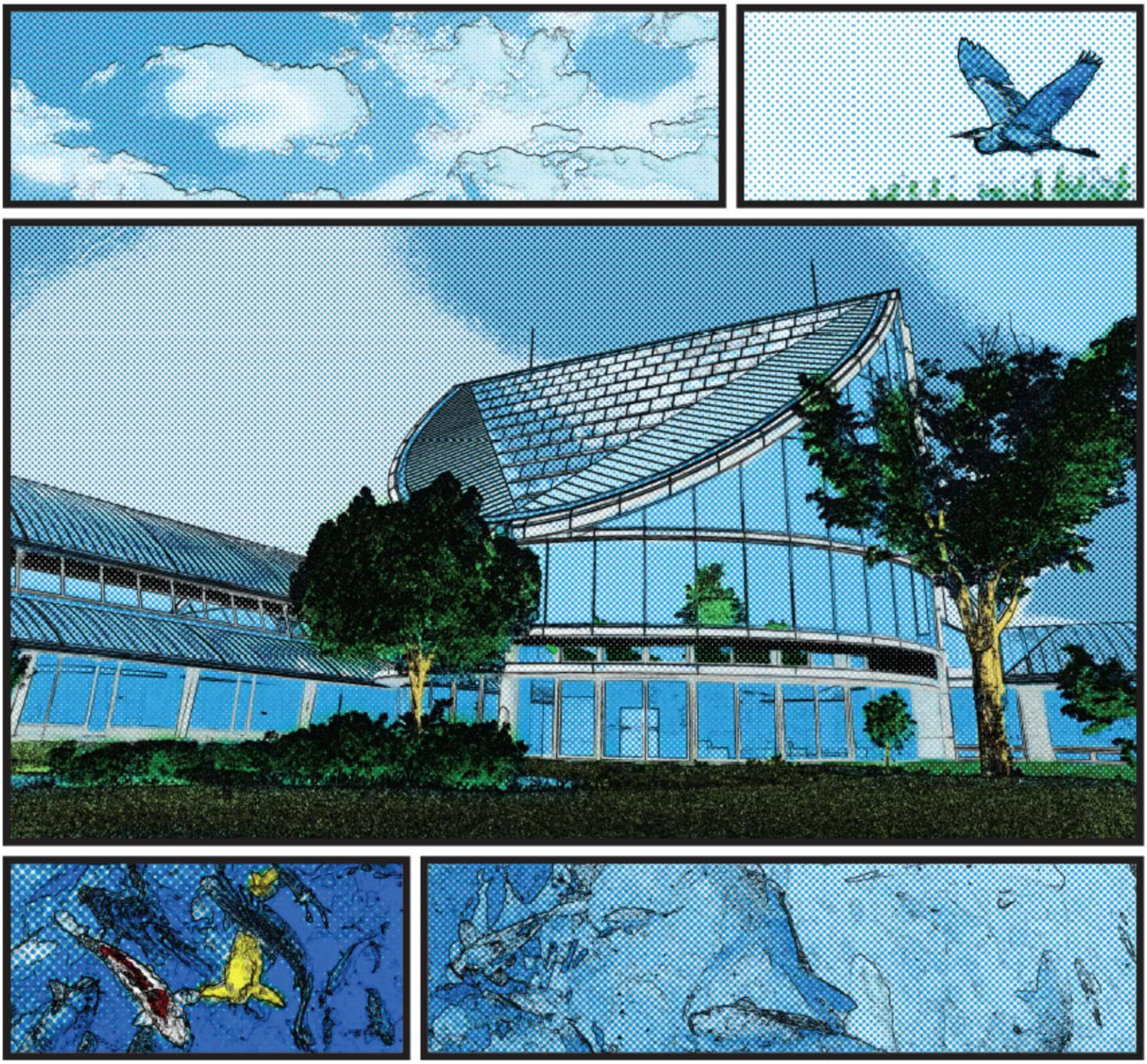
2021 Vol.16

RITE Today

Annual Report

Research Institute of Innovative Technology for the Earth



RITE Today 2021 Vol.16

Contents

Efforts for Radical Innovation

Yutaka Kawakami
Managing Director,
Research Institute of Innovative Technology for the Earth (RITE)

I am Yutaka Kawakami, the Managing Director of the Research Institute of Innovative Technology for the Earth (RITE).

Last year, RITE celebrated the 30th anniversary of its establishment, so this year marks the first year in our next ten years of progress. All of the members will work together to increase our efforts with a fresh attitude, to strive for self-improvement, produce results, and contribute to society as a public interest incorporated foundation, so I ask you all for your continued support, guidance, and cooperation.

RITE is a research organization that is engaged in the development of technologies to solve global environmental problems, particularly the problem of global warming. There is a sense that the global coronavirus crisis may have diminished the public's interest in the global warming problem. However, the importance of the problem of global warming, which is a long-term issue, does not change. In his policy speech in October last year, Prime Minister Suga declared that the aim of achieving carbon neutrality by 2050 was a top priority issue. This was an acceleration of efforts from the previous aim to reduce carbon emissions by 80% by 2050.

The difficulty of the global warming problem is the cost burden associated with significant reductions of greenhouse gases. There is a trade-off relationship between the reductions and the non-global warming targets in the SDGs. There is also consideration of the S+3E (the prioritization of safety with the simultaneous achievement of environmental conservation, economic efficiency, and energy security) that forms the basis for energy policies. It will therefore be essential to have radical innovation to solve the problem. Furthermore, the problem is so difficult that achievement will only be possible if we approach it by mobilizing radical innovation in every field.

Under these circumstances, we are all aware that the importance of RITE is increasing, and we are continuing our efforts each day with strong motivation.

At RITE, existing research such as CCS and biorefinery research has already progressed from the demonstration stage to the social implementation stage, and we are working to further accelerate it. Furthermore, as I said before, efforts are required in every field, so while we are steadily advancing those existing technologies, we are also tackling new challenges. The following are some examples of those new efforts.

In the Systems Analysis Group, the previous focus was on the energy supply side. However, with the advances in AI and IT technologies, the Group is now also proceeding with simulations that take into account the possibility of significant reductions in energy consumption on the demand side.

The Chemical Research Group has started working on the development of DAC technology, to directly capture CO_2 from the atmosphere. This has the potential to be an effective technology for significant CO_2 reduction in the future.

The CO_2 Storage Research Group is not only looking at storage in Japan, but also promoting the deployment of the technologies overseas.

The Molecular Microbiology and Biotechnology Group has started the development of biodegradable plastics using bioprocessing, as a technology that can make a contribution for both the global warming problem and the waste plastics problem.

The Inorganic Membranes Research Center was previously focused on the development of hydrogen-related technology, but has now started the development of fuel production technology using CCU with inorganic membranes.

RITE will continue to make full use of our technological seeds, knowledge, and know-how to make it possible to accomplish radical innovation in a wide range of fields and to take a balanced response to risks through the research results we produce.

Please pay attention to the research results of RITE from now on.

Beyond Zero Expo

Takashi Honjyo, Senior Managing Director
Isamu Yagyu, Group Leader, Chief Researcher, Research & Coordination Group
Yoshifumi Kawaguchi, Deputy Group Leader, Research & Coordination Group
Yasuaki Minoura, Manager, Research & Coordination Group
Haruo Kanaboshi, Planning Manager, Research & Coordination Group
Michiyo Kubo, Research & Coordination Group
Nami Tatsumi, Research & Coordination Group
Keigo Akimoto, Group Leader, Chief Researcher, Systems Analysis Group
Toshiyuki Hasegawa, Deputy Group Leader, Chief Researcher, Chemical Research Group
Katsunori Yogo, Associate Chief Researcher, Chemical Research Group
Hidetaka Yamada, Senior Researcher, Chemical Research Group
Kenji Uchida, Deputy Group Leader, Chief Researcher, CO_2 Storage Research Group
Saeko Mito, Senior Researcher, CO_2 Storage Research Group
Kenichiro Yasuhara, Senior Researcher, Inorganic Membranes Research Center

1. Introduction

As indicated in Prime Minister Suga's policy speech on 26th October, 2020, it is required that our society has net-zero CO_2 emissions by 2050. In order to achieve this, it will be important to reduce energy requirements through higher efficiency, and to maximize the use of energy that does not emit CO_2, such as solar and wind power. In addition, it will also be important to establish systems that realize carbon neutrality by capturing the CO_2 that is unavoidably emitted and using underground storage or fixation and utilization. Through the spread and development of this underground storage technology and fixation and utilization technology, and through the further reduction of CO_2 emissions, it is thought that we will be able to approach the realization of a Beyond Zero state which exceeds neutral (in other words, zero), as described in the Environment Innovation Strategy. At the Osaka, Kansai Expo in 2025 (Fig.1), rather than a simple exhibition of Beyond Zero, we will propose the Beyond Zero Expo as a pioneering system for achievement within the venue during the exhibition period.

Fig.1 Conceptual image of the Osaka, Kansai Expo venue (Courtesy of the Japan Association for the 2025 World Exposition)

To construct this system, it will be necessary to limit the power supplied to the venue during the period to energy that does not emit CO_2. Also, for city gas, the CO_2 emissions from production and consumption will be offset with credits. The hydrogen used will also be either green or blue hydrogen and be carbon neutral. In addition, electric or hydrogen vehicles will be used inside the venue and the CO_2 generated by any gasoline vehicles will be offset with credits in the same way as for city gas. We will achieve carbon neutrality as a starting point through these efforts.

As the next step, in this proposal, we will capture CO_2 from the atmosphere in the venue and either store it underground or fix and utilize it, in order to realize a state Beyond Zero and to promote environmental technology.

The concentration of CO_2 in the atmosphere is about 400 ppm, which is only a few hundredths of the concentration of CO_2 in the current practical applications of capture technology. It is not really possible to say that the technology to capture this efficiently has already been established. However, if we make full use of Japan's cutting-edge technology, then we believe that it will be possible to produce a DAC (Direct Air Capture) device that efficiently captures CO_2 in units of tons (per day) by 2025, and to install and operate it at the venue.

Next, we will also perform underground storage (part of a process called CO_2 Capture and Storage, or CCS) within the venue in order to process the captured CO_2 permanently. The amount stored during the period will only be a few hundred tons, which is actually quite small (as there are proven results of 300,000 tons over three years at Tomakomai). However, the fact that the storage will be in Osaka, which is a large city, will make it a revolutionary attempt unprecedented in the world, so it will have great significance.

In addition, carbon recycling technology will also be realized within the venue as an environmental technology. Specifically, a methanation device for producing methane from CO_2 from the DAC device mentioned above and carbon-free hydrogen will be installed within the venue. The methane produced will then be supplied to the guest house kitchen and elsewhere as city gas. Similarly, CO_2 will be supplied to the plant factory installed in the venue and the vegetables cultivated will be provided to the guest house kitchen on a daily basis. In addition, acrylic resin made using methanol produced from CO_2 fixation as a raw material will be used to manufacture fixtures and fittings for the venue and souvenirs.

Fig.2 shows a summary of these proposals. Furthermore, we want to position the equipment as exhibition displays at the Expo venue. We want to create a Beyond Zero Pavilion of the equipment together with an exhibition of carbon neutral, DAC, underground storage, and other CO_2 fixation and carbon recycling technologies, to promote Japan's environmental technologies to the many visitors.

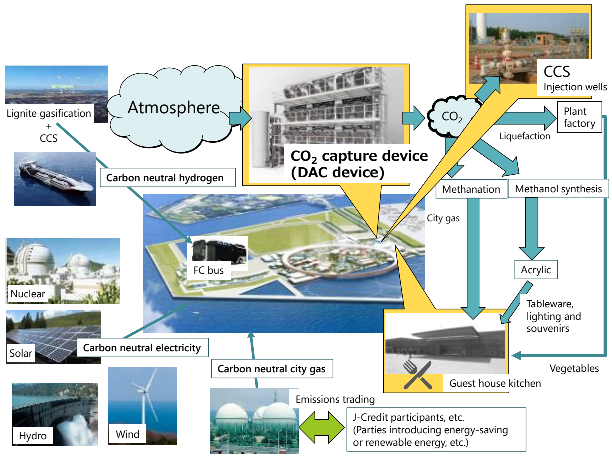


Fig.2 Conceptual image of the Beyond Zero Expo proposal

This special issue gives a detailed introduction to each technology for the realization of the Beyond Zero Expo. First, Chapter 2 discusses the need to achieve carbon neutrality and the prospect of achieving Beyond Zero. Chapter 3 then introduces DAC, underground storage, and other technologies. As a summary, Chapter 4 discusses the relationship between this proposal and the basic policy of the Osaka, Kansai Expo.

2. For the achievement of carbon neutrality

As described in the previous chapter, on 26th October, 2020, Prime Minister Suga declared the intention to "Aim for carbon neutrality and decarbonization by 2050". Here we discuss what measures are required to achieve carbon neutrality.

2.1. Multiple possibilities for carbon neutrality achievement

The Special Report on Global Warming of 1.5°C (SR15) by the Intergovernmental Panel on Climate Change (IPCC) noted that to limit the increase to 1.5°C, it will be necessary to achieve a net near-zero level of global CO_2 emissions in around 2050[1]. Carbon neutral in 2050 is in line with this.

In SR15, four typical pathways are presented. Of these four, the two extreme pathways are as follows. The first is a scenario of exhaustive energy conservation, known as the Low Energy Demand (LED) scenario. On the energy demand side, the amount of energy currently being used greatly exceeds the level that is originally necessary. There is a possibility that the use can be greatly reduced by changes such as advances in digitization technology. The scenario shows that if social changes also occur, then a society with low energy demand and low CO_2 emissions can be realized. (The RITE Systems Analysis Group launched the research project, EDITS (Energy Demand changes Induced by Technological and Social innovations) research project in FY2020 and started detailed international studies on low-energy demand scenarios.) The LED scenario described in SR15 does not assume the use of CDR (Carbon Dioxide Removal) technology. Another model scenario is the achievement of carbon neutrality during the time when fossil fuels continue to be cheap, by using fossil fuels whilst also using a large amount of CDR technology. In addition to CCUS, the CDR also includes biomass with CCS (BECCS), which produces negative emissions, and the direct capture and storage of atmospheric CO_2 (DACCS). It will be desirable to have multiple scenarios as we go on to enhance the feasibility of carbon neutrality so that it can be achieved at an early stage.

2.2. Image of carbon neutrality achievement

Fig.3 shows a conceptual image of measures for net zero emissions (= carbon neutral) in terms of greenhouse gas emissions. Broadly speaking, there is energy conservation and there is the reduction of CO_2 emissions per unit of power. Firstly, what is fundamentally important is the conservation of energy, including through the reduction of materials and energy services through digitization. For the reduction of CO_2 emissions per unit of power, it tends to be easier to reduce these for electricity than for non-electric power, so the IPCC also emphasizes the importance of promoting electrification whilst simultaneously promoting the decarbonization of power sources[2]. On the other hand, for both energy conservation and the reduction of CO_2 emissions per unit of power, when the effort for a large reduction is increased, in other words, when the effort to bring the figures to close to zero is increased, the costs increase rapidly. Furthermore, there are some sectors where the reductions are more difficult than those for CO_2, such as methane from livestock production. One major direction for achieving carbon neutrality will be to cancel out those remaining emissions by using negative emission technologies (NETs). However, as mentioned in the previous section, there are several different prospects for the level of contribution of each. We should aim for carbon neutrality with a wide range of options.

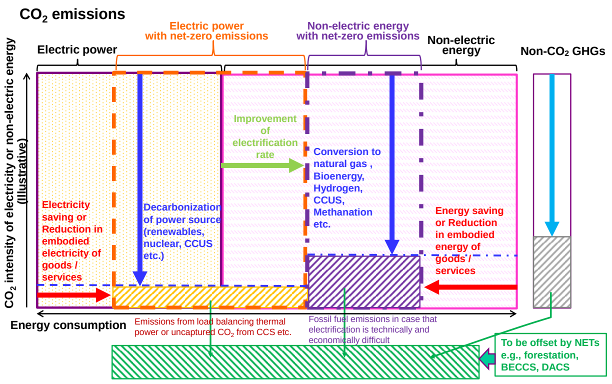


Fig.3 Conceptual image of measures for net zero emissions in terms of greenhouse gas emissions

In the same way, Fig.4 shows an image of measures for net-zero from the viewpoint of primary energy supply in Japan. In principle, it is necessary that primary energy only consists of renewable energy, nuclear energy, and fossil fuels with CCS. However, it is also important to consider the utilization of overseas resources for renewable energy and CCS, and in doing so, conversion to hydrogen is important. Hydrogen is also called green hydrogen when it originates from renewable energy and blue hydrogen when it originates from fossil fuel + CCS. To improve convenience, it may also become important to convert hydrogen to ammonia or synthetic fuel for transportation and utilization. However, there is a high possibility that fossil fuel use without CCS will also remain. It will be necessary to cancel this out with measures such as afforestation, BECCS, and CO_2 mineralization (CO_2 fixation in concrete sector, etc.). However, due to volume constraints, the use of DACCS is also considered important. There is a limit to the storage capacity of CCS, which includes BECCS and DACCS, so it is important to secure CO_2 storage sites and also it is very important to consider the utilization of CO_2 storage sites overseas.

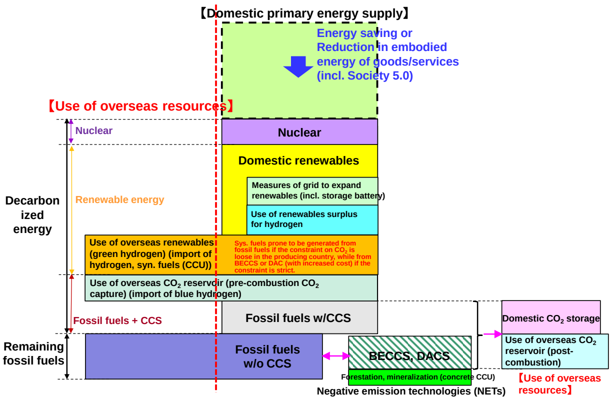


Fig.4 Conceptual image of measures for net zero emissions in terms of primary energy supply in Japan

2.3. Example of comprehensive analysis using the global energy and climate change mitigation assessment model: The role of DACCS

Next is an example analysis of the total global measures for carbon neutrality by using the global energy and climate change mitigation assessment model, DNE21+. In the emissions scenarios, in the scenarios for less than 2°C and for less than 1.5°C, the CO_2 emissions reach net zero in around 2060 and 2050 respectively, and then become negative (Beyond Zero). For greenhouse gas emissions, the scenarios have net zero reached in around 2100 and 2065, respectively, and then a negative figure after that. For the 1.5°C scenario, in the assumptions for this model, there were no feasible solutions without the assumption of DAC (Table 1).

Table 1 DAC-related model analysis scenarios

	Emission scenarios	DAC costs	Feasibility
2℃(No DAC)	<2℃ (>66%)	No DAC	○
2℃(DAC, High cost)		High cost	○
2℃(DAC, Low cost)		Low cost	○
1.5℃(No DAC)	<1.5℃ in 2100 (>66%), Overshoot of temperature	No DAC	×
1.5℃(DAC, High cost)		High cost	○
1.5℃(DAC, Low cost)		Low cost	○

Note) The assumptions for DAC are based on Ref. 4). The required energies in 2050 are 5.5-7.2 GJ/tCO_2 and 4.7 GJ/tCO_2 for the high and low cost scenarios, respectively.

Fig.5 shows the balance between global CO_2 capture and storage/use in the results from this model analysis. (For details of the analysis, see reference 3.) Even under the scenario where the cost of DAC is assumed to be high (a maintenance of the current technology level), the cost of the energy inputs will be reduced by utilizing surplus renewable energy, so when aiming for carbon neutrality, it is evaluated as a cost-efficient option in around 2050. In the scenario where it is low cost, there is even more extensive use. As the use of DACCS makes negative emissions possible, it will still be possible to use fossil fuels without CCS at an appropriate level. There is still a long way to go in DAC technology development, but it will contribute to the achievement of cost-effective carbon neutrality as a whole, and also bring achieving Beyond Zero into view.

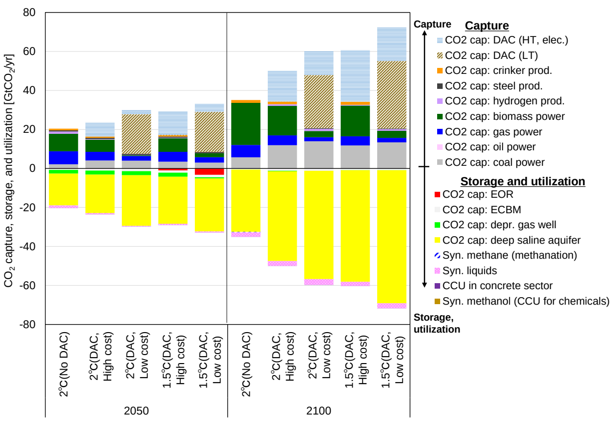


Fig.5 Balance between global CO_2 capture and storage/use

3. Technology introduction

3.1. DAC

Since the concept to capture CO_2 from the atmosphere was proposed as a feasible option for climate mitigation technology, development of direct air capture (DAC) technologies have attracted much attention. According to the Energy Technology Perspectives 2020, for the achievement of sustainable development scenarios, BECCS (Bio-energy with CCS) and DACCS (Direct Air CO_2 Capture and Storage) are expected to achieve negative emissions of 3 Gt-CO_2/y by 2070. The utilization of captured CO_2 by DAC is also be considered, however, the effect of removing the CO_2 from the atmosphere by CCU is small. DAC can be used as a negative emission technology by combining it with storage as DACCS.

DAC is considered to be energy intensive and costly, but it does use less land area and water than BECCS, afforestation, or reforestation, so it is possible to suppress the problem of competition with land use for food production, and the adverse impacts on biodiversity.

As shown in Table 2, some researches are being carried out in the United States and Northern Europe. However, the capture cost is currently high. Therefore, based on a detailed cost estimation, the reduction of both costs (CAPEX) and thermal and electric energy (OPEX) are required.

