	Development of CO_2 Molecular Gate Membranes for post-combustion and pre-combustion	Teruhiko Kai, Shuhong Duan, Shin-ichi Nakao	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019
12	Advanced CO_2 Capture Technologies in RITE Chemical Research Group	Shin-ichi Nakao	5TH POST COMBUSTION CAPTURE CONFERENCE (PCCC5), Kyoto, Japan, Sep. 17-19, 2019

Other Oral Presentation and Non-Journal Publication

	Title	Researchers	Forum
1	Advanced CO_2 capture Technologies: Absorption, Adsorption, and Membrane Separaton Methods	Shin-ichi Nakao, Katsunori Yogo, Kazuya Goto, Teruhiko Kai, Hidetaka Yamada	"SpringerBriefs in Energy ISBN 978-3-030-18858-0 May 8th, 2019"
2	Development of CO_2 Capture	Kazuya Goto	CEM10/MI-4 Innovation Showcase, Vancouver Canada, May 28–29, 2019
3	RITE Solid Sorbent for Energy-Saving CO_2 Capture	Kazuya Goto	CEM10/MI-4 Innovation Showcase, Vancouver Canada, May 28–29, 2019
4	Development of CO_2 Molecular Gate Membrane for IGCC with CO_2 Capture	Kazuya Goto	CEM10/MI-4 Innovation Showcase, Vancouver Canada, May 28–29, 2019

CO_2 Storage Research Group

Original Paper

	Title	Researchers	Journal
1	Fiber optic sensing for geomechanical monitoring: (1)-Distributed strain measurements of two sandstones under hydrostatic confining and pore pressure conditions	Ziqiu Xue, Ji-Quan Shi, Yoshiaki Yamauchi, Sevket Durucan	Applied Sciences、8, 11, 2103, 2018, https://doi.org/10.3390/app8112103
2	Fiber optic sensing for geomechanical Monitoring: (2)- Distributed strain measurements at a pumping test and geomechanical modeling of deformation of reservoir rocks	Xinglin Lei, Ziqiu Xue, Tsutomu Hashimoto	Applied Sciences, 9, 3, 417, 2019, https://doi.org/10.3390/app9030417
3	Shear-induced permeability reduction and shear-zone development of sand under high vertical stress	Sho Kimura, Hiroaki Kaneko, Shohei Noda, Takuma Ito, Hideki Minagawa	Engineering Geology, 238, 86–98, 2018
4	Depressurization and electrical heating of methane hydrate sediment for gas production: Laboratory-scale experiments	Hideki Minagawaa, Takuma Ito, Sho Kimura, Hiroaki Kaneko, Shohei Noda,Norio Tenma	Journal of Natural Gas Science and Engineering 50, 147-156, 2018
5	Gas-Tight pH Measurements to Assess an Effect of CO_2 on Groundwater	Saeko Mito, Ziqiu Xue, Bracken Wimmer, Abbas Iranmanesh, Hongbo Shao, Randall Locke II, Sallie Greenberg	SSRN (https://ssrn.com/abstract=3366313), 2019
6	Field Measurement Using Distributed Fiber-Optic Sensing Technology and Numerical Simulation of Geomechanical Deformation Caused by CO_2 Injection	Yankun Sun, Ziqiu Xue, Yi Zhang, Tsutomu Hashimoto, Hyuck Park	SSRN (https://ssrn.com/abstract=3365651), 2019
7	A Preliminary Experiment on the Detection of Bubbles in the Sea with Side-Scan Sonar	Uchimoto, Keisuke and Nishimura, Makoto and Xue, Ziqiu and Watanabe, Yuji	SSRN (https://ssrn.com/abstract=3365765), 2019
8	Micro-seismic monitoring data analysis system based on sequentially discounting autoregressive and its application to offshore CO_2 storage safety operation	Luchen Wang, Tetsuma Toshioka, Takahiro Nakajima, Akira Narita, Ziqiu Xue	SSRN (https://ssrn.com/abstract=3366201), 2019
9	Advanced well log analyses using image data at the Nagaoka CO_2 injection site	Takahiro Nakajima, Ziqiu Xue	SSRN (https://ssrn.com/abstract=3366058), 2019