Table 2 Status of DAC technology development overseas [5)]

Company name	Materials	Energy /Cost of CO_2 separation and capture	Remarks
Climeworks (Swiss)	Amine modified filter (Solid sorbent material and resin filter)	9.0 GJ/t-CO_2, 600 \$/t-CO_2(Target cost around 2025: 100 \$/t-CO_2)	Launched the world's first commercial plant(900t-CO_2/y), which has already been installed in eight locations. Energy and costs are high.
Carbon Engineering (Canada)	Aqueous solution containing $KOH/Ca(OH)_2$	5.3 GJ/t-CO_2, 94-232 \$/t-CO_2	Plan to put two 500,000 t-CO_2/y DAC plants into operation in 2022 with Occidental Petroleum. The only company using alkaline aqueous solution.
Global Thermostat (USA)	Amine-containing ceramics(Solid sorbent material)	4.4 GJ/t-CO_2, 150 \$/t-CO_2 (Target cost: 50\$/t-CO_2)	Working in cooperation with Georgia Institute of Technology. Has already installed six units and constructed 4,000 t-CO_2/y pilot plant.
Center for Negative Carbon Emissions (USA)	Ion-exchange resin	220 \$/t-CO_2 (Target cost: 30 \$/t-CO_2)	Adsorption/desorption using dehumidification/humidification swing. Proposing installation of AT along expressways.
The VTT Technical Research Center (Finland)	Ion-exchange resin	8.9GJ/t-CO_2	1～2kg-CO_2/d on Day/night capture cycle

The target CO_2 concentration of DAC is only 400 ppm. This is two to three orders of magnitude lower than that of exhaust gas from coal- and natural gas-fired power plants. This is a main reason that the DAC cost will be high. The amount of air that contains one ton of CO_2 is approximately 1.27 million m^3. What this means is that even if the capture rate is 100%, it would take the air of one Tokyo Dome to capture 1 ton of CO_2 from the air.

In order to make DAC realistic, it will be necessary to develop CO_2 separation materials with unprecedented high performance, and to construct a process that makes it possible to absorb and desorb large amounts of air efficiently. Now, RITE is working on the development of new materials based on our experience in the development of solid sorbents and amine compounds and a highly efficient DAC system with the cooperation of private companies and universities (Fig.6).

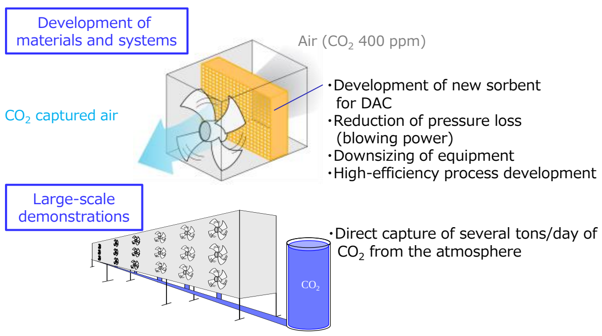


Fig.6 Development of technology to capture CO_2 from the atmosphere

In this proposal, we want to make full use of Japan's cutting-edge technology to produce a DAC device that efficiently captures CO_2 in units of tons (per day), and to install and operate it at the venue.

3.2. Underground storage of CO_2

Methods for CO_2 injection and storage in the ground include EOR (Enhanced Oil Recovery), where CO_2 is injected into oil fields to perform enhanced oil recovery, ECBM (Enhanced Coal Bed Methane), where CO_2 is injected into coal seams to recover methane, and CO_2 geological storage in deep saline aquifers.

The geological structures necessary for the storage of CO_2 underground include a "reservoir" and a "seal layer". Sedimentary layers such as porous sandstone are suitable for the "reservoir", and saline aquifers with large permeability correspond to this.

Saline aquifer storage is a method of storage that targets sandstone layers at depths of 800 m or more below ground. The sandstone layers are geological strata formed by the accumulation of sand grains. Salt water which is not used for groundwater utilization fills the gaps between the sand grains. Fig.7 shows a conceptual image of saline aquifer storage. CO_2 is injected into the sandstone layer via a well that is drilled from the ground surface. CO2 pushes away the part of salt water and accumulates in the gaps, and also some of it is dissolved in the salt water. It is possible to store the CO_2 stably over a long period of time if there is a seal layer such as mudstone above the sandstone layer. Mudstone has strong sealing properties and allows hardly any gas or liquid to pass through.

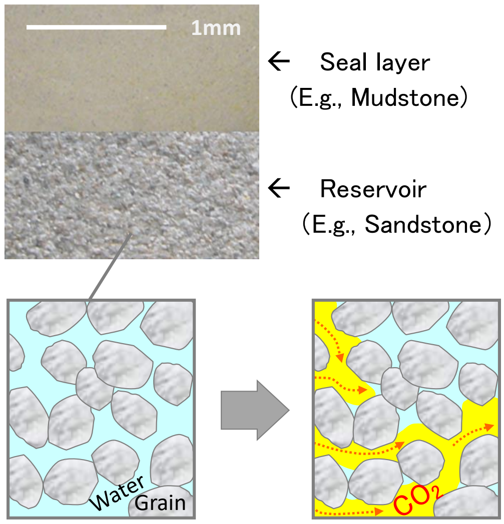


Fig.7 Schematic diagram of underground CO_2 storage

Fig.8 shows a general outline of a CO_2 storage site. The CO_2 is captured from the source generating it and then either stored directly below ground from facilities on the surface, below the seabed from ground facilities, or below the seabed from offshore facilities.

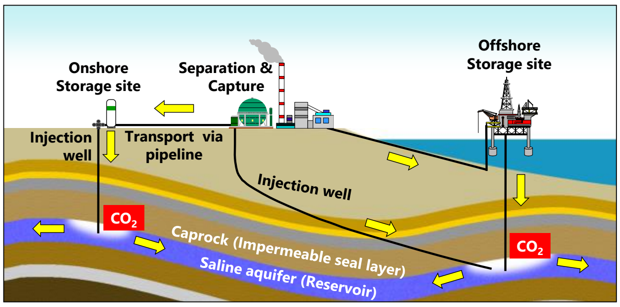


Fig.8 General outline of an underground CO_2 storage site

As discussed in the previous chapter, the underground storage of CO_2 is one of the important options for sequestering the CO_2 that is captured.

A large number of CO_2 injection wells would be required for CCS at a level that would suppress global warming. However, the number is only a small fraction of the number of oil production wells that have been drilled to date around the world. It is expected that the underground storage of CO_2 will be utilized in earnest and become one of the measures against global warming. An introduction to this kind of underground CO_2

storage at the Osaka, Kansai Expo will be very meaningful for spreading knowledge of CCS to a wide audience.

In this proposal, underground storage will be carried out within the venue. The amount stored during the period of the event will only be a few hundred tons, which is actually quite small (as there are proven results of 300,000 tons over three years at Tomakomai). However, the fact that the storage will be in Osaka, which is a large city, will make it a revolutionary attempt unprecedented in the world, so it will have great significance.

3.3. Other

3.3.1. Methanation

Methanation is a technology to synthesize methane from CO_2 and hydrogen. The synthesis requires energy, but unlike hydrogen, it has the major advantage that it is possible to utilize the existing city gas infrastructure, so it is attracting much attention.

The technology itself is an existing technology that was discovered in 1911 by the French chemist Sabatier. In Japan, as part of a NEDO project to develop effective CO_2 utilization technologies, INPEX and Hitachi Zosen constructed a test facility with a methane synthesis capacity of 8 Nm^3/h in 2019 and have conducted demonstration testing such as continuous operation. On the other hand, there have not yet been any examples of utilization as city gas. The issues for this are scaling up and the improvement of the conversion efficiency and economic efficiency. The synthesis requires four times as much hydrogen as CO_2, but if the hydrogen is produced using the surplus electricity from renewable energy sources, then the use of synthetic methane can reduce the amount of natural gas used as a fossil fuel and contribute to decarbonization. In addition, if a large amount of renewable energy power is introduced as a measure to achieve net-zero carbon, then one issue will be the storage of the large amount of surplus electricity. There are also expectations for methanation as a technology for that storage and for the stabilization of the power system.

The reason for converting hydrogen to methane is that the storage, transportation, and use of hydrogen would require new capital investment and the development of new equipment technology. However, methane has almost the same composition as natural gas, so if it is connected to a gas pipeline, then it can be used without building new equipment. In addition, the possibilities for methane as an energy carrier are attracting attention from the viewpoint of low carbonization for the utilization of heat from primary energy.

In Europe, where decarbonization is in progress, Audi is operating a demonstration plant with a methanation capacity of 315 Nm^3/h, which makes it the largest demonstration plant in the world. It performs the methanation using electricity derived from renewable energy and CO_2 separated from biogas, with the assumption that the price for renewable energy will fall when a large amount of it is placed on the market. Also, in China, which aims to achieve net zero CO_2 emissions by 2060, Hitachi Zosen announced in December 2020 that it would conduct a feasibility study for methanation technology, and plans to evaluate the supply chain and business profitability for social implementation.

In this proposal, we are considering the installation of a methanation device within the venue. The device will use CO_2 from the DAC device mentioned above and supply the methane to the guest house kitchen and elsewhere as city gas.

3.3.2. Methanol synthesis

Methanol is used widely as a raw material to produce lower olefins such as ethylene and propylene. It is also a basic raw material for chemicals such as synthetic resins, adhesives, chemicals, and paints. The annual demand for it globally is about 80 million tons. It is produced under high temperatures and high pressures through multiple manufacturing processes, and the main raw materials currently used are fossil resources such as natural gas, liquefied petroleum gas, and coal.

Instead of using fossil resources as the raw materials to obtain methanol, it can be synthesized by using hydrogen derived from renewable energy and CO_2 obtained by capturing it from the atmosphere or from the combustion exhaust gas from facilities such as coal combustion power plants and blast furnaces. Doing this makes it possible to simultaneously reduce greenhouse gas emissions while producing the useful industrial product methanol.

The methanol that is obtained from these raw materials of CO_2 obtained from capture and hydrogen derived from renewable energy can then be reacted with methacrylic acid to synthesize an acrylic resin (PMMA). Acrylic resins have high transparency and impact resistance and are easy to process and color, so they are used in various applications such as window materials for buildings and vehicles, covers for lighting fixtures, and signboards.

In this proposal, we would like to show examples of the realization of a carbon recycling society by using this acrylic resin at the venue. This includes use in exhibits and souvenirs, and in transparent boards surrounding the DAC (Direct Air Capture) equipment displayed at the Expo venue as equipment to capture CO_2 from the atmosphere (Fig.9).

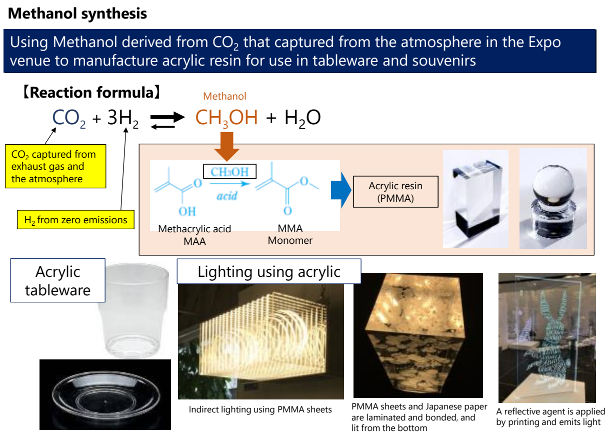


Fig.9 Methanol utilization at the Expo

3.3.3. Plant factory

Plant factories are a facility that could utilize CO_2 on a global scale in the future. Plant factories can be either the artificial light type or the solar light type. Of these, an artificial light type plant factory (Fig.10) uses artificial light as the light source and has air conditioning and liquid nutrient cultivation to control the environmental elements necessary for plant growth (light, temperature, humidity, CO_2 gas concentration, and airflow). These can stably cultivate high-quality plants throughout the year[6].

For example, for leaf lettuces, for which the technology has already been applied, it is necessary to add 22 kg of CO_2 in order to produce 3,000 leaf lettuces (of 100 g each), and this greatly contributes to productivity[6]. In addition, further development and advances can be expected, such as through the research and development currently being carried out for strawberry production.

In this proposal, carbon recycling and the latest technology for plant factories will be promoted by setting up a small factory to produce the latest vegetables for which the technology has been applied. The factory will use CO_2 captured by the DAC within the venue and will supply the vegetables to the guest house kitchen.

Fig.10 Example of an artificial light type plant factory
(Source: Techno Farm™ Website)

4. Conclusion

At the 2025 Osaka, Kansai Expo, rather than just exhibiting about Beyond Zero, we are proposing a pioneering system that uses technologies such as those described above to achieve Beyond Zero within the venue during the period of the Expo.

The outline of this proposal was already presented on September 24, 2020 at a symposium hosted by RITE, and it was also reported on October 14 as an article in the Chemical Daily.

Also, in the basic policy for the Osaka, Kansai Expo that was decided by the Cabinet on December 21, 2020, the third of the twelve basic concepts is active efforts for radical innovation toward carbon neutrality. We will make further efforts to refine and actualize our proposal for the realization of this basic policy.

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Research & Coordination Group

Members (As of Dec. 2020)

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

Research of the Decarbonized Society to Achieve Carbon Neutrality

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

In 2020, Japan declared the goal of realizing a carbon-neutral, decarbonized society by 2050, so it is outlined at first.

1. Actions towards achieving 2050 carbon neutrality

In 2020, Paris Agreement, the International Framework on Climate Change, started the full implementation. Therefore, Japan formulated "Environmental Innovation strategy"[2] in January, 2020, which aims at the establishment of the "Beyond Zero" Technologies in 2050 to reduce CO_2 that were emitted in the past and promote the social implementation clarified for the long-term strategy, so as to achieve the carbon neutrality as early as possible in the second half of this century.

"The Moonshot Research and Development Program, Goal 4：Realization of sustainable resource circulation to recover the global environment by 2050"[3] was started and RITE's proposal was selected, too.

In October 2020, Prime Minister Suga declared the goal of realizing a carbon-neutral, decarbonized society by 2050 at the 203rd extraordinary Diet session[4], so the action to achieve the carbon neutrality was accelerated. The Minister of Economy, Trade and Industry Kajiyama explained," The challenging goal of achieving carbon neutrality by 2050 is the new growth strategy in Japan and METI will implement every possible policy measure to create a virtuous circle of economy and environment."

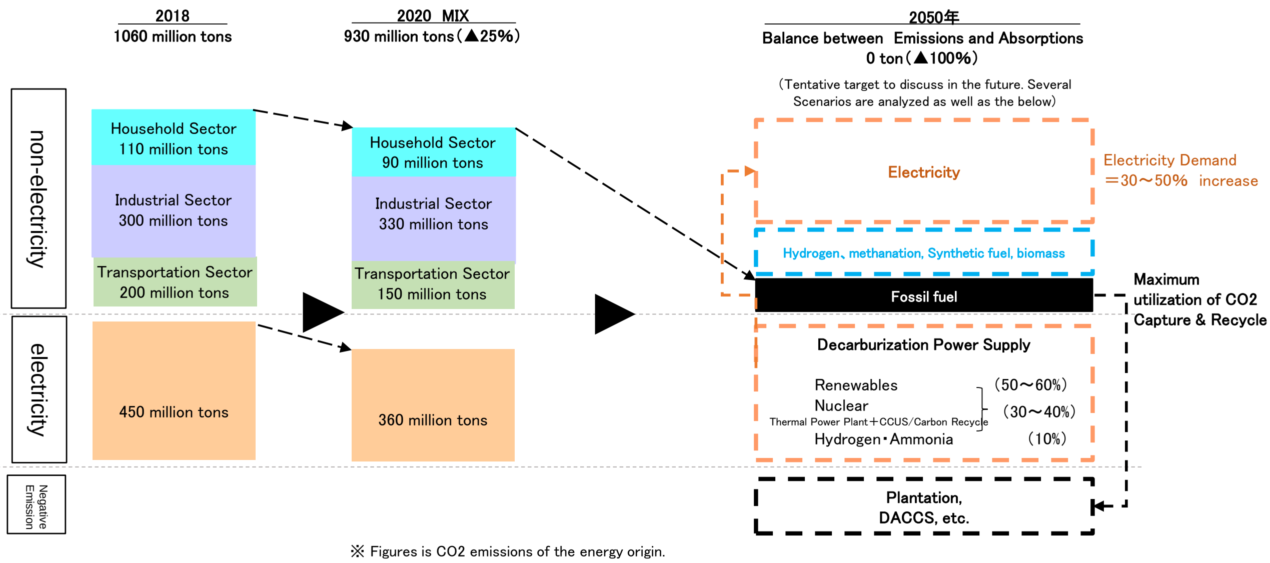
The idea that to cope with global warming is the constrains and the cost of economic growth should be switched and to positively take the countermeasures leads to the reforms of the industrial and social structure and promotes towards the next growth. And "Green Growth Strategy towards 2050 Carbon Neutrality"[5] was formulated in October 2020 as an industrial policy to aim toward a positive cycle of economic growth and the environmental protection.

The Strategy towards 2050 Carbon neutrality indicates the tentative goal of the 2050 Energy Demand and Supply as a reference figure, in order to discuss Energy Policy and the future goal of energy demand and supply as it is important to reduce the emission of greenhouse gases in energy sector which occupies more than 80% of total amount (Fig.1).

The Strategy determined 14 priority fields to achieve 2050 carbon neutrality (Fig.2) and formulated "action plans" covering comprehensive policies in areas such as ①goals scheduled towards 2050, ②research & development and demonstration, ③regulation reforms and standardization, ④ international collaboration, etc. (Fig.3).

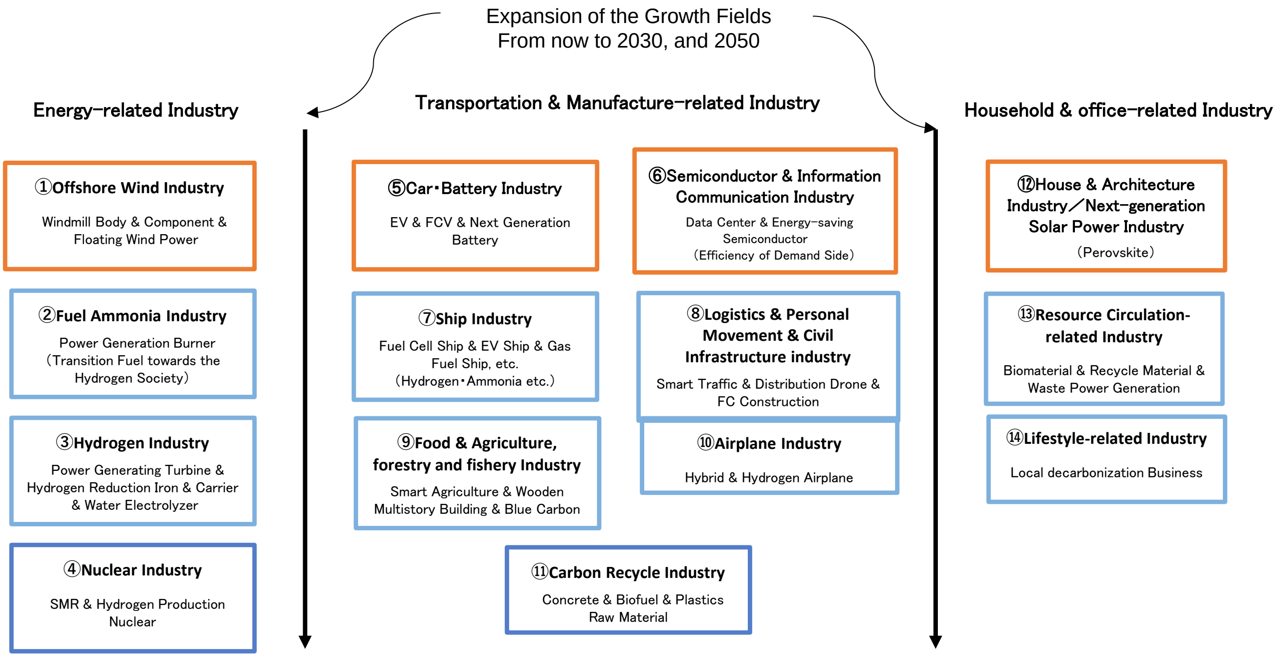
This strategy will be reviewed about the implementation of action plans in a steady manner and the improvement of goals and measures, in order to revise the strategy in the future.

The Research and Coordination Group aims to early establish the innovative technology mentioned "Environmental Innovation Strategy" with the research groups & center to achieve 2050 carbon neutrality.



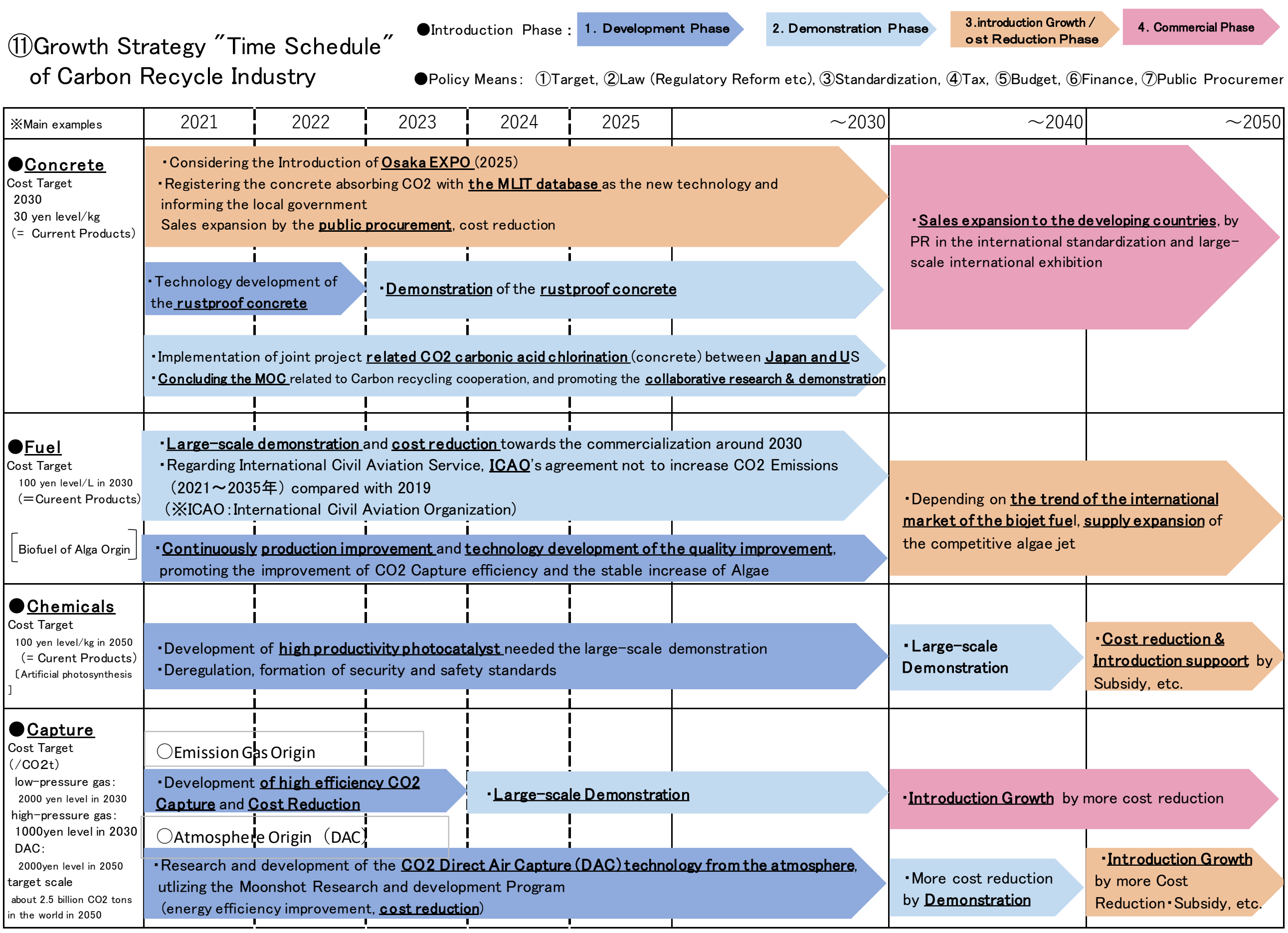
(Source) "Green Growth Strategy towards 2050 Carbon Neutrality" (Dec. 2020)

Fig.1 Image towards carbon neutral



(Source)"Green Growth Strategy towards 2050 Carbon Neutrality" (Dec, 2020)

Fig.2 Arranged figure of important industry



(Source)"Green Growth Strategy towards 2050 Carbon Neutrality" (Dec, 2020)

Fig.3 Example of "Time Schedule" of time schedule

2. Research activities

It is expected that the CO_2 reduction effect of CCUS (Carbon dioxide Capture, Utilization and Storage) technology would be 9% by 2050 in the IEA's World Energy Outlook 2019[6] (Fig. 4).

RITE studied the investigation of CCS introduction entrusted by METI which was the investigation research related to the global warming & resources circulation measures[7], so it is outlined in the below.

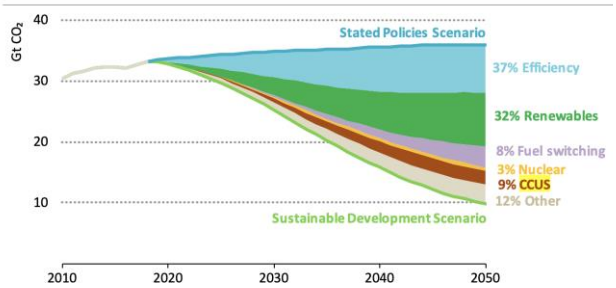


Fig.4 Estimated CO_2 reduction by CC(U)S technology

2.1. Global large commercial CCS projects

Global CCS Institute (GCCSI)[8] counted 21 operations and 4 constructions as large CCS projects in June, 2020 (Fig.5). GCCSI defines the large project as more than about 400,000 tons/year in the Capability of CO_2 Capture. (At present, GCCSI changed the definition and classifies CCS project as operation or not.)

Many large projects use the captured CO_2 as EOR (Enhanced Oil Recovery) and the CO_2 come from the production process of Natural Gas refinery, Fertilizer, Hydrogen production etc. The total amount of CO_2 permanently stored by the operation projects is about 37 million tons a year and it is estimated at about 40 million tons a year, adding the capacity of the construction stage.

2.2. Problem arrangement and future challenges

Regarding 21 large CCS projects operating in the world, the implementation bodies are all private companies except state-owned companies in China and Saudi Arabia. There are some requirements that these CCS projects are established, and they are pointed out as follows. At first, if CO_2 is captured in the existing process, the addition cost to be necessary on performing CCS is only investment to modify the transportation and the Injection, so they are the relatively low-cost projects. Also, the CCS projects which are able to get the profit by EOR or the natural gas production, and which get a subsidy, tax credit, etc. are economically realized. In other words, it says that their projects are the examples of Low-hanging fruits which can easily start like the low-cost realizable ones or the profitable EOR.

In addition, the system framework of CCS introduction overseas is considered, assuming the implementation of private sector. It is to make the business model, which have various incentives (subsidy, tax credits, debt guarantee, etc.) and the systems, including the transfer to the Government about the long-term responsibility after the Injection.

The mass transportation of the CO_2 is considered as pipeline or ship transportation, but ship one needs the technology developments such as the optimization of liquefaction facilities, etc. Also, it is better that the demonstration is early started because of the expectation of the cost reduction up-sizing in the future.

Also, many sites of the large-scale CO_2 Storage are essential for 100 million tons quantity a year needed the future CO_2 injection in Japan, so Japan CCS Co., Ltd. (JCCS) performed the research to select prospective sites for CO_2 Storage. According to the research, they are estimated as about 7 billion tons in the 3D exploration area and about 46 billion tons (3 billion tons in the detail investigation and 43 billion tons in the rough investigation) in the 2D exploration area.

Though the injection quantity was uncertain, Japan has enough potential quantity for CO_2 storage. But it is necessary to evaluate the potentiality of the geological layer, total economic efficiency including the emission source, and the safety, in order to select the potential sites for CO_2 Storage.

The most reasonable policy is the scenario that firstly starts the project of the Low-hanging Fruits and gradually promotes cost reduction and then begins the larger CCS projects, in order to promote CCS.

Both public and private sectors need to start to formulate the practicable roadmap and the action plan immediately, and it is important that public and private sectors share the responsibility to implement them.

Phase	Country	Title	Industry	Facility Storage Type	Operational Date	Facility Capture Rate
Operational	USA	Terrell Natural Gas Processing Plant	Natural Gas Processing	EOR	1972	0.4～0.5
		Enid Fertilizer	Fertiliser Production	EOR	1982	0.7
		Shute Creek Gas Processing Plant	Natural Gas Processing	EOR	1986	7
		Century Plant	Natural Gas Processing	EOR	2010	8.4
		Air Products Steam Methane Reformer	Hydrogen Production	EOR	2013	1
		Coffeyville Gasification Plant	Fertiliser Production	EOR	2013	1
		Lost Cabin Gas Plant	Natural Gas Processing	EOR	2013	0.7
		Illinois Industrial Carbon Capture and Sequestration	Ethanol Production	Onshore deep saline formation	2017	1
		Petra Nova Carbon Capture	Power Generation	EOR	2017	1.4
	Canada	Great Plains Synfuels Plant and Weyburn Midale	Synthetic Gas Processing	EOR	2000	3
		Boundary Dam Carbon Capture and Storage	Power Generation	EOR	2014	1
		Quest	Hydrogen Production	Onshore deep saline formation	2015	1
		Alberta Carbon Trunk Line with Agrium CO	Fertiliser Production	EOR	2020.6	0.3
		Alberta Carbon Trunk Line with North West Sturgeon Refinery	Oil Processing	EOR	2020.6	1.6
	Brazil	Petrobras Lula Oil Field	Natural Gas Processing	EOR	2013	1
	Norway	Sleipner CO_2 Storage	Natural Gas Processing	Offshore deep saline formation	1996	1
		Snøhvit CO_2 Storage	Natural Gas Processing	Offshore deep saline formation	2008	0.7
	Saudi Arabia	Uthmaniyah CO2-EOR	Natural Gas Processing	EOR	2015	0.8
	UAE	Abu Dhabi CCS	Steel production	EOR	2016	0.8
	China	CNPC Jilin Oil Field CO_2 EOR	Natural Gas Processing	EOR	2018	0.6
	Australia	Gorgon CO_2 Injection Project	Natural Gas Processing	Onshore deep saline formation	2019	3.4～4
21 large-scale CCS projects (CO_2 Capture quantity(tCO_2／year))						36.8～37.5 million
In construction	China	Yanchang Integrated Carbon Capture and Storage	Fertiliser Production	EOR	2020～2021	0.41
		Sinopec Qilu Petrochemical CCS	Fertiliser Production	EOR	2020	0.4
	USA	The ZEROS Project	Power Generation	EOR	2020	1.5
	Norway	Langskip CCS - Brevik Norcem	Cement Production	Offshore deep saline formation	2024	0.4

Fig.5 The situation of the large-scale CCS projects in the world

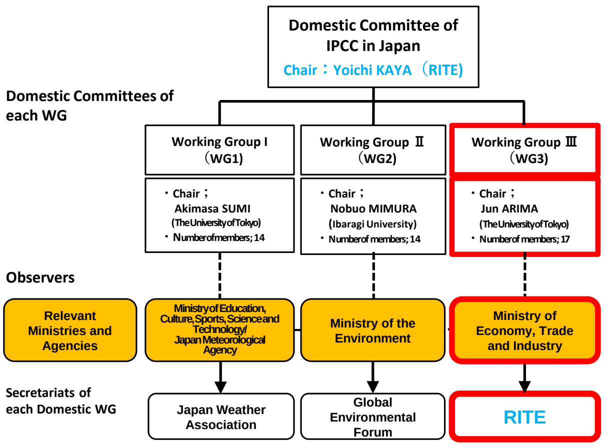
3. Promotion of international partnership

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 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. 6). 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 'Sixth Assessment Report (AR6)' 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.



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

Fig.6 Committee structure and RITE

3.2. ISO

ISO (International Standard Organization) is an organization composed of 165 standardization bodies of various countries. Carbon dioxide capture and storage (CCS) is one of the important options for global warming countermeasures because it has a great effect of reducing CO_2 emissions into the atmosphere. In the world, a number of CCS verification projects on a commercial scale are also implemented, and international collaboration is under way. The international standard plays an important role, contributing to the widespread use of safe and appropriate CCS technology.

RITE is a domestic deliberation organization on ISO / TC 265 (collection, transportation, and storage of CO_2) and is in charge of a secretariat of WG 1 (collection). Through these activities, we are conducting international standardization on design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the CCS field through international standardization (Fig. 7).

In December, 2020, nine standards related to the CCS field have been published from ISO / TC265, and six are under development. Of the standards under development, two in the CO_2 collection and storage fields are being developed by Japan.

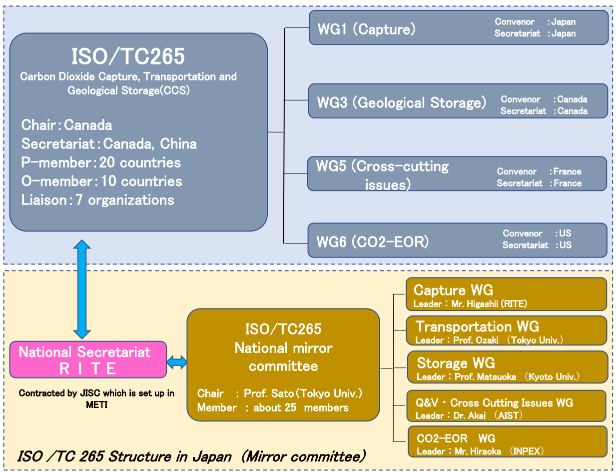


Fig.7 ISO/TC265 structure

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. But because of Novel Coronavirus in 2020, we held classes and workshops for 37 students only in January and February 2020 compared with 397 students in 2019. 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. 8).

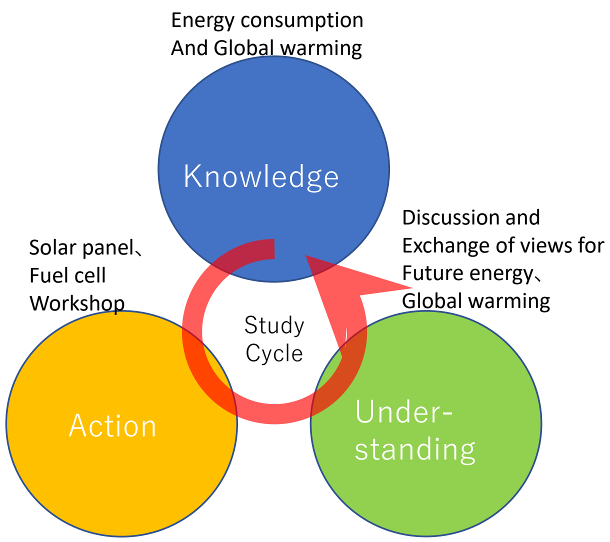


Fig.8 RITE and environment education
(Elementary, middle and high school students)

<University / Postgraduate student>

RITE is promoting collaboration of education with universities as part of human development 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. 9). 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.

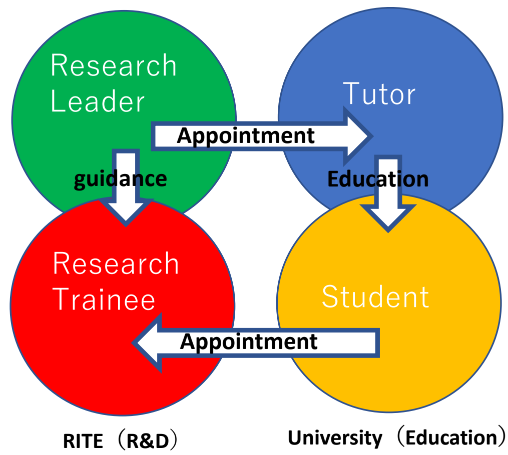


Fig.9 RITE and environment education
(University / Post graduate student)

4.2. Intellectual property and industry collaboration

RITE acquires and manages intellectual property rights such as patents and know-how strategically and efficiently on results obtained in R&D. As of the end of 2020, the patents owned by RITE are 106 domestic rights (11 of which are licensed to companies) and 49 foreign (13 of which are licensed to companies). RITE has established an IP management Committee and operates it with intellectual property experts (Fig. 10).

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.

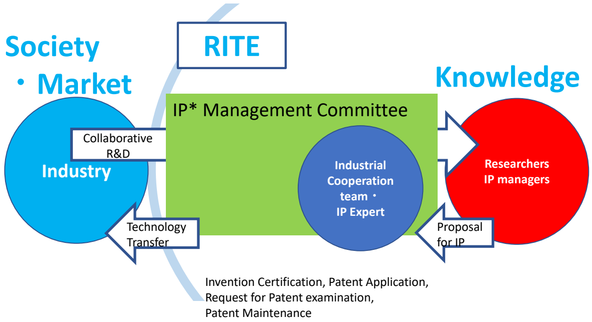


Fig.10 Strategic IP management and industrial collaboration

5. Conclusion

In 2020, Japan declared the goal of realizing 2050 Carbon Neutrality, and It is 30th years since RITE was established whose functions are to aim the achievement of a balance between Global environmental protection and economic growth. To realize 2050 Carbon neutrality, Japan needs to establish the innovative technology showed by" environmental innovation strategy" and the RITE's CO_2 Capture technology is one of the necessary technologies. But to realize 2050 Carbon neutrality is impossible by remarkable efforts. It is necessary that RITE also promotes the social implementation proactively.

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

Reference

1) RITE, "The Role of RITE" (http://www.rite.or.jp/about/)

2) "Environmental Innovation Strategy" (https://www.kantei.go.jp/jp/singi/tougou-innovation/pdf/kankyousenryaku2020.pdf)

3) "The Moonshot Research and Development Program, Goal 4：Realization of sustainable re-source circulation to recover the global environment by 2050" (https://www8.cao.go.jp/cstp/moonshot/project.html#a4)

4) Prime Minister Suga's Policy Speech at the 203rd extraordinary Diet session (https://www.cas.go.jp/jp/seisaku/seicho/seichosenryakukaigi/dai6/)

5) "Green Growth Strategy towards 2050 Carbon Neutrality" (https://www.cas.go.jp/jp/seisaku/seicho/seichosenryakukaigi/dai6/)

6) IEA, World Energy Outlook (2019) (https://www.iea.org/reports/world-energy-outlook-2019)

7) RITE's CCS research entrusted by METI (2019) (https://www.meti.go.jp/meti_lib/report/2019FY/000145.pdf)

8) GCCSI（Global CCS Institute） (https://www.globalccsinstitute.com/)

Systems Analysis Group

Members (As of Dec. 2020)

Keigo Akimoto, Group Leader, Chief Researcher
Toshimasa Tomoda, Chief Researcher
Koya Yamada, Associate Chief Researcher
Kenichi Wada, Senior Researcher
Miyuki Nagashima, Senior Researcher
Takashi Homma, Senior Researcher
Fuminori Sano, Senior Researcher
Junichiro Oda, Senior Researcher
Hironobu Yamakawa, Senior Researcher
Haruo Kanaboshi, Senior Researcher (concurrent)
Ayami Hayashi, Senior Researcher
Atsuko Fushimi, Senior Researcher
Yuko Nakano, Researcher
Naoko Onishi, Researcher
Hitotsugu Masuda, Researcher
Kiyomi Yamamoto, Assistant Researcher
Misako Saito, Assistant Researcher
Kiyomi Kitamura, Assistant Researcher
Sachiko Kudo, Assistant Researcher

Research Activities in Systems Analysis Group

The Systems Analysis Group aims to provide valuable information about response measures to global warming and energy issues through systematic approaches and analyses. This article presents the outcomes of the analyses that our group has been conducting for future scenarios with regard to the countermeasure strategies for decarbonization.

1. Role of CCU for realizing Carbon Neutrality

The direction of the measures for realizing carbon neutrality and the role of Direct Air Carbon Capture and Storage (DACCS) as a negative emission technology are explained in the featured article about Beyond EXPO. In this chapter, we introduce the role of Carbon Capture Utilization (CCU) for pursuing carbon neutrality with the analyses by our global energy and climate change mitigation assessment model, DNE21+.

1.1. Overview and Focal points of CCU

There are several forms of CCU, such as Enhanced Oil Recovery (EOR) as a form of CO_2 storage, and the use for fuels, chemicals and promoting mineralization, and so on. CO_2 is chemically stable thus additional energy with synthesized hydrogen etc. is necessary to utilize it for energy or chemicals. On the other hand, the promotion of mineralization, such as mineralization of cement, does not require additional energy during the process.

It should be noted that the fuel use, for instance, does not have CO_2 emission reduction effect since CO_2 captured and used for synthesis is emitted at combustion. In that case, CO_2 plays a role as an intermediary for hydrogen transport to enhance the convenience of hydrogen. CO_2 can be reduced by replacing fossil energy with carbon-free hydrogen energy. The CO_2 emission reduction effect by the alternative is the same as the amount of CO_2 used for synthesis.

In principle, there is no difference in the CO_2 used for synthetic fuels regardless of its source, even if the CO_2 from fossil fuel combustion is captured and used. However, in that case, fossil fuel combustion is performed separately, and gross zero emission cannot be achieved. Therefore, in order to achieve net zero emission, negative emission technologies (NETs) should be conducted somewhere in the world to cancel out the CO_2 emission from the fossil fuel combustion. There are some arguments on one hand that the CO_2 used for synthetic fuels should be limited to the CO_2 captured by DAC or from bioenergy emission, however, it is necessary to evaluate in terms of economic efficiency for the whole system. Although the evaluation of CCU is difficult, which may lead to both overevaluation and under-evaluation, it is important to make a better assessment in the whole system considering the current status.

1.2. Evaluation of the role of synthetic fuel, a representative example of CCU by DNE21+

This section shows the example of the analyses on the countermeasures for global carbon neutrality by global energy and climate change mitigation model, DNE21+. The DNE21+ can make an assessment until 2100, with 54 regions, in which around 500 technologies can be assessed. Here, we introduce the analysis results about synthetic fuels for which systematic analysis is considered particularly important. For detailed assessment of synthetic methane and synthetic oil, please refer to Reference 1) and 2), respectively. Reference 1) indicates that applying synthetic methane would be economically efficient in the case that there are large differences in the marginal abatement cost (MAC) of emission reduction target among nations, as it would be economically rational that methanation is conducted in the country where MAC is relatively low and the methane is exported to and used in the country where MAC is relatively high. The result of the scenario where the globally equalized MAC is assumed, which tends to show slightly conservative result for synthetic fuels, is introduced in this article.

Table 1 shows the assumed scenarios for model analysis.

The production and consumption of hydrogen which is an energy source of synthetic fuels are shown in Fig. 1. The major production method will be gasification from coal and lignite with CCS (blue hydrogen) in the standard cost case of PV (2DS_1 scenario) and water electrolysis by solar PV (green hydrogen) in the low-cost case of PV (scenarios other than 2DS_1). As for consumption, hydrogen will be used as itself in various ways, including power generation, hydrogen direct reduction steelmaking, and transportation, and also the use for synthetic fuels with captured CO_2, such as synthetic methane and synthetic oil, is evaluated as an economically efficient measure. Fig. 2 shows the global CO_2 consumption for synthetic fuels. This amount is equal to CO_2 reduction effect caused by replacing fossil fuels with use of synthetic fuels (carbon-free hydrogen). The result shows that the CO_2 used for synthetic fuels is not limited only to captured CO_2 by DAC or from biomass combustion but mainly captured CO_2 from fossil fuel combustion, even under B1.5D_3_DAC, where DAC is assumed available.

Table 1 Model analysis scenarios

Scenario name	Global emission scenarios	[Supply side] PV cost	[Demand side] Fully autonomous cars and Share mobilities acceleration	[NETs] DAC
2DS_1	Below 2 °C (>50%): Corresponding to IEA ETP2017 [2DS]	Standard cost reduction	w.o. consideration	w.o. consideration
2DS_2		Low cost particularly in Middle-East & N. Africa		
2DS_3			Share mobilities acceleration (Fully autonomous cars)	
B2DS_2	Below 2 °C (>66%): Corresponding to IEA ETP2017 [B2DS]	Low cost particularly in Middle-East & N. Africa	w.o. consideration	w.o. consideration
B2DS_3			Share mobilities acceleration (Fully autonomous cars)	
B1.5D_3_DAC	Below 1.5 °C in 2100 (>66%): overshoot of temperature	Low cost particularly in Middle-East & N. Africa	Share mobilities acceleration (Fully autonomous cars)	Available (Low cost) No feasible solution if DAC not available

Note) 1: The assumed PV costs in the standard scenario are below 60$/MWh accounting for about 6% of the global PV potential and 60-80$/MWh for about 24% in 2050. Those in the low cost scenarios are below 30$/MWh accounting for 15% of the global PV potential and 30-40$/MWh for about 14%. 2: It is assumed that fully autonomous cars are available in 2030 and ride-/car-sharing is accelerated in the fully autonomous cars and share mobilities acceleration scenarios. 3: The assumed necessary energy for DAC is 4.7GJ/tCO2 in 2050.