CO_2 Storage Research Group

	Title	Researchers	Journal
10	Utilization of wave attenuation in time-lapse sonic logging data for the monitoring of CO_2 migration along the well	Takahiro Nakajima, Luchen Wang, Ziqiu Xue	SSRN (https://ssrn.com/abstract=3366057), 2019
11	Can We Detect CO_2 Plume by Distributed Fiber Optic Strain Measurements?	Yi Zhang, Hyuck Park, Tamotsu Kiyama, Yankun Sun, Ziqiu Xue	SSRN (https://papers.ssrn.com/abstract=3366224), 2019
12	Tracking CO_2 Plumes in Clay‐Rich Rock by Distributed Fiber Optic Strain Sensing (DFOSS): A Laboratory Demonstration	Zhang, Yi, Ziqiu Xue, Hyuck Park, Ji‐Quan Shi, Tamotsu Kiyama, Xinglin Lei, Yankun Sun, Yunfeng Liang	Water Resources Research 55, 1, 856-867, 2019
13	Distributed Fiber Optic Sensing System for Well‐based Monitoring Water Injection Tests—A Geomechanical Responses Perspective	Yankun Sun,Ziqiu Xue, Tsutomu Hashimoto, Xinglin Lei, Yi Zhang	Water Resources Research, 2019, https://doi.org/10.1029/2019WR024794
14	Stratigraphy and depositional cycles recognized in event deposits in sediment core taken from the Kzusa Group, Central Eastern Boso Penisula, Japan	Takuma Ito, Hiroomi Nakasato, Tsutomu Hashimoto	The Quaternary research, submitted
15	Deformation‐Based Monitoring of Water Migration in Rocks Using Distributed Fiber Optic Strain Sensing: A Laboratory Study	Yi Zhang, Ziqiu Xue	Water Resources Research, 2019, https://doi.org/10.1029/2019WR024795
16	Experimental and numerical simulation of supercritical CO_2 microbubble injection into a brine-saturated porous medium	Anindityo Patmonoaji,Yi Zhang, Ziqiu Xue, Hyuck Park, Tetsuya Suekane	International Journal of Greenhouse Gas Control 91, 2019,
17	Bubble detection with side-scan sonar in shallow sea for future application to marine monitoring at offshore CO_2 storage sites	Keisuke Uchimoto, Makoto Nishimura, Yuji Watanabe, Ziqiu Xue	American Journal of Marine Science, 7, 1, 1-6, 2019
18	Utilization of wave attenuation in the time-lapse sonic logging at the Nagaoka site for a near well monitoring of CO_2 migration	Takahiro Nakajima, Luchen Wang, Ziqiu Xue	International Journal of the Greenhouse Gas Control, 88, 342-352, 2019
19	A field experiment of walkaway distributed acoustic sensing vertical seismic profile in a deep and deviated onshore well in Japan using a fibre optic cable deployed inside coiled tubing	Yuki Kobayashi, Yuto Uematsu, Shimpei Mochiji, Ziqiu Xue	Geophysical Prospecting, 68, 2, 501 - 520, 2020
20	Geophysical monitoring at the Nagaoka pilot-scale CO_2 injection site in Japan	Takahiro Nakajima, Ziqiu Xue	Active Monitoring, 2nd ed., 563-569, Elsevier, 2019
21	Towards Designing a National Public Engagement Framework for Carbon Capture and Storage in Japan	Akihiro Nakamura	Annual International Social Sciences Conference 2019, submitted

Non-Journal Publication

	Title	Researchers	Magazine, Newspaper, etc.
1	Report on the 14th International Conference on Greenhouse Gas Control Technologies	Ryozo Tanaka	IEEJ Transactions on Power and Energy, July 2019
2	Research and Development of Geological Storage of CO2 in Deep Saline Aquifers	Ziqiu Xue	Energy and resources, 40,3,24-27,2019
3	Speed-up of optimization tool for well placement in Carbon dioxide Capture and Storage	Atsuhiro Miyagi, Youhei Akimoto, Hajime Yamamoto, Ziqiu Xue	Report of Taisei Technology Center, Dec, 2019