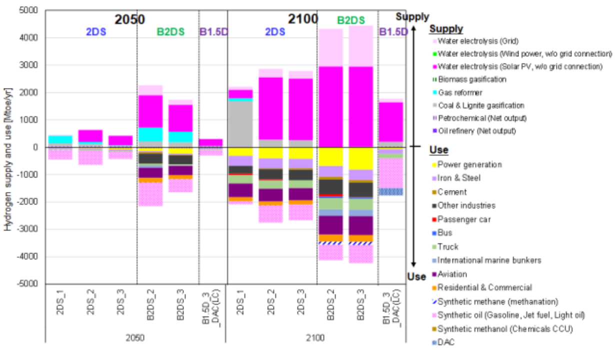


Fig.1 Global hydrogen balances

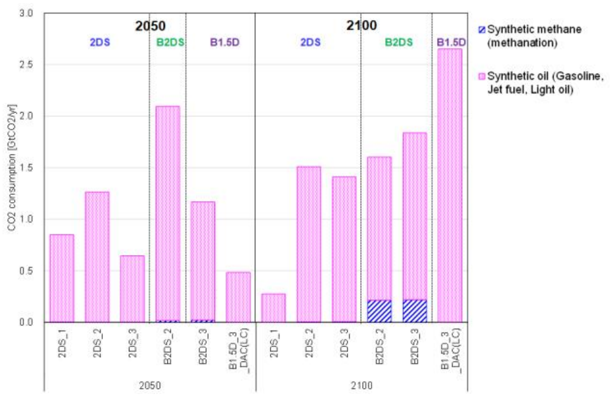


Fig. 2　Global CO_2 consumption for synthesis fuels

The use of synthetic methane can contribute to realizing carbon neutrality with utilizing existing infrastructure and gas appliances by use of piped gas. As for synthetic oil, it will be possible to achieve carbon neutrality while utilizing existing infrastructure and technologies, such as hybrid vehicles, in the road transport sector. Also, the use of those synthesis fuels will be effective for the measures which are difficult to replace with electricity or hydrogen in the aviation, marine bunkers, industry, and other sectors. The role of synthetic fuel as CCU should be evaluated integrally with hydrogen supply, and the evaluation is not simple. However, our analyses suggest that it can be an important piece of measures for achieving carbon neutrality.

2. Assessing impacts of border carbon adjustment using global energy-economic model

2.1. Background of border carbon adjustment (BCA)

The goal of achieving net zero emissions by 2050 has been set by countries around the world. If the cost of burden of reducing GHG emissions in one country is greater than that in other countries, it will affect the international competitiveness of energy intensive countries in that country and will lead to leakage of CO_2 emissions to other countries (substitution of domestic products by overseas products and transfer of production bases overseas). Border Carbon Adjustment (hereinafter referred to as BCA) is being discussed as one of the options to deal with this problem. In general, the BCA is a border measure that imposes the same burden on imported products from countries with insufficient emission reduction efforts as domestic products.

In December 2019, Ursula von der Leyen, the president of the European Commission, announced the European Green Deal (see Reference 3), that contains a goal of net zero greenhouse gas emissions by 2050. It also includes a roadmap for the carbon border adjustment mechanism (CBAM). At the European Council meeting in July 2020, it was agreed that the institutional design would be completed in the first semester of 2021 with a view to its introduction at the beginning of 2023. It should be noted that introduction of BCA involves challenging issues, regarding such as compatibility with World Trade Organization (WTO) rules, the methodology for assessing the carbon content of products and how the tax rate is adjusted.

2.2. Methodology

We examine the impacts of BCA by using the global energy-economic model that we have developed, called the DEARS model[4)]. The model is an integrated model of a top-down economic module (general equilibrium type) whose objective function is to maximize the global utility of consumption, and a simplified bottom-up energy system module. In the economic module, 16 non-energy industries are assumed, and the input-output (IO) structure based on the GTAP (global IO table), is explicitly modeled. Regarding trade, the Armington structure with the substitution between imported and domestic products is formulated.

This study focuses on steel products as a case study and shows the economic impacts and CO_2 emissions under multiple cases, by assuming two types of tariff methods for border adjustment as follows.

I. BCA tariff

In general, the BCA tariff rate is determined by the average CO_2 intensity embodied in the imported products made in the country of origin. In this case, heterogeneity within the same products is not considered.

II. CSTR (Cooperative Sectoral Tariff Reduction) tariff

The CSTR tariff, proposed by Banks and Fitzgerald (2020)[5], is based on the differentiated CO_2 intensity embodied in the imported products, taking into account the heterogeneity within the same ones. The CSTR tariff will encourage a shift to the products with relatively low intensity, which leads to more reduction in CO_2 emissions. However, because of the considerable difficulty involved in estimating the distribution of energy intensity of steel production within each country, the following assumptions were made for this analysis. First, steel products are classified into three product groups (universal grouping) according to their energy intensity: (i) Good (0.10[GJ/$]), (ii) Middle (0.80), and (iii) Poor (1.50) (hereinafter referred to as Good, Mid., and Poor, respectively). Then, the ratios belonging to each product group by region are assumed to be consistent with the statistical data of regional average energy intensity in steel production.

Following previous studies[6)7)], we assume substitutability between demand of imported products and that of domestic ones by using a CES-type function with the elasticity of substitution (δ) that is assumed to be 1.5 in the standard case. Furthermore, we assume an elasticity of substitution of 2.0 for the demand between the product groups.

Table 2 shows the simulation cases in this study. We examine the impact of BCA and retaliatory measures based on a simplified scenario in which Japan, the US and the EU cooperate in implementing domestic emission reduction measures while the rest of the world (ROW) do not take any measures. Two types of carbon tariff are assumed as mentioned above, and we explore the impact of favorable treatment for the product group with the lowest intensity.

Table 2 Simulation cases

Case name	Regions with domestic carbon tax: 32$/tCO2	Carbon tariffs: 32$/tCO2	Favorable treatment for good performer [w/o tax and tariff] (-G)	Retaliatory tariffs by ROW (-R)
(1) TRI	[US, EU, JPN]	×	×	×
(2) WLD	All regions	×	×	×
(3) TRI-BCA	[US, EU, JPN]	BCA	×	×
(4) TRI-BCA-R	[US, EU, JPN]	BCA	×	○
(5) TRI-CSTR	[US, EU, JPN]	CSTR	×	×
(6) TRI-CSTR-R	[US, EU, JPN]	CSTR	×	○
(7) TRI-CSTR-G	[US, EU, JPN]	CSTR	○	×
(8) TRI-CSTR-G-R	[US, EU, JPN]	CSTR	○	○

We assume that the carbon price and carbon tariff are 32$/t$CO_2$ referring to the EUA price of EU-ETS (July 2019), and the tax revenue is used for government consumption (the general account). The carbon price and carbon tariff are assumed to be levied on emissions after allocating electricity and heat. Export tax rebate, the refund of carbon tax paid on exported products, is also considered. Although various types of retaliatory measures can be considered, we assume that the same rate as carbon tariff is levied on the steel products as a retaliatory tariff. The baseline (without additional climate policies) socio-economic scenario in this study is assumed to be the median scenario (SSP2)[8)].

2.3. Results

(1) Impacts of different carbon tariffs

In the BCA (Cases 3 and 4) and CSTR (Cases 5 through 8) implemented by the US, the EU and Japan, the steel production values have turned positive, respectively, relative to Case 1, therefore, both types of carbon tariffs will reduce the decline in international competitiveness (Fig. 3). Also, the introduction of BCA and CSTR has the effect of reducing carbon leakage when compared to Case 1 (Fig. 4).

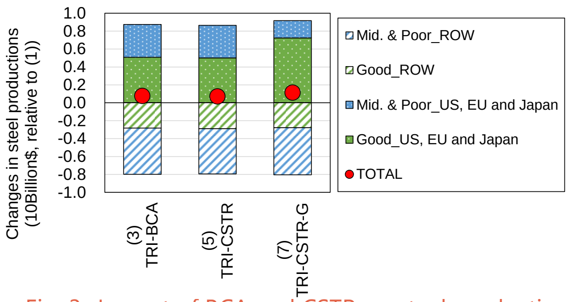


Fig. 3 Impact of BCA and CSTR on steel production (2020)

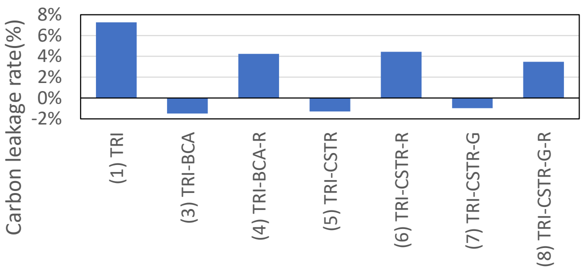


Fig. 4 Carbon leakage (2020)

Note) Carbon leakage is expressed as increase in CO_2 emissions (for steel productions) in the rest of the world (ROW) over CO_2 reductions in the US, the EU and Japan relative to the baseline.

It is estimated that both BCA and CSTR will promote the production shift to steel products with the lowest intensity (classified as "Good"), however, the impact of differences in tariff methods is not significant. Similarly, with regard to the global CO_2 reduction effect, the difference caused by the differentiated tariff methods is not large, such as from the comparison between Case 3 and Case 5 in Fig. 4. Rather, the exemption for products "Good" has a large impact on the production shift to products "Good", but the impact on the global emission reduction is limited.

(2) Impacts of retaliation

In the case of retaliatory measures by ROW in response to the border adjustments by the US, the EU and Japan, the relative price of import from the US, the EU and Japan in ROW relative to the cases without retaliation will increase, resulting in a shift of steel production from the US, the EU and Japan to ROW (Fig.5). In addition, retaliatory tariffs will reduce the international competitiveness of the US, the EU and Japan, and worsen leakage (Fig. 4). The impact on global emission, however, is also estimated to be very small.

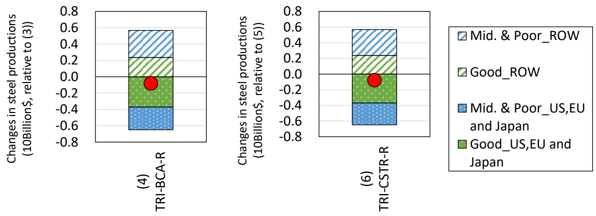


Fig. 5 Impact of retaliatory tariffs on steel production (2020)

(3) Impacts of international cooperation

In Case 2, which assumes all countries cooperate to reduce emissions and impose the same rate of carbon price on domestic production of steel in all countries, the steel production of "Mid" and "Poor" in ROW decreases compared to Case 1, while the production by the US, the EU and Japan increases (Fig. 6).

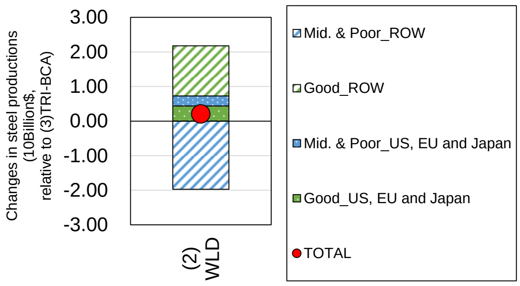


Fig. 6 Impact of international cooperation on steel production (2020)

(4) Comparison of impacts by region

When the US, the EU and Japan implement border adjustment measures, other countries such as China have higher incentives to implement retaliatory measures (Fig. 5). Under such circumstances, the impact on the US, the EU and Japan will differ, with the negative impact of retaliation being relatively large in Japan and small in the US (Fig. 7). The following two factors can be considered. First, although Japan has a lower intensity of both converter steel and electric furnace steel than that of other countries[9], Japan's superiority is not properly reflected in a framework that does not distinguish between converter steel and electric furnace steel. Therefore, the rate of increase in the price of steel products after tariffs are levied, is estimated to be in the order of "Japan (high ratio of converter steel) > the EU> the US (high ratio of electric furnace steel)". Second, the export-import ratio of steel products is also a factor in the different regional impacts of border adjustment and retaliatory measures. The ratio of steel product export to import in the baseline scenario in 2020 is estimated to be 5.0 for Japan, 0.9 for the US, 2.0 for the EU, and 1.5 for China. Japan's high ratio will result in small benefits of border measures and large negative impacts of retaliatory measures.

Conversely, the US has a high import ratio, suggesting that the benefits of border measures are large and the negative impacts of retaliatory measures are small. In addition, under the framework that does not distinguish between converter steel and electric furnace steel, the US with its high ratio of electric furnaces, is estimated to be superior in terms of intensity. Therefore, in this framework, the US has a high incentive to implement border adjustment measures even with retaliation.

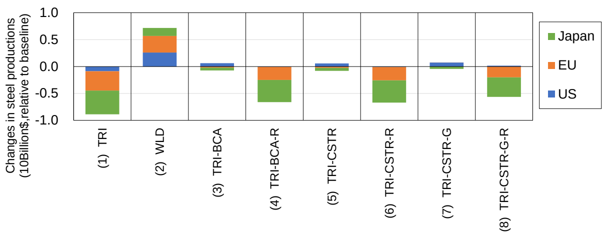


Fig. 7 Changes in steel production by region (2020)

(5) Sensitivity analysis on elasticity of substitution between domestic and imported products

When the elasticity of substitution between domestic and import products is large (δ=2.8)[10], the carbon leakage rate increases in Case 1 compared to the standard assumption (δ=1.5) due to a larger shift to other regions (Fig. 8). Moreover, while the border adjustment measures have the effect of reducing leakage, the retaliatory measures increase the leakage rate compared to the standard case.

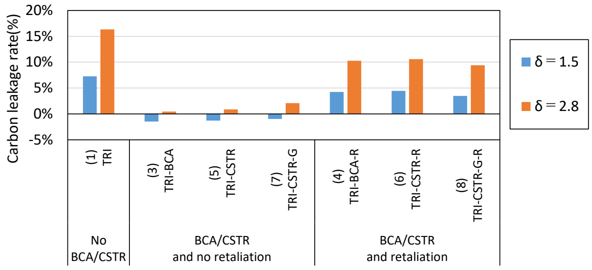


Fig. 8 Impact of change in elasticity of substitution on carbon leakage rate (2020)

2.4. Conclusion

The two types of carbon tariffs methods, a general BCA tariff based on the average product intensity and a CSTR tariff based on the intensity of each product, were estimated to reduce the loss of international competitiveness due to domestic reduction measures and to reduce carbon leakage, with little difference between the tariff methods.

Conversely, retaliatory measures were estimated to reduce the international competitiveness of Japan, the US and the EU and to worsen carbon leakage, although the impact on global emissions was very small. Under the framework we examined, the results implied that the incentives to introduce border adjustments would differ depending on the regional structures of production and trade.

For future work, it will be important to consider the extension of the classification of converter steel and electric furnace steel with respect to steel products, as well as the extension to other energy-intensive and major trade products.

3. Overview of Research Project (EDITS) on Low Energy Demand Society Affected by Technological Innovation and Social change

In 2020, RITE started a new research project, EDITS (Energy Demand changes Induced by Technological and Social innovations), which includes international model comparisons of analyses on energy demand changes and their impacts. The project is supported by Ministry of Economy, Trade and Industry (METI).

3.1. Background

We do not consume energy because we want to. We consume its embodied energy for obtaining services. A lot of energy is wasted to obtain that service, especially near the final demand (Fig. 9).

The energy required for the final services is estimated to be around 5% of the total primary energy consumption. However, the over consumption will be basically rational if we consider the "hidden costs" that hinder our convenience, and the energy supplies and demands in the current society was determined with over energy consumptions. Although having said that, it is being changed along with technological progress. For example, lighting has been practical use which turns off automatically when there are no people around and air conditioners can also cool a specific area where people are intensively. These technologies led to energy savings while suppressing service degradation. On the other hand, there is still a lot of waste as a social system.

The progress of information and communication technology (ICT) has the potential to induce social innovation on the final energy demand side and to leads to triggering: (1) from independent technology to connection between technologies, (2) from possession to use, and (3) inducing sharing economy and circular economy.

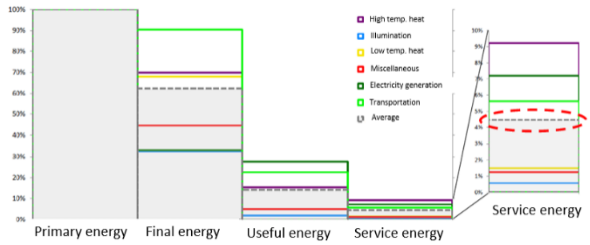


Fig. 9 Global Energy Consumption by Usage
(when primary energy consumption is 100%)[11)]

For example, advances in ICT can have a significant impact on mobility. A change called Connected; Autonomous; Service & Shared; Electric (CASE) is happening. The utilization rate of private cars is estimated to be about 4-5%, and private cars are not used for many hours.

However, if a fully autonomous vehicle is realized, even with ride sharing or car sharing, it will not impair convenience significantly and likely to be used at a low cost because of an increase of operation rate. Ride sharing can directly reduce the energy consumption of automobiles, and car sharing can reduce the number of automobiles, reduce the use of materials such as iron and plastic as well as the energy consumption required for the manufacture. These reductions can contribute to the simultaneous achievement of the SDGs. Excessive production is being carried out not only in automobiles but also in apparel, food systems, etc., and there is a possibility that these can be reduced by the progress of ICT. It is important to control total energy demand of society by not only directly reducing energy but also reducing the energy embodied in services and products. On the other hand, ICT can increase energy consumption in data centers and other various rebound effects, so comprehensive analysis including behavioral changes is required.

3.2. Overview of EDITS

Under these circumstances, the EDITS project has just started the following research:

- Building a research community: Promoting better understanding through interaction between research and policy analysis with sharing new data, new concepts, methodologies, and policy analysis focused on the demand side.
- Improvement of state-of-the-art demand side model: Further refinement of environmental and climate policy analysis by mutual comparison and sharing of methodologies and models across disciplines and environmental fields.
- Model-to-model comparative analysis: Conduct model analysis and simulation to assess synergies and trade-offs, potential impacts and barriers to SDGs from demand-side policies while particularly focusing on digitization, sharing economy, and policy design with synergies from the integration of SDGs and climate goals

Many domestic and foreign research institutes and researchers will work together to tackle this important and difficult analytical tasks. RITE and the Institute for International Applied Systems Analysis (IIASA) playing a central role and collaborate with Tokyo University, Osaka University, Lawrence Berkeley National Laboratory (LBNL), Stanford University, Wisconsin University, Tsinghua University of China, and other institutes in South Korea, Italy, Germany, Thailand, Brazil, etc.

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Molecular Microbiology and Biotechnology Group

Members (As of Dec. 2020)

Masayuki Inui, Group Leader, Chief Researcher
Haruhiko Teramoto, Associate Chief Researcher
Kazumi Hiraga, Associate Chief Researcher
Hajime Terasaki, Associate Chief Researcher
Masato Miyamoto, Associate Chief Researcher
Yuya Tanaka, Senior Researcher
Masako Suda, Senior Researcher
Yukihiro Kitade, Senior Researcher
Koichi Toyoda, Senior Researcher
Naoto Kato, Senior Researcher
Satoshi Hasegawa, Senior Researcher
Akira Watanabe, Senior Researcher
Takahisa Kogure, Senior Researcher
Takeshi Kubota, Senior Researcher
Toshihiro Oshima, Senior Researcher
Shinichi Oide, Senior Researcher
Tetsu Shimizu, Researcher
Tomoaki Hara, Researcher
Akiyoshi Higo, Researcher
Natalia Maria Theresia, Researcher
Norimasa Kashiwagi, Researcher
Jyumpei Kobayashi, Researcher
Ryoma Hashimoto, Researcher
Naoki Saruya, Researcher
Yuki Nozaki, Researcher
Junko Watanabe, Assistant Researcher
Yuko Ikenaga, Assistant Researcher
Shoko Minakuchi, Assistant Researcher
Miyuki Nagamori, Assistant Researcher
Kae Naito, Assistant Researcher
Noriko Ikeda, Assistant Researcher
Kazuyo Yoneda, Assistant Researcher
Mayu Koizumi, Assistant Researcher
Junko Nishi, Assistant Researcher
Kayoko Mori, Assistant Researcher
Motomi Iwashima, Assistant Researcher
Kayo Yoshida, Assistant Researcher
Aya Okada, Assistant Researcher
Kimiyo Kishi, Assistant Researcher

Development of Biorefinery Technology to Realize a Sustainable Society

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic has had a great impact on economic and social activities worldwide. Meanwhile, environmental problems such as global warming and marine plastic pollution remain are becoming more serious. Under these circumstances, the promotion of the bioeconomy is becoming increasingly important for economic recovery after the convergence of infectious diseases and for solving environmental problems.

The concept of "bio-economy," which aims to expand a sustainable, renewable and recycling-oriented economic society while solving global issues by utilizing biotechnology and renewable biological resources (Fig.1).

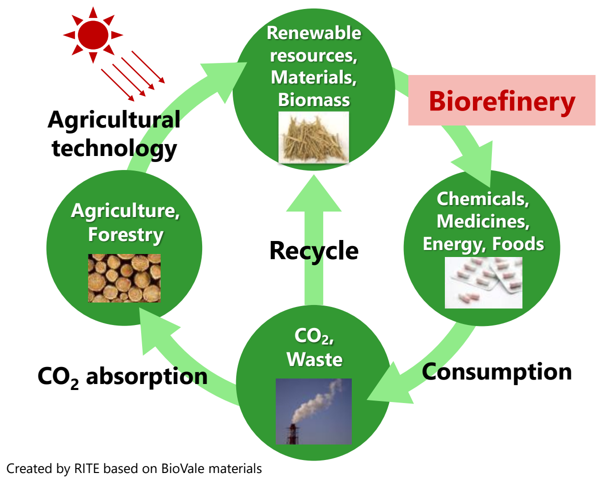
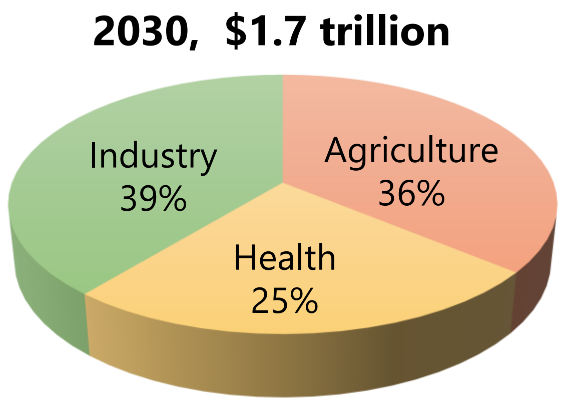


Fig. 1 Economic contribution of biotechnology

According to the Organisation 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. 2). It is said that all of these industries are bio-based.



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

Fig. 2 Economic contribution of biotechnology

Under such circumstances, the government formulated “Bio-Strategy 2019” in June 2019, with the overall goal of “achieving the world's most advanced bioeconomy society in 2030.” This was to be promoted while being updated every year, and in June 2020, "Bio-Strategy 2020 (Basic Measures)" was announced, followed by "Bio-Strategy 2020 (Final version of Market Area Measures)" in January 2021.

Our group is promoting the development of biorefinery technology, the core of bioeconomy, by using microorganisms. Biorefinery technology is used for producing biofuels and green chemicals, using renewable resources (biomass) as raw materials.

This first section provides an overview of the current status of biofuel and bioplastic (a substitute for general-purpose plastics) research and development (R&D).

1.1. Biofuels

Bioethanol, a major biofuel, is produced from raw materials such as corn (in the U.S.) and sugarcane (in Brazil). It is mixed with 10%–25% gasoline for use in automobile engines. The highest production and consumption of bioethanol occurs in the United States (U.S.) where corn is a major crop. According to estimates provided by the U.S. Energy Information Administration, 15.8 billion gallons (59.81 million kL) of bioethanol was produced in the U.S. in 2019. Similarly the Agricultural Outlook 2020–2029 report, published jointly by the OECD and the Food and Agriculture Organization, states that 129 million kL of bioethanol was produced worldwide in 2019, with the U.S. accounting for approximately half of this production.

Cellulose ethanol, a second-generation biofuel, is produced from raw materials that do not compete with food resources, such as the agricultural waste corn stover. On the basis of Renewable Fuel Standard (RFS) rules, the Environmental Protection Agency's final volume for the production of cellulosic biofuel in 2020 was 590 million gallons (2.23 million kL), which was slightly more than 5.6% of the RFS target set in 2007. The acceleration of biofuel commercialization is required in the future. The Research Institute of Innovative Technology for the Earth (RITE) is developing a bioprocess that can efficiently utilize cellulosic biomass (see Chapter 2).

With regard to aviation fuel, the International Civil Aviation Organization decided at their 2010 General Assembly not to increase total greenhouse gas emissions after 2020. At the 2016 General Assembly, a decision was made to introduce a greenhouse gas reduction system using market mechanisms (GMBM: global market-based measures) after 2020. On the basis of this decision, the International Air Transport Association has formulated a concrete action plan, including the uses of bio-jet fuel and emissions trading (Fig. 3). The GMBM are expected to be launched in 2021. Along with these, bio-jet fuel has been widely spread mainly in Europe and the U.S. every year, and commercial flight has been continued as a sustainable aviation fuel using cooking waste oil and the like.

Our group is also conducting R&D on biofuels. In a project sponsored by Japan Airlines Co., Ltd. (JAL), we have succeeded in producing domestic bio-jet fuel for the first time in Japan, and this bio-jet fuel was refueled on a regular domestic flight (see Section 4.1).

We are also conducting R&D on a green jet fuel that can be used as is, that is, without limitation of mixing ratio to petroleum fuels.

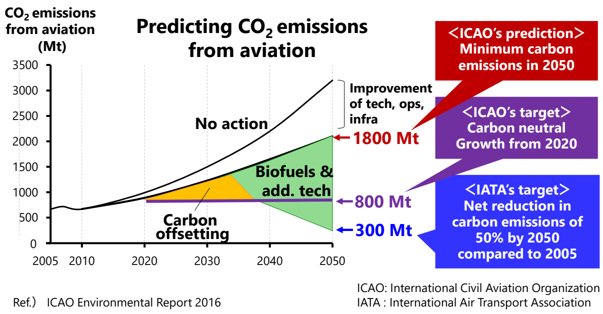


Fig. 3 Emissions reduction roadmap

With regard to marine fuels, Japan's International Shipping Greenhouse Gas Zero Emission Project, established in collaboration with the Japan Ship Technology Research Association, aims for a zero emissions target by 2050 through the promotion of technological innovations, such as alternative low-carbon fuels of the next generation like biohydrogen. The Project has developed a roadmap toward accelerating efforts to achieving zero emissions.

1.2. Bioplastic

Efforts to reduce greenhouse gases by spreading and generalizing the use of plastics that do not depend on fossil resources have stagnated, and the environmental pollution caused by marine plastic wastes has become a serious global issue. Against this background, there are great expectations from bioplastics and biodegradable plastics made from biomass, which is a renewable resource.

“Bio-Strategy 2020” places great importance on the immediate and continuous promotion of bioplastics (a general-purpose plastic alternative), which is one of the nine market areas shown in “Bio-Strategy 2019.”

Our group is involved in the Moonshot R&D project (Development of Multi-lock Biopolymers Degradable in Ocean from Non-food Biomasses) of the New Energy and Industrial Technology Development Organization (NEDO). Participation in the project “Production of Bio-monomers from Non-food Biomass and Development of Polymer-degrading Enzymes” will be undertaken.

2. Core technology of our group

Our group has established an innovative bioprocess on the basis of a new technological concept. This trademark, registered RITE Bioprocess®, has achieved great results in the development of technologies for producing green chemicals (e.g., biofuels, amino acids, and aromatic compounds), exhibiting high efficiency. Furthermore, it has received high praise both in Japan and abroad (Fig. 4).

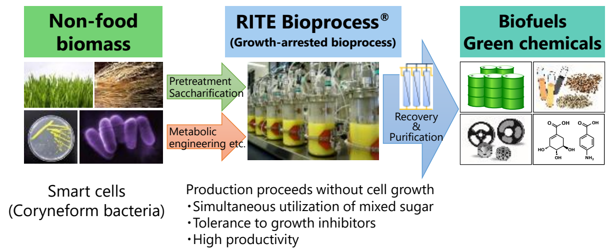


Fig. 4 Biorefinery concept using the RITE Bioprocess®

2.1. Features of the RITE Bioprocess®

2.1.1. Feature ①: Growth-independent bioprocess

The RITE Bioprocess® involves cultivating a large amount of coryneform bacteria (smart cells) that are metabolically designed to produce the target substance efficiently; filling a reaction tank with a high density of these cells; and finally, creating anaerobic conditions. Alternatively, the reaction is performed in a state where cell division is stopped by removing the factors essential for cell proliferation (Fig. 5).

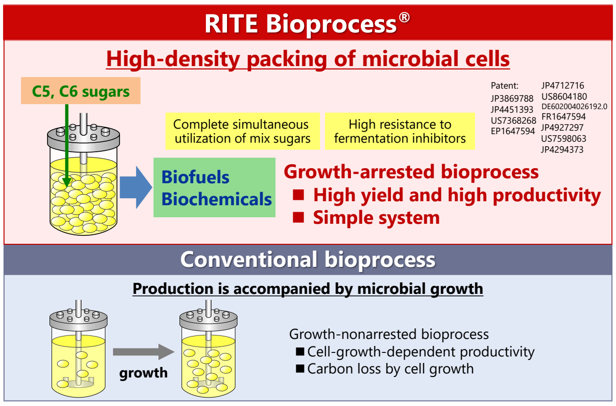


Fig. 5 Features of the RITE Bioprocess® ① (Growth-independent bioprocess)

The key to high efficiency is to produce compounds in a state in which the growth of the microorganisms is suppressed (i.e., a growth-independent bioprocess) thereby eliminating the need for nutrients or energy to achieve microbial growth. As a result, it is possible to use microbial cells extremely efficiently. The RITE Bioprocess® has succeeded in realizing a bioprocess with high productivity equal to or higher than that of a normal chemical process.

2.1.2. Feature ②: Simultaneous utilization of mixed sugars

A cellulosic biomass consists of mixtures of hemicellulose-derived pentoses (C5) and hexoses (C6). The simultaneous utilization of both pentoses and hexoses is essential for microbial biofuel production.

However, wild coryneform bacteria use xylose (C5 sugar) and arabinose (C5 sugar) at a slower rate than they do glucose (C6 sugar) (see the graph on the left side of Fig. 6). When raw materials are continuously added, the C5 sugars accumulate, and their production efficiency eventually decreases.

Our group has succeeded in improving the metabolic system of coryneform bacteria by introducing into them several genes involved in the utilization of C5 sugar thereby increasing its utilization rate to the same level as that of C6 sugar (see the graph on the right side of Fig. 6).

As a result, C5 and C6 saccharides can be used at the same time (simultaneous utilization of mixed sugars), and cellulosic raw materials can be used efficiently.

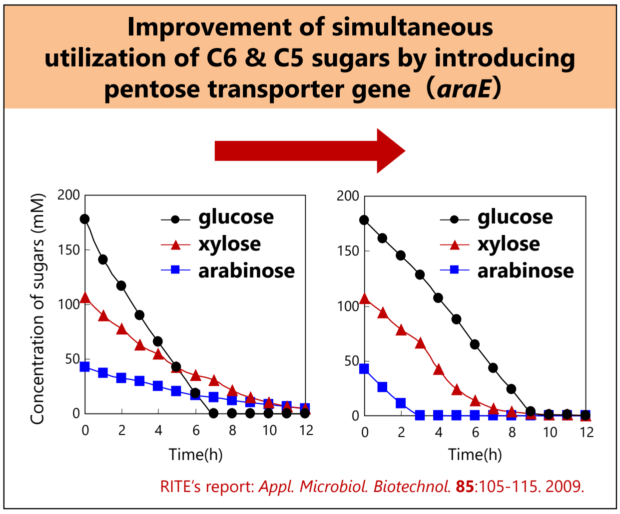


Fig. 6 Features of the RITE Bioprocess® ② (Simultaneous utilization of mixed sugars)

2.1.3. Feature ③: High tolerance to fermentation inhibitors

Fermentation inhibitors (phenols, furans, etc.) that are formed during the pretreatment of lignocellulosic biomass are known to exhibit strong inhibitory activity in the bioethanol production process. Therefore, in order to be able to produce the target substance efficiently, an increase in the tolerance of microorganisms (bacteria) to the fermentation inhibitors is indispensable.

The coryneform bacterium developed by our group has been demonstrated to have high tolerance to fermentation inhibitors rendered through the introduction of several genes (Fig. 7).

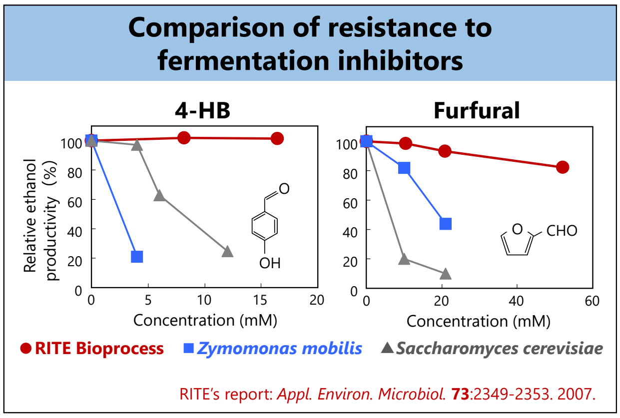


Fig. 7 Features of the RITE Bioprocess® ③
(High tolerance to fermentation inhibitors)

2.2. Examples of substances produced by the RITE Bioprocess®

Currently, in addition to the highly efficient production of various substances, such as ethanol, L-lactic acid, D-lactic acid, and amino acids, we are expanding our business to the production of high-performance chemicals, such as butanol, jet fuel materials, and aromatic compounds (Fig. 8).

Biofuels	Green chemicals
■ Gasoline additives ★ Ethanol * ■ Bio-jet fuels ★ Isobutanol * ☆ n-butanol * ★ C9~C15Saturated hydrocarbon + Aromatics ■ ★ Biohydrogen	■ Aromatics ★ Shikimic acid (Anti-influenza drug; Tamiflu raw materials) ★ Phenol * (Phenolic resins, Polycarbonates) ★ 4-hydroxybenzoic acid * (Polymer raw materials) ★ Aniline * (Natural resource tire (Age resistor)) ★ 4-aminobenzoic acid * (Pharmaceutical raw materials) ★ Protocatechuic acid * (Cosmetic raw materials) ■ Organic acids ★ D-lactate *, L-lactate * (Stereo-complex PLA) ☆ Succinate * ■ Amino acids ★ Alanine (Chelators) ★ Valine (Next-generation feed-use amino acids) ☆ Tryptophan (Next-generation feed-use amino acids) ☆ Methionine (Feed-use amino acids, Seasoning) ■ Alcohols ☆ Isopropanol (Propylene raw materials) ★ Xylitol (Sweetener) * : Polymer raw materials ★ Red character : World's highest productivity achieved

Fig. 8 Examples of substances produced by the RITE Bioprocess®

In the following sections, we describe the efforts in the national projects in which our group is participating, the development of production technology for green chemicals containing biofuels and aromatic compounds, which are the main targets, and introduce the efforts for their practical application.

3. Next core technology

3.1. NEDO Smart Cell Project

NEDO launched the project "Development of Production Techniques for Highly Functional Biomaterials Using Smart Cells of Plants and Other Organisms" (Smart Cell Project) in 2016. Our group has participated in this project since its inception. Members of the project develop technologies for designing the Smart Cell (defined as a finely designed and expression-controlled cell) and validate these Smart Cell design systems.

We have selected catechol as our target compound in the project. Catechol has not been produced in high concentration by fermentation until now, even though it is in high demand in various industrial fields. It is presumed that the reasons are its high toxicity to microorganisms and the high complexity of the metabolic pathways from glucose to catechol. Furthermore, wild-type *Corynebacterium glutamicum* does not have its own genes for catechol production. To solve these problems, we applied the Smart Cell design systems to create a *C. glutamicum* catechol overproducer in a short period of time.

In collaboration with universities, research institutes, and one company, which all have their own original Smart Cell design systems, several genetic modification points were proposed for improving catechol productivity. The proposals were integrated into a *C. glutamicum* strain to realize its high catechol-producing potential. As a result, the concentrations of catechol were gradually increased in stages, and the final strain achieved a very high production concentration, far exceeding the highest reported worldwide (Fig. 9).

This fiscal year (FY 2020) is the final year of the project, and we have already achieved productivity that exceeds its target value of the project. Continued efforts towards development for practical use is being undertaken, which will contribute to the realization of a new bio-based industry, the Smart Cell industry.

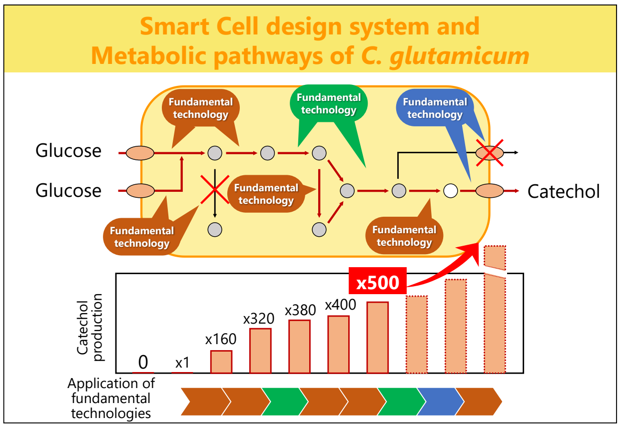


Fig. 9 Development of catechol production by applying Smart Cell design systems

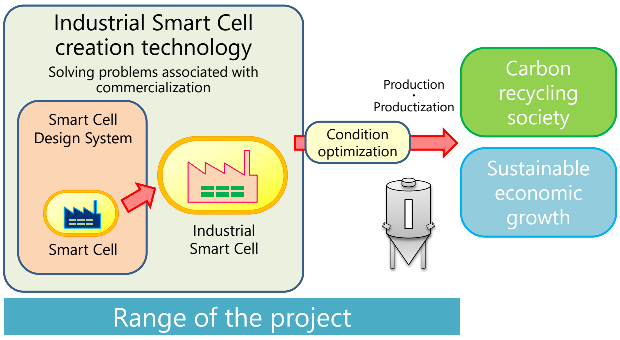


Fig. 10 Development of bio-derived material production technologies

3.2. NEDO Carbon Recycle Project

NEDO has launched a new project, "Development of Bio-derived Material Production Technologies that Accelerate the Realization of Carbon Recycling." In the ongoing Smart Cell Project (from 2016 to 2020), Smart Cell design systems have been developed to create smart cells. On the basis of this achievement, the development of industrial material production technology using biological functions is being carried out in the new project. The aim is to accelerate the social implementation of bio-derived products by developing technologies related to production processes for industrialization, including bioreactor scale-up and refining processes (Fig. 10).

Our group participated in this project with the goals of identifying problems associated with the practical application of microbial fermentation and contributing to the development of "Industrial Smart Cell creation technology" to solve the problems. Furthermore, we selected terpenoids as our target chemical compounds and started developing industrially applicable overproducers.

4. Development of target products

4.1. Biofuel production research and development

4.1.1 Biobutanol

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

We have developed a genetically engineered *C. glutamicum* strain that is highly efficient in producing biobutanol. Furthermore, we had conducted a research project from 2015 to 2019 to investigate cellulosic butanol production (see Topics in RITE Today, 2016). The project was funded by the Ministry of Economy, Trade and Industry. The advantages of our production process are as follows: (i) cellulosic biomass-derived mixed sugars can be used as feedstock, and (ii) production is fast and generates a high product yield (Fig. 11).

Because butanol is highly toxic, we have developed a genetically engineered *Corynebacterium* strain that has high tolerance to its toxicity. The strain has further enhanced the high productivity of the RITE Bioprocess®. Through collaboration with the U.S. National Renewable Energy Laboratory, we have accelerated the R&D of biobutanol production from non-food biomass.

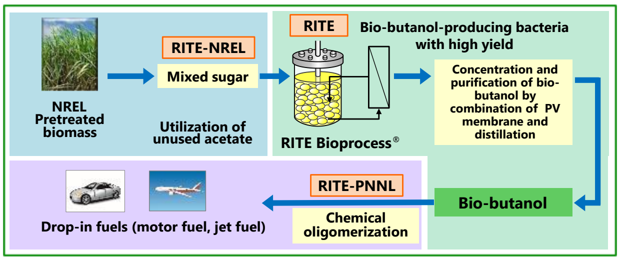


Fig. 11 Production of biobutanol and bio-jet fuel using the RITE Bioprocess®

Since 2017, we have also collaborated with the U.S. Pacific Northwest National Laboratories in researching and developing the production of jet fuels by the chemical oligomerization of biobutanol. This was based on a new idea that if acetic acid is included in mixed sugars from a pretreated biomass, it can be converted to ethanol by an engineered *C. glutamicum* strain into which new genes have been introduced. Therefore, the mixtures are utilized for the bioproduction of butanol and ethanol, which can then be subjected to chemical oligomerization for use as jet fuels.

The distillation of a 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. This resulted in energy savings of up to 90% and the achievement of the highest biobutanol productivity in the world. The project successfully achieved the original goals of improving the butanol tolerance and optimizing the metabolic pathway of the producing bacterial strain, and developing an energy-saving butanol recovery technology.

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

Green Earth Institute Co., Ltd. (GEI), a venture company originating from RITE, also participated in this project, and isobutanol was produced by the RITE Bioprocess® using coryneform bacteria developed by RITE. In 2020, the bio-jet fuel produced from this isobutanol passed the international standard ASTM D7566 Annex5 Neat for the first time as a purely domestic bio-jet fuel. On February 4, 2021, it was used as the first domestically produced bio-jet fuel on a JAL commercial flight, JL319, from Tokyo Haneda to Fukuoka Airport.

In the future, by combining these elemental technologies and a variety of procedural knowledge, we aim to produce jet fuel from biobutanol and put it into application and commercialization.

4.1.2. 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. Any jet fuel must meet strict standards with regard to its physical properties, such as a specified freezing point and density.

So far, ASTM International has approved six production pathways for bio-jet fuels, such as the production of HEFA fuel by the hydroprocessing of fatty acid esters, FT-SPK fuel by the Fischer–Tropsch synthesis of hydrocarbons from syngas, and ATJ fuel by the oligomerization of alcohol. In 2020, ATJ fuel coupled with our biobutanol production technology was approved. However, these certified bio-jet fuels consist mostly of isoparaffins and are lacking in other essential components: cycloparaffins and aromatics. They do not meet ASTM standards on their own and are required to be blended with petroleum-based jet fuel so as to be 50% or less in total when used. Therefore, even when the production capacity of bio-jet fuels catches up with demands, more than 50% of fuel demands will still be occupied by petroleum-based jet fuel.

To overcome this blending ratio limitation of the certified bio-jet fuels, we are additionally developing a high-performance green jet fuel that contains cycloparaffins and aromatics in addition to isoparaffins. The novel jet fuel meets ASTM standards and is expected to be used alone. In the R&D of the high-performance bio-jet fuel, we have achieved some promising results, such as a novel biocatalyst that enables the cross-coupling reactions between C2 and C8 compounds for the synthesis of C9–C15 branched and cyclic compounds, which can then be chemically converted to jet fuel components.