Oral Presentation (International Academic Society)

	Title	Researchers	Forum
1	DAS VSP Acquisition Through Coiled Tubing Fiber-Optic Cable	Tsunehisa Kimura, Yanyan Chen, Yuki Kobayashi, Keita Adachi, Ziqiu Xue	European Association of Geoscientists and Engineers, London, UK, Nov 18, 2019
2	Development of a high speed optimization tool for well placement in Geological Carbon dioxide Sequestration	Atsuhiro Miyagi, Youhei Akimoto, Hajime Yamamoto, Ziqiu Xue	"International Society for Rock Mechanics & Rock Engineering YSRM: Young Scholars Symposium on Rock Mechanics, Okinawa, Japan, Dec, 2019
3	Improving Subsurface Images for Better Reservoir Management by CT-DAS-VSP in a Production Well Onshore Japan	Yuto Uematsu, Yuki Kobayashi, Shimpei Mochiji, Ziqiu Xue	Fifth EAGE Workshop on Borehole Geophysics, Hague, Netherlands, Nov 19, 2019
4	A comprehensive experiment to reveal he ability of Side-Scan Sonar to detect CO2 bubbles in shallow sea	Keisuke Uchimoto, Makoto Nishimura, Yuji Watanabe, Ziqiu Xue	IEAGHG Monitoring & Environmental Research – Combined Networks Meeting, Calgary, Canada, Aug 21, 2019
5	Geomechanical Footprint for Downhole Water Injection via Distributed Optic Fiber Sensing Integrating hybrid Brillouin-Rayleigh Backscattering	Yankun Sun, Ziqiu Xue, Tsutomu Hashimoto, Xinglin Lei, Yi Zhang	16th Annual Meeting Asia Oceania Geosciences Society , Singapore, Aug 1, 2019
6	Monitoring of Dynamic Stability of Geological Formations using Fiber-Optic Sensing	Tsutomu Hashimoto, Ziqiu Xue, Ryozo Tanaka	CEM10/MI-4 Innovation Showcase, Vancouver, Canada, May 27, 2019

CO_2 Storage Research Group

	Title	Researchers	Forum
7	Microbubble CO_2 Injection for Geological CO_2 Storage and CO_2-EOR	Ziqiu Xue, Hyuck Park, Ryozo Tanaka	CEM10/MI-4 Innovation Showcase, Vancouver, Canada, May 27, 2019
8	Permanent Ocean Bottom Cable (OBC) System for Offshore CO_2 Storage	Ryozo Tanaka	CEM10/MI-4 Innovation Showcase, Vancouver, Canada, 2019/5/27
9	Proposal of a New Standard of CO_2 Concentration in Seawater	Shunsuke Nishimura, Toru Sato, Keisuke Uchimoto, Koichi Goto, Meguru Miki	2019 Carbon Management Technology Conference, Jul 15, 2019
10	DAS field comparison test for seismic monitoring in wells	Luchen Wang, Ziqiu Xue, Tsutomu Hashimoto	OFSC2019, Wuhan, China, Apr 29, 2019
11	Towards Designing a National Public Engagement Framework for Carbon Capture and Storage in Japan	Akihiro Nakamura	Annual International Social Sciences Conference 2019, Danang, Vietnam, Oct 17, 2019
12	Well Placement Optimization under Geological Statistical Uncertainty	Mitsuhiro Miyagi, Hajime Yamamoto, Yohei Akimoto, Ziqiu Xue	Genetic and Evolutionary Computation Conference, Prague, Czech, June 13, 2019

Oral Presentation (Domestic Academic Society)