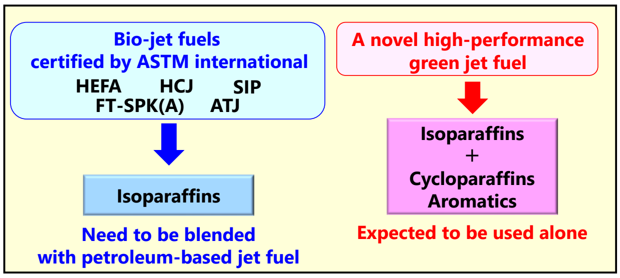


Fig. 12 Research and development of a novel high-performance bio-jet fuel

4.1.3. Biohydrogen

Hydrogen, the combustion of which generates only water, is considered the ultimate clean energy source. However, CO_2 emissions during the hydrogen production processes currently in use are a problematic issue, 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 the development of innovative CO_2-free hydrogen production technologies to realize a hydrogen society over the medium to long term. The aim is to achieve this by 2050, based on the goals set to develop commercial-scale hydrogen supply chains by circa 2030.

Although bioprocesses have significant potential for CO_2-free hydrogen production, innovative improvements in technology are necessary to establish a cost-effective process for producing biohydrogen. In collaboration with the Sharp Corporation, our group has developed a biohydrogen production process. The hydrogen production rate achieved by our process is two orders of magnitude higher than that of conventional fermentation processes. On the basis of this achievement, our group is now working on the metabolic engineering of hydrogen-producing microorganisms to improve hydrogen yields from cellulosic biomass.

Photosynthetic bacteria produce hydrogen gas (H_2) using nitrogenase (a nitrogen-fixing enzyme) and the reducing power generated from the degradation of organic compounds (Fig. 13). Although H_2 is a byproduct of the nitrogenase reaction that generates ammonia (NH_3) from nitrogen gas (N_2), only H_2 is produced by the reduction of H^+ in the absence of N_2. This photofermentative process can produce hydrogen from acetate (a thermodynamically unfavorable reaction) using light energy. Thus, a major improvement in hydrogen yield is expected by integrating this process with the dark fermentative process of hydrogen production, which produces acetate as a byproduct. However, in photosynthetic bacteria, reducing power is consumed by CO_2 fixation and polymer synthesis for carbon storage, thereby limiting its use for hydrogen production. Moreover, hydrogen is reused by uptake hydrogenase for providing cells with reducing power. On the basis of these findings, the metabolic engineering of H/C/N metabolic pathways has resulted in a marked increase in the hydrogen yield from acetate.

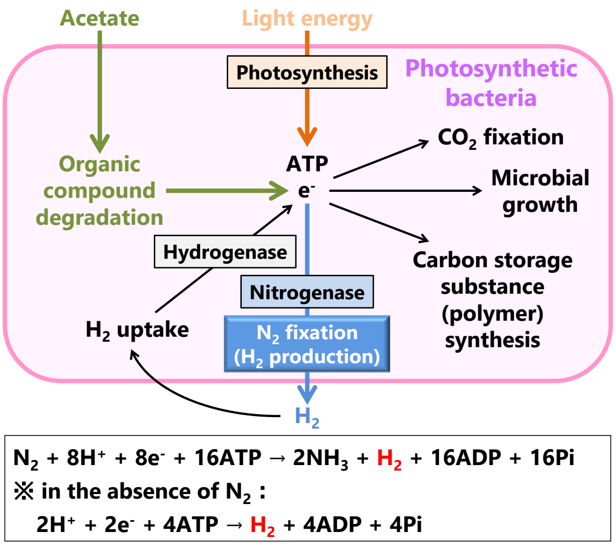


Fig. 13 Competition with H_2 production (N_2 fixation) for reducing power (e^-) in photosynthetic bacteria

4.2. Amino acids (alanine and valine)

Normally, amino acid fermentation is carried out under aerobic conditions, where high productivity requires the aeration and agitation of the system to be properly controlled. However, this is often difficult to achieve in large-scale fermenters because their internal oxygen concentration is not homogeneous. To overcome this problem, we have developed a new, genetically modified *Corynebacterium* strain with 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 successfully introduced an artificial pathway for amino acid biosynthesis into the microbial cells thereby solving the technological hurdle. Our group published this accomplishment in an international journal in 2010 (Appl. Microbiol. Biotechnol. 87: 159–165).

GEI was established in 2011 for the industrialization of the RITE Bioprocess®. In 2011, RITE and GEI began collaborative research on amino acid production using the RITE Bioprocess® and developed technologies for scaling up production, growing efficient production strains, and reducing production costs. In 2019, RITE succeeded in producing a strain that yielded the world's highest production concentration of L-valine with the best production efficiency. Furthermore, RITE has completed commercialization projects with GEI and overseas partners to achieve the commercial production of these amino acids. 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 L-alanine production technique by using the commercial-scale facilities of our partner company, which was an important milestone for its industrialization. One of our group members also participated in the first operation and worked with local employees to lead the project to a successful conclusion. As the result of an evaluation by the Food Safety Committee in August 2017, the safety of the L-alanine produced by our strain for use as a food additive was confirmed, allowing it to be made commercially available for this purpose besides its use for industrial applications. We are now working on a joint research project for the production of other amino acids.

4.3. Green-aromatic compounds

Aromatic compounds are important industrial chemicals used for the synthesis of polymers as well as a diverse group of value-added chemicals that are applied in the pharmaceutical, nutraceutical, flavor, cosmetic, and food industries. Although they are currently derived from petroleum or natural plant resources, their environmentally friendly biotechnological production from renewable feedstocks is desirable 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, and tryptophan), folate (vitamin B9), and coenzyme Q, all of which are derived from the shikimate pathway (Fig. 14). By employing the metabolically engineered *C. glutamicum*, we have successfully established a highly efficient bioprocess for producing the following aromatic compounds from non-food feedstocks: 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, cosmetic, and adhesive material industries. Currently, we are seeking to develop new strains for the production of useful aromatic compounds that the wild-type *C. glutamicum* is unable to produce. This will be achieved by introducing genes derived from versatile biological resources into the bacterium. The techniques developed in the Smart Cell Project, as described earlier, will help to accelerate the development of strains and improve their productivity.

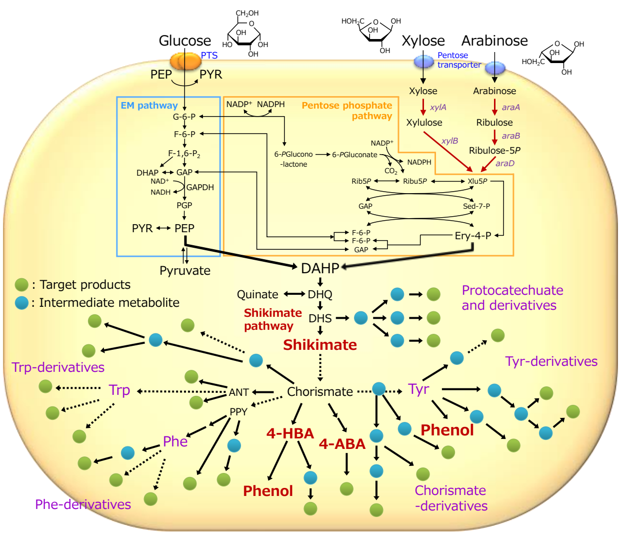


Fig. 14 Biosynthetic pathway for various aromatic compounds

4.4. Strategic Innovation Promotion Program (SIP)

The cross-ministerial Strategic Innovation Promotion Program seeks to promote R&D, from the basic research stage to the final outcome, in a seamless manner by endeavoring to strengthen cooperation among industries, academia, and governments beyond the framework of government ministries and traditional disciplines. The theme "Technologies for Smart Bio-industry and Agriculture", one of the 12 themes in the SIP at Second Phase, aims to realize a sustainable growing society that uses manufacturing technologies developed through the integration of biotechnology and digital resources.

RITE is participating in "Development of Technologies for Functional Design and Production of Innovative Biomaterials (Fig. 15)," a consortium comprising the theme. This consortium consists of two groups: the polymer group for designing polymers with marketable properties and predicting the function of polymers consisting of particular monomers; and the monomer group for selecting biosynthesizable monomers and designing biosynthetic pathways 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 are predicted to be required for the synthesis of target monomers by bioinformatics teams in the group. The enzymes involved in the synthesis of an aromatic diol and a precursor of an aromatic diamine are current targets to be modified. Thus far, the predicted modification of amino acid sequences has successfully improved the activity of the enzymes and altered their substrate specificity. We are improving the accuracy of the technologies by evaluating more enzymes.

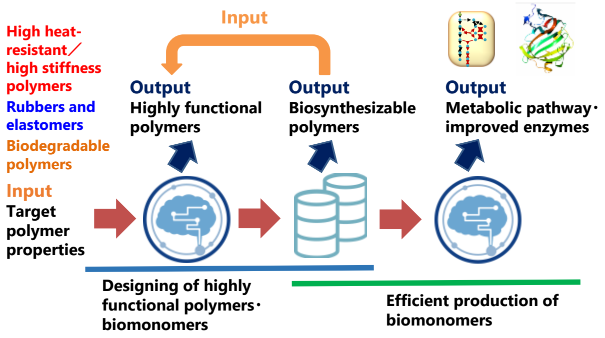


Fig. 15 Integrated design and production technology system for biomaterials

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

This project aims to develop a "multi-lock-type biopolymer" that is as tough as conventional petroleum-derived polymers when in use but can be rapidly degraded by external stimuli in the marine environment after its use (Fig. 16). We aim to simultaneously solve the problems of global warming and environmental pollution in the field of polymers. Generally, there is a trade-off between plastic toughness and marine degradability (biodegradability), but this project aims to achieve both.

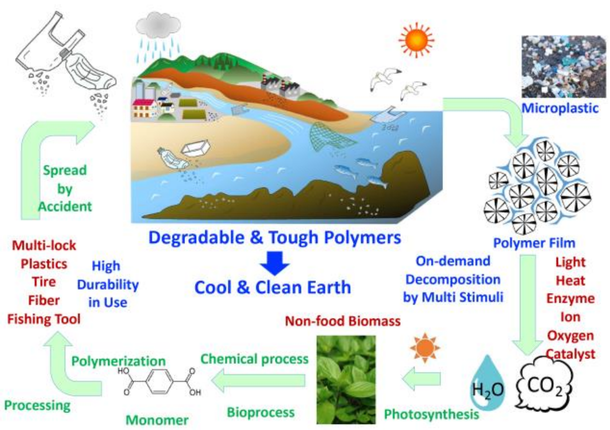


Fig. 16 Research and development of marine-degradable multi-lock biopolymers made from non-food biomass

https://www.nedo.go.jp/english/news/ZZCA_100007.html

In this project, RITE will promote the production of biomonomers and the development of polymer-degrading enzymes from non-food biomasses. Specifically, (1) in order to establish a bioprocess that enables the high production of biomonomers, which are the raw materials for multi-lock biopolymers, RITE will promote the construction of a high biomonomer-producing strain and the development of scale-up production technology. Additionally, (2) for the practical use of multi-lock biopolymers, we will promote the development of highly functionalized polymer-degrading enzymes for efficient enzymatic degradation in the multi-lock mechanism and of high production technologies for these enzymes.

5. Toward the industrialization of our technologies

5.1. Green Chemicals Co., Ltd.

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

Currently, commercial phenol can only be derived from petroleum. We have taken on the challenge of developing the world's first biomanufacturing process for biomass-derived phenol, with the ultimate goal being 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, named the "Two-Stage Bioprocess." In April 2018, GPD changed its name to Green Chemicals Co., Ltd. (GCC).

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 customer needs are in progress (see Section 4.3).

The present product lineup of GCC is shown in Fig. 17. In 2020, using the pilot-scale facilities of GCC, we succeeded in demonstrating the high-concentration production of two target compounds, protocatechuic acid and shikimic acid, which was an important milestone for industrialization.

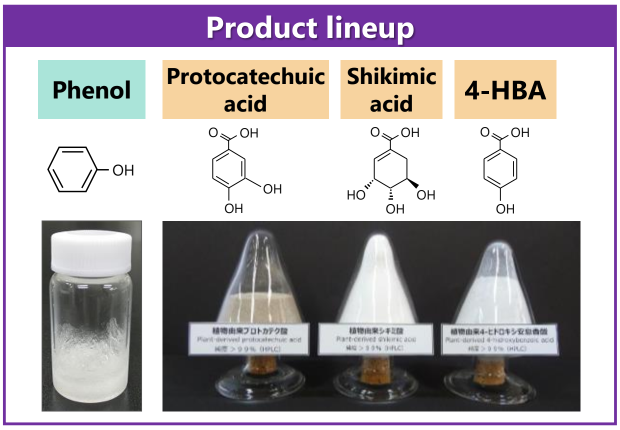


Fig.17 Product lineup of Green Chemicals Co., Ltd.

5.2. Green Earth Institute Co., Ltd.

(Headquarters: Bunkyo-ku, Tokyo, Japan; Research Institute: Kazusa, Kisarazu City, Chiba, Japan)

GEI is a RITE-launched venture company that was established on September 01, 2011, to facilitate the quick commercialization of the research results of the aforementioned innovative RITE Bioprocess®. GEI is conducting both joint research and activities aimed at commercialization with RITE in order to realize the practical uses of the green chemicals and biofuel production technologies produced using the microorganisms (coryneform bacteria) generated in the RITE Bioprocess®.

With regard to amino acids, as mentioned earlier, GEI has succeeded in producing L-alanine and L-valine on a commercial scale using the production strain developed by RITE. Currently, commercial production is being realized through license agreements with domestic and overseas partner companies (see Section 4.1). Additionally, the safety of L-alanine as a food additive has been confirmed by the Ministry of Health, Labour and Welfare, paving the way for its use in the food industry.

With regard to bio-jet fuels made from non-food biomass, which are highly expected to reduce CO_2 emissions from aircraft, GEI is continuously conducting joint research with RITE in this area and is working toward commercialization (see Section 4.1).

Additionally, GEI is developing green chemicals (e.g., cosmetic materials) in cooperation with RITE, and the marketing for commercialization and the scaling up for mass production are under way.

As a venture company that realizes the commercialization of RITE-originated technology and by contributing to the development of the biorefinery industry, GEI will continue toward the realization of a society that does not rely on fossil resources.

6. Closing remarks

As mentioned earlier, in anticipation of a rapid economic recovery after the COVID-19 pandemic has subsided, the promotion of the bioeconomy is expected to become increasingly important in the future.

Under such circumstances, in recent years, the understanding of life phenomena by the "data-driven" approach of discovering the law from a large amount of life information has been progressing.

Against this background, research on the biology of synthesis (fusion of bio and digital processes) that accumulates data and understands biological functions by repeating the cycle of design (Design), build (Build), evaluation (Test), and learning (Learn) (i.e., the DBTL cycle) is developing rapidly. Our group also participates in multiple national projects (see Section 3).

In these projects, the biorefinery technology based on the Smart Cell described earlier is expected to play a major role as a core technology and have a large ripple effect on the industrial (manufacturing) and energy fields (Fig. 18).

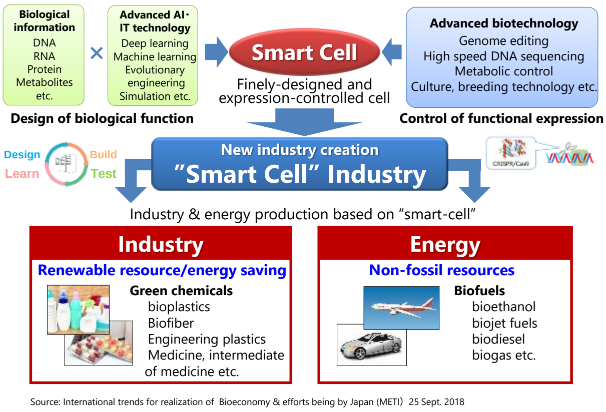


Fig. 18 Fusion of industrial/energy fields changed by bio and digital processes

In 2021, we will continue to develop innovative bio-refinery production technologies centered on the cutting-edge biotechnology of the Smart Cell and contribute to the construction of a sustainable low-carbon society.

※ RITE Bioprocess® is a registered trademark of RITE.

Chemical Research Group

Members (as of Dec. 2020)

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

Challenges Associated with the Advanced Industrialization of CO_2 Capture Technologies

1. Technologies for CO_2 capture

In December 2015, the Paris Agreement was adopted at COP21.* 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 a long-term strategy as the growth strategy based on the Paris Agreement and the Integrated Innovation Strategy 2019, where it has been shown that the carbon capture, utilization and storage and carbon recycling (CCUS/carbon recycling) process is an important innovative technology that enables carbon neutrality in the world. In CCUS/carbon recycling, the combination of the reuse of separated and recovered CO_2 from fossil fuels and materials by treating CO_2 as a carbon resource (CCU) and the storage of separated and recovered CO_2 underground (CCS) is expected to have a significant CO_2 reduction effect. Furthermore, it has been shown that CO_2 separation and capture technologies are the basis for CCUS, and the targets for the technologies are to reduce the cost of CO_2 separation and capture to 1,000 yen/t-CO_2 by 2050 and to establish CO_2 separation and capture technologies for various CO_2 emission sources. Recently, in a policy statement speech of the 203rd extraordinary session of the Diet in October 2020, Prime Minister Suga said, "Eliminate greenhouse gas emissions to zero by 2050. In other words, we aim to realize a carbon neutral, decarbonized society by 2050." Negative emission technology is required to achieve carbon neutral, and direct air capture (DAC) of CO_2 from the atmosphere, which has been attracting attention recently, is particularly important.

Against this background, it is necessary to promote the practical application of CCUS by proposing optimal separation and capture technologies for the various CO_2 emission sources. In particular, in order to introduce and put into practical use CCS, which is expected to reduce CO_2 on a large scale as a measure to address global warming, it is estimated that it will account for about 60% of the cost. CO_2 separation and recovery from emission sources as a means of cost reduction are important.

The Chemical Research Group studied the different

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

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

With regard to 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. Research on practical application is now underway in collaboration with a private company. In the near future, we will install a test facility 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 to selectively capture CO_2 from pressurized gas mixtures containing H_2, such as those generated in the integrated coal gasification combined cycle (IGCC) at low cost and with low energy use. We are also developing membranes with large areas using the continuous membrane-forming method and developing membrane elements for the mass production of membranes and membrane elements in the future. In addition, we evaluated the separation performance and process compatibility of our membrane elements using coal gasification real gas and are proceeding with development aimed at commercialization.

RITE joined the International Test Center Network (ITCN) and now actively uses overseas networks towards the commercialization of CO_2 separation and recovery technology.

*COP21: 2015 United Nations Climate Change Conference

2. Chemical absorption method for CO_2 capture

In the absorption method, CO_2 is separated by using the selective dissolution of CO_2 from a mixed gas into a solvent. In particular, the chemical absorption method based on the chemical reaction between amine and CO_2 in a solvent can be applied to gases with a relatively low CO_2 concentration, such as combustion exhaust gas, and the method is one of the most mature CO_2 capture technologies.

Energy consumption in the process of solvent regeneration and the degradation of amines are factors in the cost increase of the chemical absorption method. Focusing on the fact that the structure of amine molecules is closely related to these factors, RITE started a new amine solvent: since the COCS project (METI's Subsidy Project) started in 2004, RITE has been working on the development of a high-performance amine solvent that reduces the cost of CO_2 capture.

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

ESCAP® Unit 1 was constructed on the premises of Muroran Works for general industrial use including beverages (120t-CO_2/day). This is the world's first commercial facility using the chemical absorption method for the combustion exhaust gas from a hot blast furnace at a steelworks as a CO_2 source. In 2018, ESCAP® Unit 2 started operation at the Niihama Nishi Thermal Power Station (143t-CO_2/day). This is the first commercial facility in Japan to capture CO_2 by the chemical absorption method from the combustion exhaust gas of coal-fired power generation as the CO_2 source. The recovered CO_2 is used as a raw material in a nearby chemical factory.

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

3. Solid sorbent method for CO_2 capture

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

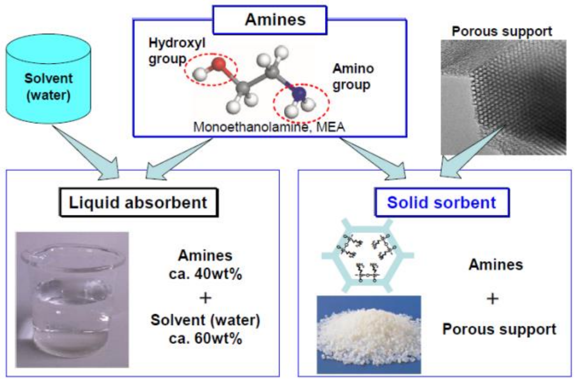


Fig. 2 Liquid absorbent and solid sorbent

In 2010, RITE started the development of solid sorbent materials mainly for CO_2 capture from the combustion exhaust gas of coal-fired power plants (METI consignment project). In the fundamental research phase (FY 2010–2014), we succeeded in developing a new amine suitable for solid sorbents and achieved a capture energy of 1.5 GJ/t-CO_2 or less in a laboratory scale test. This solid sorbent is an innovative material that enables not only low energy capture but also a low temperature process at 60℃.

In the practical application research phase (METI/NEDO consignment project) from FY 2015 to 2019 with Kawasaki Heavy Industries, Ltd., as a partner, scale-up synthesis of solid absorbent (>10 m^3), bench scale test (>5 t-CO_2/day), and real-gas exposure tests at a coal-fired power plant were conducted, which achieved a CO_2 capture cost of less than 3,000 yen/t-CO_2. Compared to other projects that used amine solid sorbents, the capture scale, energy, and cost of this project were all at the top level globally.

In 2020, RITE was adopted by the NEDO commissioned project with Kawasaki Heavy Industries, Ltd. In this project, with the cooperation of Kansai Electric Power Co., Ltd., a pilot scale test facility (~40 t-CO_2/day) will be constructed at the Maizuru power plant, and CO_2 capture tests from the combustion exhaust gas emitted from the coal-fired power plant will start in 2022. Currently, RITE is proceeding with rationalization and the cost reduction of solid sorbent material manufacturing technology, elucidation of a material degradation mechanism, development of degradation prevention technology, and the upgrading of process simulation technology toward pilot scale tests.

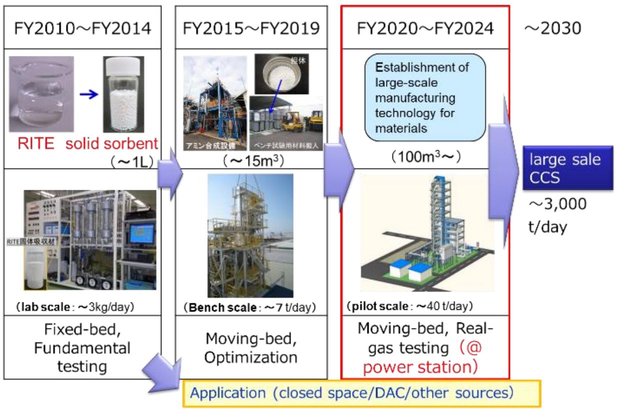


Fig. 3 Development roadmap of solid sorbent method for CO_2 capture

4. Membrane separation

CO_2 separation by membranes involves the selective permeation of CO_2 from the pressure difference between the feed side and the permeate side of the membrane. So, CO_2 capture at low cost and energy is expected by applying the membrane processes to pre-combustion (Fig. 4). For this reason, we are currently developing novel CO_2 selective membrane modules that effectively separate CO_2 during the IGCC process.

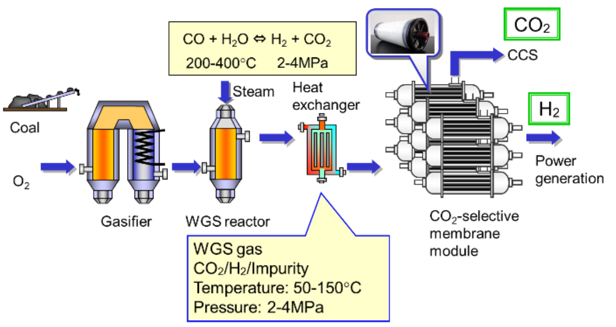


Fig. 4 Schematic of the IGCC process with CO_2 capture by CO_2 selective membrane modules

We found that novel polymeric membranes composed of dendrimer/polymer hybrid materials (termed molecular gate membranes) exhibited excellent CO_2/H_2 separation performance. Fig. 5 presents a schematic that summarizes the working principles of a molecular gate membrane. Under humidified conditions, CO_2 reacts with the amino groups in the membrane to form either carbamate or bicarbonate, which then blocks the passage of H_2. Consequently, the amount of H_2 diffusing to the other side of the membrane is greatly reduced, and high concentrations of CO_2 can be obtained. A poly(vinyl alcohol) (PVA) polymer matrix is used for pressure durability and to immobilize the dendrimers.

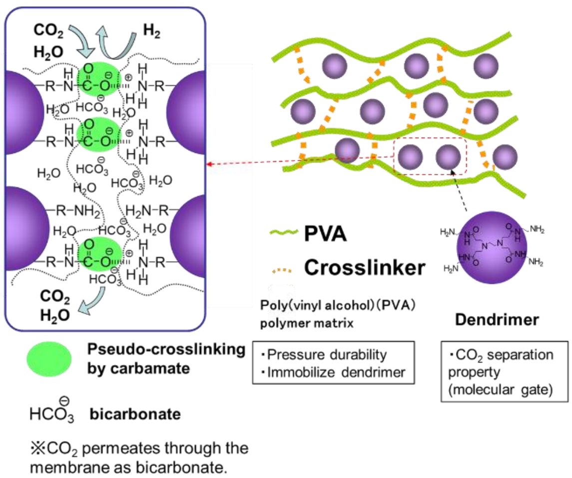


Fig. 5 Schematic illustration of the working principles of the molecular gate membrane

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. 6), and membrane separation systems.

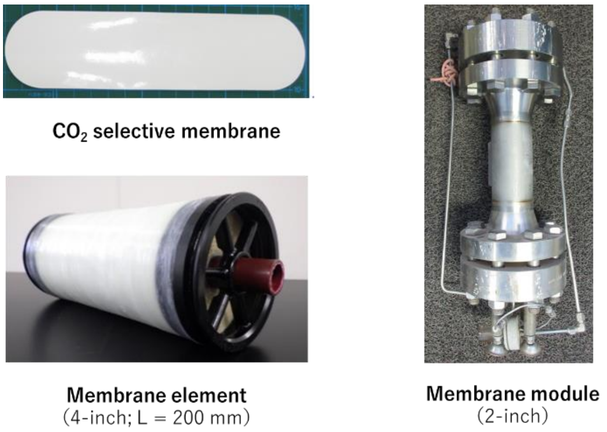


Fig. 6 CO_2 selective membrane, membrane element, and membrane module.

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

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

Based on the achievements of the project by the Ministry of Economy, Trade and Industry (METI), Japan, the CO_2 Separation Membrane Module Research and Development Project (FY 2011–2014) and CO_2 Separation Membrane Module Practical Research and Development Project (FY 2015–2018) in the current NEDO project, CO_2 Separation Membrane Module Practical Research and Development (FY 2018–2021), we are developing membranes with large areas using a continuous membrane-forming method while developing membrane elements. As a result, two-inch and four-inch membrane elements with enough pressure durability were successfully prepared.

In addition, we conducted pre-combustion CO_2 capture tests of the membrane elements using coal gasification gas at the Wakamatsu Research Institute, Electric Power Development Co. Ltd. in Japan in order to identify and then solve the technical problems of the membrane elements (Fig. 7). As a result, it was confirmed that the membrane elements were durable against the real gas (containing impurities, such as H_2S).

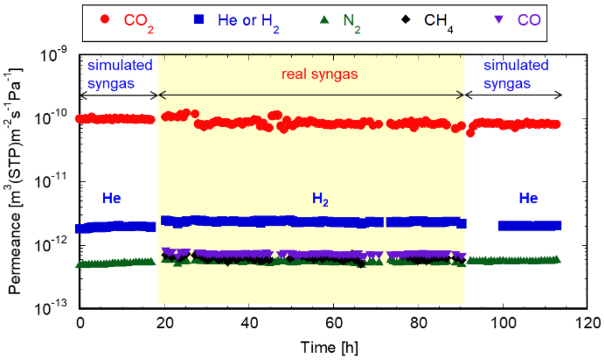


Fig. 7 Separation performances of four-inch membrane module using real gas and using simulated gas before and after the real gas test.

Temperature: 85°C, Total pressure 0.8 MPaA

Simulated gas: CO_2/He/N_2.

In the future, we plan to develop commercial-scale membrane modules and the membrane systems, based on the results of the projects.

5. New challenges

As mentioned above, the Chemical Research Group has been focusing on the development and practical application of CO_2 capture technologies for large-scale CO_2 emission sources, such as steel industries and power plants. Finally, we will introduce two examples of new challenges. One is the capture of CO_2 from the atmosphere, or direct air capture (DAC), and the other is the development of technology to immobilize CO_2 as carbonate.

In order to achieve carbon neutrality, a technology that can remove CO_2 emitted into the atmosphere, that is, a negative emission technology, is indispensable. In recent years, DAC has been attracting attention as one of the representative negative emission technologies, and is being studied overseas. It is hoped that the recovered energy and costs will be significantly reduced for future implementation. In Japan, challenging research and development is being carried out in NEDO's "Moonshot R & D Project" that started in 2020. RITE has started studying the optimum materials and systems for

DAC in cooperation with Kanazawa University and private companies in this project: the following three items will be developed to establish carbon recycling technologies that capture CO_2 from the atmosphere and convert the recovered CO_2 into valuable resources.

R&D items 1: Development of a new solid sorbent material for low-concentration CO_2 capture and a system to recover low-concentration CO_2 with high efficiency.

R&D items 2: Development of CO_2 conversion technology (Fischer–Tropsch synthesis) using an inorganic separation membrane for synthesizing liquid hydrocarbon fuel from CO_2 with high efficiency and low energy consumption.

R&D items 3: Life cycle assessment (LCA) evaluation and economic evaluation regarding the conversion process to liquid hydrocarbon fuel using CO_2 recovered from the atmosphere.

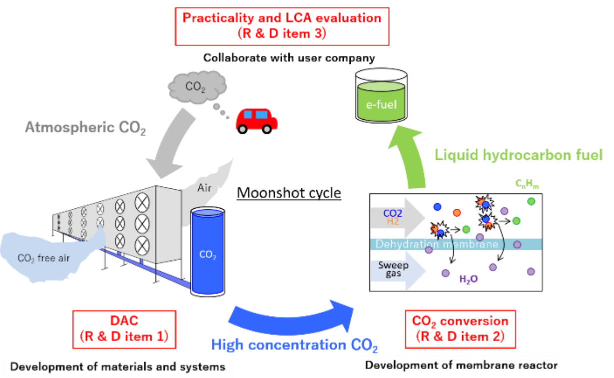


Fig. 8 Development of highly efficient direct air capture (DAC) and carbon recycling technologies

In the technology of CO_2 fixation as a carbonate, RITE developed a unique process over many years. From 2020, JFE Steel Co., Ltd., Taiheiyo Cement Co., Ltd., and RITE set up a study group to target steel slag and waste concrete and then use alkaline earth metals extracted from these for utilization with the CO_2 emitted from factories and other facilities. We are cooperating in the development of technology for recovering as carbonates, which is a stable compound, by reacting with CO_2 (Fig. 9). By combining the unique processes developed by RITE and R&D skills with the technological capabilities and broad insights of the two leading steel and cement industries, synergistic effects are expected for technological development.

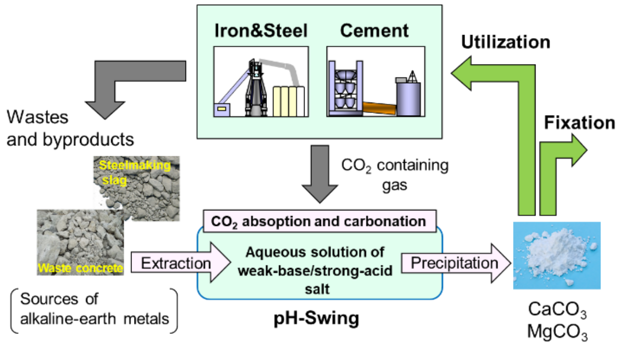


Fig. 9 CO_2 fixation as carbonates

6. Conclusion

As stated above, the Chemical Research Group has energetically promoted the development of CO_2 separation and recovery technology mainly for the chemical absorption method, the solid sorbent method, and membrane separation. The chemical absorption method has been deployed from the demonstration stage to commercial machines for blast furnace exhaust gas and combustion exhaust gas from coal-fired power plants and has already been put to practical use as a CO_2 separation and recovery technology. In the solid sorbent method, we have begun studying combustion exhaust gas from coal-fired power plants for a 40 t-CO_2/day scale pilot test from FY 2020. In membrane separation, we confirmed the separation ability of CO_2 and H_2 in an actual gas test using a membrane element from coal gasification gas. In addition, we have just begun to develop DAC technology newly adopted in NEDO's Moonshot R&D Project and CO2 fixation technology using steel slag and waste concrete.

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

CO_2 Storage Research Group

Members (As of Dec.2020)

Ziqiu Xue, Group Leader, Chief Researcher
Kenji Uchida, Deputy Group Leader, Chief Researcher
Satoru Yokoi, Chief Researcher
Makoto Nomura, Chief Researcher
Nobuo Takasu, Associate Chief Researcher
Takahiro Nakajima, Associate Chief Researcher
Takeshi Myoi, Associate Chief Researcher
Ryozo Tanaka, Associate Chief Researcher
Tsutomu Hashimoto, Senior Researcher
Saeko Mito, Senior Researcher
Yasuhiro Okabayashi, Senior Researcher
Tetsuma Toshioka, Senior Researcher
Osamu Takano, Senior Researcher
Keisuke Uchimoto, Senior Researcher
Hironobu Komaki, Senior Researcher
Atsushi Ibusuki, Senior Researcher
Nobutoshi Shimizu, Senior Researcher
Tsutomu Soejima, Senior Researcher
Yuji Watanabe, Senior Researcher
Yi Zhang, Senior Researcher
Hyuck Park, Senior Researcher
Jiro Suekuni, Senior Researcher
Satoko Fuchikami, Chief
Kimiko Nakanishi, Chief
Yankun Sun, Researcher
Takayuki Miyoshi, Researcher
Masafumi Kotani, Researcher
Takeya Nagata, Researcher
Rasha Amer, Researcher
Hiroto Yoshikawa, Researcher
Junko Hirai, Research Assistant
Shiori Tsuji, Research Assistant
Yuko Himi, Research Assistant
Akemi Nishide, Research Assistant
Megumi Okumichi, Research Assistant
Megumi Sasaki, Research Assistant
Tokio Sasai, Research Assistant

Research and Development on Geological CO_2 Storage for Safe CCS Operation

1. Introduction

In terms of capturing and sequestrating of CO_2 from large scale emission sources geological CO_2 storage is one of the most important options for achieving ambitious net zero CO_2 emission goals.

The CO_2 Storage Research Group as a member of the Geological Carbon Dioxide Storage Technology Research Association has conducted a project funded by the New Energy and Industrial Technology Development Organization (NEDO), called "Research and Development of CO_2 Storage Technology to implement safe CCS".

The project is in a technology development phase for large-scale CO_2 storage, which is qualified with safe injection and storage of more than 1 Mt CO_2/y under the ground. To achieve the goal, our group has been developing technologies for safety management, efficient injection and effective resource utilization for large scale CO_2 reservoirs.

Our development up to now has moved a number of technologies into a stage of demonstration in the fields: safety management systems for injection, assessment/monitoring technologies for the stability of geological formations and an efficient injection technology.

To contribute to large-scale CO_2 storage, it is critical to prove these technologies applicable for an actual site at scale. The CO_2 Storage Research Group has been working closely with universities and research institutes internationally to move forward with technical demonstration at large sites overseas.

Highlighted in the following sections are our outstanding achievements in 2020: a microbubble CO_2 injection technology, a safety management system for CO_2 storage (ATLS: Advanced Traffic Light System) and systems for CO_2 leakage detection and marine environmental impact assessment. We have developed these technologies as systems with high practicability and applicability. The microbubble CO_2 injection technology will be applied to multiple overseas geological CO_2 storage sites, including that in North Dakota, USA and that of the Junlun Petroleum Company in China.

Other technologies of ours being demonstrated at a CO_2 storage site include Distributed Fiber Optical Sensing (DFOS). We have created our own method to measure strains of geological formations and integrated it into multi-sensor systems capable of concurrent measurements of temperature, pressure, acoustic wave, and strain of geological formations. That system is also being implemented and demonstrated at an overseas site.

Through improving our technologies and implementing them in the fields, our group continues to contribute to CCUS deployment.

2. Major Research Topics and Outcomes

2.1. Microbubble CO_2 Injection technology

Microbubble CO_2 injection technology is to turn CO_2 into microbubbles through a special ceramic filter and then to inject the microbubble CO_2 under the ground. Microbubble CO_2 has the following advantages in injection for geological CO_2 storage:

- To easily enter gaps (pore throat) of sandstone that is composed of reservoir,
- To access more pore space than where CO_2 injected by a conventional way, and
- To easily dissolve in saline water.

The CO_2 Storage Research Group has demonstrated these advantages in lab and field tests. In the lab tests, we used core samples of rock in an X-ray CT scanner. The upper panel of Figure 1 shows a result from a series of tests. The panel illustrates CO_2 distribution at a time when CO_2 injected at the left edge reached a point 82mm away from the edge with warm color contour. The two core samples are comparable in terms of their pore space volume. Microbubble CO_2 fills the space more densely (upper panel of Figure 1) and is injected and dissolved more (lower panel) than conventionally-injected CO_2, so called normal bubble.

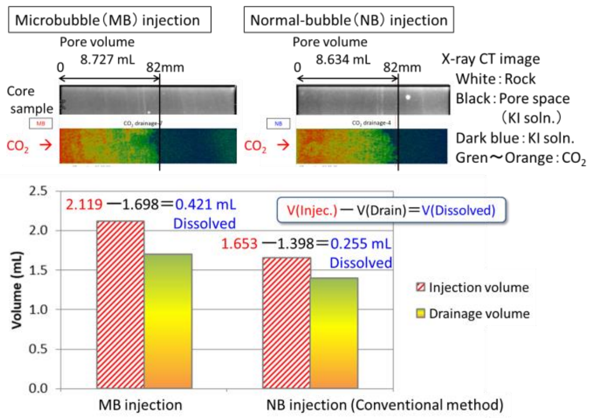


Fig. 1 Evaluation for storage efficiency of microbubble CO_2 using core samples

For the field tests of microbubble injection in 2020, we used the Sarukawa oil field owned by JAPEX in Oga, Akita, where we did previous tests last year. The targeted formation for injection there was a low permeable sandstone layer at a depth of around 800 m. In order to improve efficiency in installation of our microbubble CO_2 generator, we have designed a smaller system, length of which below the packer is 14 m, 1/6 in comparison with the last year one, 84 m (Figure 2). Thanks to the design change, time for installment and de-installment was reduced to about 1/3 from 15 hours to 4 hours.

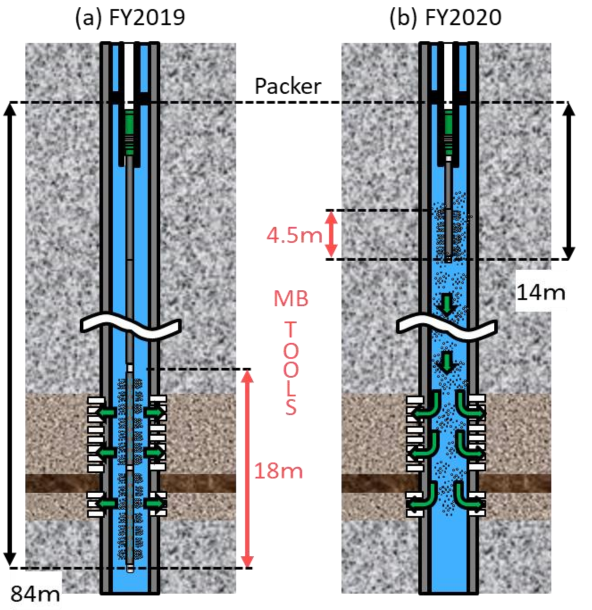


Fig. 2 Overview of the microbubble CO_2 injection tools settings in a borehole

The system downsizing also reduced the size of the microbubble generator from 18m to 4.5m. These changes resulted in shallower microbubble generation (Figure 2b), whereas it was at a depth of the formation targeted for injection in 2019 (Figure 2a). Microbubble injection tests were conducted to verify whether the new configurations can still exploit the advantages of microbubble CO_2 by comparing the performance in 2019. The injection rate was set out at 1.5 tonnes per day, the same as last year. The wellhead pressure was 8.4 MPa, whereas the bottom-hole pressure was risen from 8.8 MPa to 14.9 MPa and then was kept at the level. The CO_2 injection index, which is an injection rate per MPa, was 0.25 tonnes/day/MPa. This is comparable with the last year performance of 0.36 tonnes/day/MPa and higher than the performance of conventional injection of 0.09 tonnes/day/MPa. These results proved that microbubble injection with the new configuration is also capable of injecting more CO_2 than the conventional one. The CO_2 storage efficiency was high enough at 82.9%, equivalent to the last year rate.

The field tests demonstrated the validity of the smaller microbubble generator and the improvement of its installing work successfully. This will contribute to cost saving in the production, installation and de-installation of the microbubble injection system.

Our development of the microbubble CO_2 generation technology was initiated by a fundamental study in collaboration with Tokyo Gas. We have acquired a patent of the technology (registered patent No. 5399436), titled “storage device and storage method for stored substances”. Through various lab tests and field demonstration, we have completed its development phase. At present, we are attempting to deploy the technology globally, applying it to actual projects, including those in North Dakota in the USA and in Junlun Petroleum Company’s field in China.

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

In various underground fluid injection projects, there are concerns that an increase of formation pressure induces earthquakes. Operation in waste water injection and enhanced geothermal systems (EGS), is therefore, managed in a way that prevents induced seismicity around its site with Traffic Light Systems (TLS). According to reports 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 and implement risk management at a CO_2 storage site, taking the possibility of the seismicity into account.

Our group has been developing a microseismicity management system for CO_2 storage in Japan, called ATLS (Advanced TLS). The requirements for the system suitable for Japan are:

- Capability to extract microseismic events from ground motion data that include data of a number of natural earthquakes and high-level environmental noise caused by human activities,

- Function to determine the hypocenters of micro-seismic events, and
- Capability to process data in real time automatically.

In order to build a management system that meets these requirements, we have been conducting R&D for ATLS using data from the Tomakomai Demonstration Site, where microseismicity has been monitored at its CO_2 storage site. Figure 3 illustrates a schematic view of the workflow of ATLS. After obtaining ground motion data, the extraction of seismic events and the identification of their locations are automatically carried out. In parallel, a latest hypocenter catalog is obtained from the Japan Methodological Agency (JMA), which is used to exclude natural earthquakes from the catalog generated in ATLS.

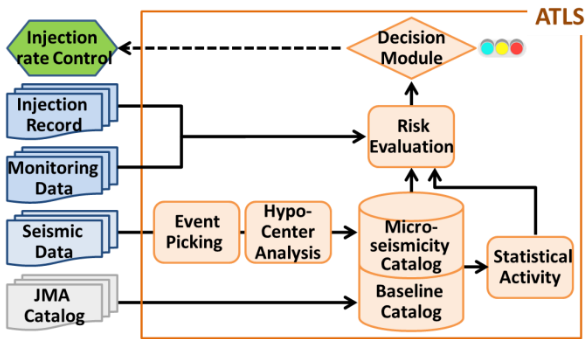


Fig. 3 Flow diagram of ATLS

Using the continuous observation data for 2 years or more in Tomakomai, it was demonstrated that ATLS has the capability to automatically analyze ground motion data and to locate each of the detected microseismic events near at the injection point. Figure 4 shows an image of the output report of ATLS. This presents the frequency and locations of micro- and natural earthquakes in the monitoring area and the colors of traffic light determined by the ATLS.

In addition to the main system, we have developed auxiliary tools to support this system to be more applicable to various sites. An example is to support seismic observation planning which, using a layout of seismometers and an event location as input, calculates an event location to be estimated by ATLS. Comparison the actual event location with the estimated one makes it possible to assess the adequacy of planned seismometer locations and an expected accuracy of event positioning beforehand from the viewpoint of ATLS operation.