	Title	Researchers	Forum
1	Simulated passive tracer regarded as CO_2 leaked from sub-seabed reservoir	Keisuke Uchimoto, Kazuhiro Misumi, Takaki Tsubono, Daisuke Tsumune, Ziqiu Xue	The Oceanographic Society of Japan Fall meeting in 2019, Sep 27, 2019
2	Stratigraphy and depositional cycles in sediment core taken from Kazusa Group, Central Eastern Boso Peninsula, Japan	Takuma Ito, Hiroomi Nakazato, Tsutomu Hashimoto, Ziqiu Xue	Japan association for Quaternary research, Aug 2019
3	Pilot test for microbubble CO_2 injection to reservoir in oil field - Test planning and preparation -	Kazunori Nakagawa, Ryo Ueda, Masanori Nakano, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
4	Evaluation of seismic event location accuracy of Tomakomai CO_2 injection site: a numerical simulation case study	Luchen Wang, Takahiro Nakajima, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
5	Technical Challenges of Machine Learning Approach for Porosity Estimation in Nagaoka CCS site	Takayuki Miyoshi, Takahiro Nakajima, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
6	Utilization of wave attenuation in time-lapse sonic logging data to evaluate the effect of super-critical CO_2 in the reservoir	Takahiro Nakajima, Luchen Wang, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
7	Bed deformation measured by distributed optical fiber and its sedimentological interpretation: alternated sandstone and mudstone aquifer, Boso Peninsula, Japan	Takuma Ito, Tsutomu Hashimoto, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
8	Field Testing of Hybrid Brillouin-Rayleigh Distributed Sensing System for Subsurface Water Injection Monitoring	Yankun Sun, Ziqiu Xue, Tsutomu Hashimoto, Xinglin Lei, Yi Zhang	JPGU Meeting 2019, May 29, 2019
9	Comparison of measured strain behavior and quantified deformation of rock using optic fiber sensing technology and strain gage	Shogo Hirota, Tomohiro Tokunaga, Ziqiu Xue, Hyuck Park	JPGU Meeting 2019, May 29, 2019
10	CO_2 migration characteristics of microbubble and conventional sequestration in Berea sandstone revealed by X-ray CT imaging	Hongyu Zhai, Yi Zhang, Hyuck Park, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
11	Strain detection by optical fiber for CO_2 injected core specimen	Hyuck Park, Yankun Sun, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
12	Monitoring hydromechanical responses in aquifer by distributed fiber-optic strain sensing: From lab to field	Yi Zhang, Ziqiu Xue, Tsutomu Hashimoto, Hyuck Park	JPGU Meeting 2019, May 29, 2019
13	Mechanisms inducing anomalously high pCO_2 without CO_2 leakage in coastal environment	Yuji Watanabe, Keisuke Uchimoto, Makoto Nishimura, Saeko Mito, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
14	How many data are necessary to make a suitable threshold for anomalous pCO_2 owing to CO_2 leakage?	Keisuke Uchimoto, Yuji Watanabe, Makoto Nishimura, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019
15	CO_2 behavior analysis using large scale geological model	Yuki Shigeoka, Haruki Nishiyama, Hiroshi Kinoto, Takaomi Tobase, Takahiro Nakajima, Ziqiu Xue	JPGU Meeting 2019, May 29, 2019

Inorganic Membranes Research Center

Original Paper

	Title	Researchers	Forum
1	Development of CVD silica membranes having high H_2 permeance and steam stability and a membrane reactor for water gas shift reaction	Ryoichi Nishida, Toshiki Tago, Takashi Saito, Masahiro Seshimo, Shin-ichi Nakao	Membranes 2019, 9(11), 140

Oral Presentation (International Academic Society)

	Title	Researchers	Forum
1	Dehydrogenation of metylcyclohexane by a membrane reactor with silica membranes	Shin-Ichi Nakao, Hiromi Urai, Kazuaki Sasa, Masahiro Seshimo, Hitoshi Nishino	World Hydrogen Technologies Convention (WHTC2019), Tokyo International Forum, Jun 03, 2019
2	Influence of steam on permselective performance of dimethoxydiphenylsilane-derived silica membrane	Masahiro Seshimo, Hiromi Urai, Yuichiro Yamaguchi, Shin-ichi Nakao	18th Asian Pacific Confederation of Chemical Engineering Congress (APCChE2019),Sep 23 – 27, 2019

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