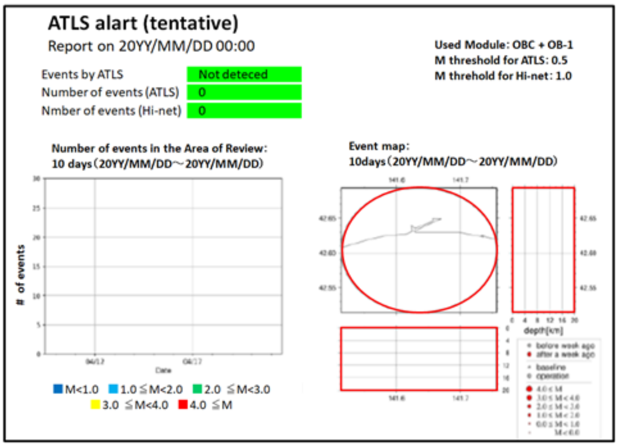


Fig. 4 An example of the output from ATLS

Another example is a tool for the conversion of input data formats. ATLS had initially been designed only for the SEGD format, which is used in the Tomakomai test site. With the developed tool, ATLS is now capable of handling min-SEED and ASCII formats, which are widely used in natural seismic observation.

The validation of ATLS by applying it to the actual CO_2 storage site in Tomakomai and the expansion of applicable sites with additional tools has completed our development of ATLS.

2.3. Integrated system of CO_2 leakage detection and marine environmental impact assessment

Since CO_2 storage sites are deliberately selected to store CO_2 stably and safely, it is considered that CO_2 leakage from the geological reservoirs is remotely possible. Monitoring a CO_2 behavior is, however, still essential as there are public concerns about CO_2 leakage. In addition, when storing CO_2 in the sub-seabed geological formation in Japan, it is mandated to assess marine environmental impacts based on the supposition of CO_2 leakage and to monitor to verify that there are no signs of CO_2 leakage or migration from the reservoir. Hence, our group has studied and developed methods of the marine environmental impact assessment and those of the monitoring for several years. This year, we have combined our developed methods into an integrated system. Here, we outline the methods that we have developed.

For marine environmental impact assessment, we focus on increase of pCO_2 (ΔpCO_2; pCO_2 is an index of CO_2 concentration in seawater). Firstly the distribution of the elevation of pCO_2 is estimated based on supposed CO_2 leakage, and then it is projected how the estimated ΔpCO_2 could impact which organisms. As the leaked CO_2 is dispersed by ocean currents, the distribution of ΔpCO_2 is computed with currents in the sea calculated by an ocean model. The calculation of the distribution of ΔpCO_2 requires a relatively small area, whose sides are smaller than a hundred kilometers. On the other hand, the calculation of the ocean currents needs a much wider area because they are driven under the influence of meteorological conditions and ocean topography over several hundred kilometers. In our method, realistic currents oceanic data are calculated in a larger area model with a lower resolution and then we obtain the calculated current data as the boundary conditions for a simulation of ΔpCO_2 distribution which is simulated in the smaller area with a higher resolution.

The simulated ΔpCO_2 are used to assess what impacts they could make on which organisms. The relation between ΔpCO_2 and its impacts on a marine organism have been reported in many studies, but those data were not compiled into one. We have, hence, constructed a database, with which we can extract correlation between values of ΔpCO_2 and their impacts easily. By given features of organisms (e.g. taxonomic groups, habitats), the database selects organisms that meet the conditions and outputs data on how they could be affected by different levels of ΔpCO_2. Combining the output data from the database and the simulated distribution of ΔpCO_2, we can deduce what kinds of marine organisms could be how affected in which areas.

To identify signs of CO_2 leakage, the scope of monitoring should cover a wide range from deep geological formations, including CO_2 reservoir, to the sea. The reservoir is at a depth of around 1 kilometer or deeper under the seabed. According to a simulation that we conducted previously, the amount of time that CO_2 migrates from a reservoir to the seabed right above would be more than 5 years. Since the pathway of the CO_2 migration would depend on the characteristics of the formations between the reservoir and the seabed, CO_2 would not necessarily leak into the sea in the area right above the reservoir. Taking these into consideration, we propose the following strategy for the monitoring. Initially, we should put the focus on the deep formations including the reservoir to detect signs of CO_2 migration from the reservoir. Then, if detect, we move to in-depth investigation, targeting at overburden, to narrow the potential area for CO_2 to leak out. Lastly, we prove the narrowed area to detect signals of leaked CO_2 in water column.

Regarding the monitoring in the water column, we have explored and developed methods to detect signals of CO_2 leakage. There are 2 kinds of signals of the leakage: one is CO_2 bubbles and the other is elevated CO_2 concentration. Considering that a promising option for detection of CO_2 bubbles is side-scan sonar (SSS, a kind of sonar system), we conducted an in-situ experiment to investigate the capability of SSS to detect CO_2 bubbles in the sea. The experiment was to test whether SSS can detect CO_2 bubbles released on the seabed in various conditions. Our findings include that SSS is capable of detecting bubbles released at a rate of higher than 2-4 tonnes per annum and that the distance between the neighboring observation lines in the monitoring should be shorter than the altitude of SSS (i.e. the distance between SSS and the seabed beneath it). The 4 tonnes of CO_2 are remarkably small quantities; they are comparable to CO_2 that 10 people breathe out in a year.

As to detection of CO_2 concentration elevated by CO_2 leakage, we have studied identification of anomalously high values of pCO_2 caused by CO_2 leakage if any. CO_2 is naturally contained in seawater, and its concentration naturally fluctuates. This makes it challenging to determine whether high pCO_2 values are derived from CO_2 leakage or from natural variability, and to define a threshold for the judgement (Fig. 5). The threshold that we put forward is based on covariance between dissolved oxygen (DO) and pCO_2 (referred to as the pCO_2-DO threshold, hereafter). First, we have examined its validity through an analysis of natural fluctuation in quarterly data of its kind acquired in Osaka Bay, an enclosed bay in Japan, over 9 years. Our conclusions include that, in the identification of anomalous pCO_2 due to CO_2 leakage in summer, when natural variability in pCO_2 is large, or in areas where so is it, the proposed pCO_2-DO threshold is superior to a threshold simply based on pCO_2, and that the threshold should be set out based on data for at least 5 years. As a next step, we have carried out a continuous observation of pCO_2, DO and so on in Osaka Bay more than a year and analyzed their natural fluctuation. This has revealed that pCO_2 in the innermost part of the bay in summer fluctuates largely and that pCO_2 occasionally changes significantly within a few hours. The data over 1 year has revealed that a rate of false-positives to be given by the pCO_2-DO threshold can be varied, depending on seasons. We have also found out that in evaluating the covariance of pCO_2 and DO, it is necessary to take account of a difference in the response times of the sensors. As has been stated, we have proposed the pCO_2-DO threshold to detect signs of CO_2 leakage and clarified its various features, which would be important in actual monitoring operation. It should be, however, highlighted that to detect anomalies in pCO_2 caused by CO_2 leakage at a small leakage rate, it is essential to observe in sea at high resolution both spatially and temporally. This is because dissolved CO_2 is easily dispersed by currents and because even though the leak point is the same, the area where pCO_2 becomes anomalous is varied depending on flow direction and strength and leakage rate. We, therefore, suggest that indexes of CO_2 concentration such as pCO_2 and pH be monitored not for detection of CO_2 leakage but for confirmation that marine environment remains unchanged after commencement of CO_2 storage.

We will incorporate these outcomes into the best practice manual that we have been compiling, hoping that they are used in full-scale offshore CO_2 storage operation.

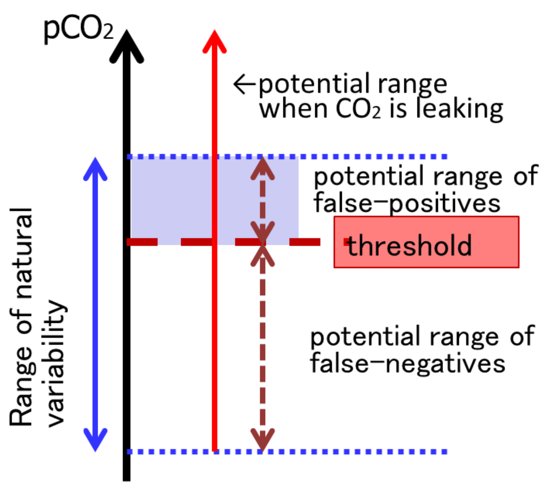


Fig. 5 The relation between the threshold and false-positives and -negatives

2.4. Contribution to the world by cutting-edge technology development

There are a number of large-scale geological CO_2 storage projects in operation worldwide, including Snøhvit in Norway, Quest in Canada, Gorgon in Australia. All these projects have successfully injected and stored CO_2 at about 1Mt/y.

Such large-scale CO_2 storage has unfortunately not yet been implemented in Japan. Nevertheless, our group intends to contribute to global CCS deployment through international cooperation by providing our core competency technologies for large scale geological CO_2 storage.

One of our core technologies is the aforementioned microbubble CO_2 injection technology which improves CO_2 storage efficiency even for low permeability formations. This will enable to use, for example, a CO_2 storage site closer to a CO_2 source, giving more flexibility in site selection. This is a pivotal contributor for CCS promotion in the world. Moreover, we will also strengthen our contribution to CO_2-EOR by demonstrating increased oil production in low-permeability fields in China, which we have been jointly researching with Junlun Petroleum Company since 2018.

Another example is Distributed Fiber Optical Sensing (DFOS). In addition to functions of fiber optical sensing to monitor pressure, temperature and so forth under the ground that have already been used in the oil industry, our group has created our own method to measure strains of geological formations and has integrated and demonstrated them as a multi-sensor system that enables concurrent measurements of temperature, pressure, seismicity and strain of geological formations.

Our DFOS system draws attention not only domestically but also internationally. We have been conducting its demonstration at a commercial CCS site in collaboration with the Energy & Environmental Research Center (EERC), the University of North Dakota, USA. We have built mutually beneficial relationships in this project: the US side is to be able to monitor the stability of the geological CO_2 storage site and CO_2 plume behaviors, and our side has got an opportunity to demonstrate our DFOS system and to improve techniques for its installation at their site.

Our optic-sensing technology will have more and more opportunities to be demonstrated and deployed around the world. It will be, for example, applied to monitor deformation of seabed surface in a European project called SENSE, which is probing the stability of offshore CO_2 storage. There also can be chances for our system to be implemented in CO_2 storage projects being planned in Asian countries.

The promotion of CCS by collaborating internationally is crucial for Japan to achieve our ambitious zero emission goal in 2050. Please keep your eye on the activities of the CO_2 Storage Research Group, RITE. We continue to contribute to CCS deployment by developing innovative technologies and consulting for their applications.

Inorganic Membranes Research Center

Members (As of Dec. 2020)
Shin-ichi Nakao, Director of the Center, Chief Researcher
Yuichiro Yamaguchi, Deputy-Director, Chief Researcher
Hidetoshi Kita, Chief Researcher
Masahiro Seshimo, Senior Researcher
Kenichiro Yasuhara, Senior Researcher
Makoto Ryoji, Senior Researcher
Hye Ryeon Lee, Researcher
Hiromi Urai, Research Assistant
Yuko Nara, Research Assistant
Kazuaki Sasa, Research Assistant
Nobuaki Oono, Research Assistant
Chiyoko Shindo, Research Assistant
Akiyoshi Fujii, Research Assistant
Keiko Komono, Research Assistant

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

1. Introduction

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 apply 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 a society that intends to use hydrogen in practical ways. 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) has 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 conducting research on the ways to more effectively use the CO_2 produced. In the Industrial Collaboration Department, the Industrialization Strategy Council, which consists of 18 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 have regular opportunities to share ideas and promote activities through study groups.

In 2020, we constructed a membrane reactor (MR) using a silica membrane and a palladium membrane in a project that directly decomposes methane and produces hydrogen, which was commissioned by the New Energy and Industrial Technology Development Organization (NEDO), and confirmed the high conversion rate of the membrane reactor with this reaction system. We reported to the committee of NEDO, and the project was completed.

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 a three-fold improvement in the conversion rate compared to conversion in the reactor. In addition, NEDO's Moonshot research and development program was commissioned jointly with Kanazawa University and the Chemical Research Group for the development of highly efficient direct air capture (DAC) and carbon recycling technologies, and IMeRC conducts research to develop a process to produce liquid fuel from the CO_2 collected from the atmosphere

At the Industrialization Strategy Council, the second phase (2019–2020) of the Common Base (Reliability Evaluation Method) Research Group and the CO_2 Separation Research Group was completed, and seminars were held on the Web.

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

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

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

Adopted as a contract project of NEDO in FY 2019, the objective was follows: a) development of a high hydrogen permselective membrane with durability under high temperature conditions (>500°C), b) development of a catalyst that activates at relatively low reaction temperatures for the membrane reactor, and c) the development of membrane reactors consisting of a hydrogen separation membrane and a catalyst with a demonstration of their effectiveness. (Fig. 1)

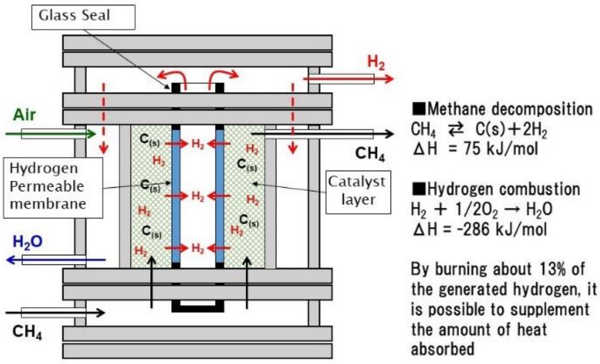


Fig. 1 Application of a membrane reactor to the hydrogen production process from methane decomposition

For the development of a hydrogen permselective membrane in a), silica and palladium membranes are candidates. The guidelines for membrane formation were narrowed down based on membrane formation experiments and literature searches. The development of silica membranes was examined using various silica sources, and the silica source was selected by evaluating permeation separation performance. As a result, we were able to achieve the target performance for this project with a membrane using dimethoxydimethylsilane (DMDMS: a silicon compound in which two methyl groups and two methoxy groups are bonded to Si as the center) as a silica source. Furthermore, by carefully examining the membrane formation conditions for DMDMS, it was possible to form silica membranes that exhibited high heat resistance (Fig. 2).

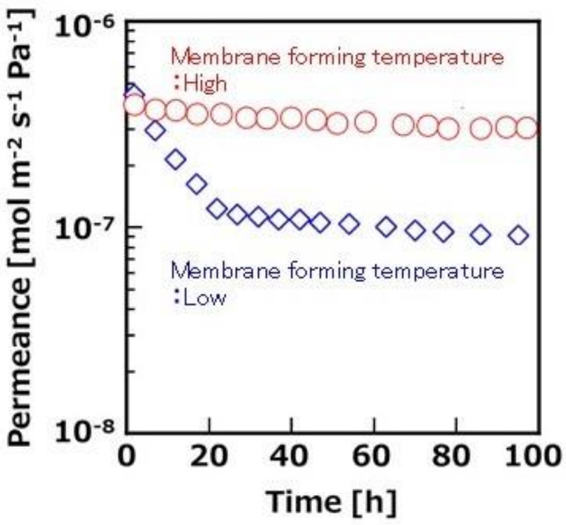


Fig. 2 Results of heat durability tests of silica membranes with different membrane forming conditions

Regarding the development of palladium membranes, we examined the membrane formation conditions of Pd-Cu alloy membranes, which are expected to improve heat resistance while maintaining high hydrogen permeability, as a pore-filled membrane, which is an inorganic membrane developed by the RITE Research Center of Technology. It was confirmed from the SEM-EDX of the formed membrane that the membrane could be formed with the desired composition (Pd 60 Cu 40 wt%). Furthermore, by scrutinizing the membrane formation conditions, the hydrogen permeability of the intrapore-filled Pd membrane at 500°C was improved to 1.3×10^{-6} mol m^{-2} s^{-1} Pa^{-1} (previously 8×10^{-7}). We developed a hydrogen permeable membrane with heat resistance and achieved the target performance.

Regarding the catalyst development in b), we conducted a literature survey targeting hydrogen production by direct decomposition of methane in Japan and other countries, grasped the technological development trends, and investigated catalysts that could be applied to membrane reactors. As a result, $Ni/Fe/Al_2O_3$ catalysts, which have been reported to produce high yields at relatively low temperatures, were selected as candidates. Regarding the catalysts, 20 types with different preparation conditions, such as coprecipitation temperature, dropping method, type of precipitant, and composition, were prototyped, and as a result of evaluating the reactivity, a catalyst with relatively high performance was selected for the membrane reactor. (Fig. 3)

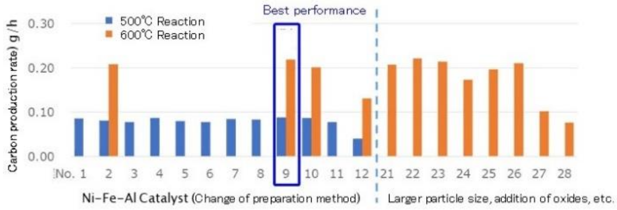


Fig. 3 Trial production and performance evaluation of catalysts for methane decomposition

Regarding the development of the membrane reactor in c), a membrane reactor was designed and manufactured, and a membrane reaction test was conducted using the $Ni/Fe/Al_2O_3$ catalyst selected in b) and a palladium membrane and a silica membrane were chosen for use as the hydrogen separation membrane. A reaction test was performed. It was confirmed that the conversion rate was improved by applying the Pd membrane and the silica membrane under the conditions of a reaction temperature of 600°C and a reaction pressure of 0.4 MPa, the effectiveness of the membrane reactor was demonstrated, and it was confirmed that the obtained carbon has a structure in which graphene is laminated around the catalyst (Fig. 4).

On the other hand, the hydrogen permeation performance of the Pd membrane after the test was reduced to about one-half. From the SEM-EDX results of the membrane after the test, it was confirmed that carbon was dissolved in the Pd layer, suggesting that the decrease in hydrogen permeation performance was due to the solid solution of carbon. We are working on countermeasures for the new issue.

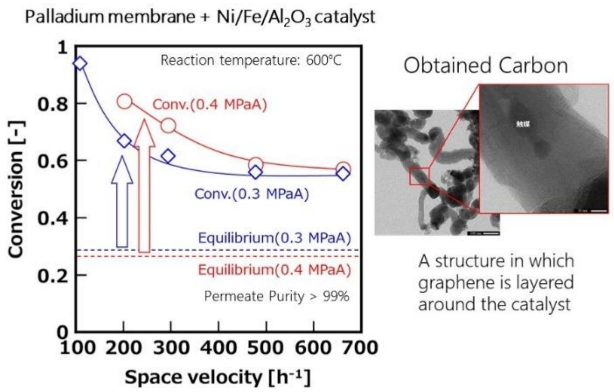


Fig. 4 Results of membrane reaction test using palladium membrane and SEM image of obtained carbon

3. CO_2 utilization technologies in RITE

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

3.1. Development of effective methanol synthesis from CO_2 hydrogenation

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

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

To solve these problems, a membrane reactor can be applied to the application because generated water can be removed from the reaction system through the membrane, and the reaction will be promoted to the methanol producing side. However, it is difficult to apply the A-type zeolite (LTA) membrane, which is often used for water separation, from the viewpoint of hydrothermal stability.

Herein, we successfully developed a novel zeolite membrane for water separation, which has higher hydrothermal stability compared to the conventional LTA-type zeolite membrane. The membrane was applied to the membrane reactor for methanol synthesis via CO_2 hydrogenation, and the CO_2 conversion from the membrane reactor showed higher rates than those from a conventional packed-bed reactor (Fig. 5). In the future, we will proceed with research and development of practical uses for the methanol synthesis membrane reactor.

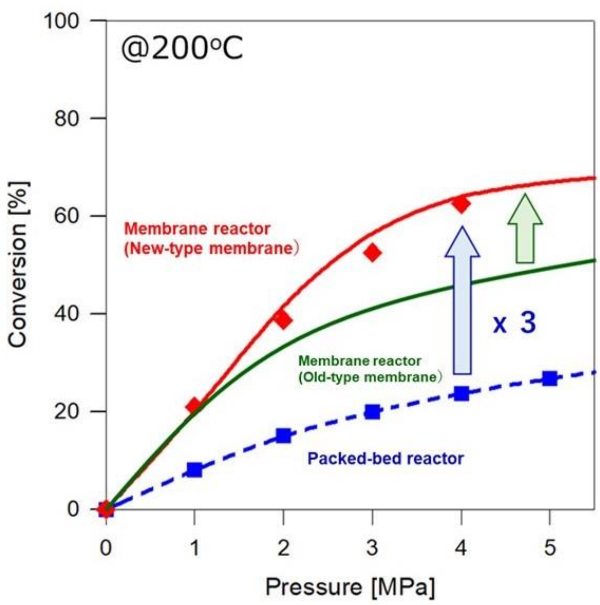


Fig. 5 Membrane reactor for methanol synthesis using a zeolite membrane

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

The NEDO project Moonshot Research & Development Program was adopted in collaboration with Kanazawa University since 2020. At the IMeRC, we accepted the challenge of developing the technology to convert the captured CO_2 into liquid hydrocarbon fuel by FT (Fischer-Tropsch) synthesis. Similar to methanol synthesis, the water produced from the reaction causes catalyst deactivation and a reaction rate reduction in FT synthesis. Another problem was that reaction control was difficult because the product followed the ASF (Anderson-Schulz-Flory) distribution.

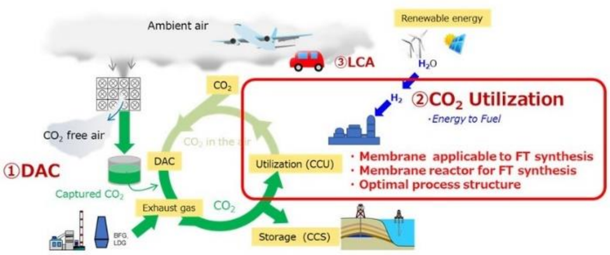


Fig. 6 Overview of the Moonshot project at RITE

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

a) Development of a membrane applicable to FT synthesis

b) Development of a membrane reactor for FT synthesis

c) Search for the optimal process structure

Catalyst deactivation can be suppressed if the generated water can be removed from the reaction side by using a hydrophilic membrane, such as zeolite. Furthermore, the reaction can be controlled by supplying H_2 to the reaction field via hydrogen permselective membranes, such as a silica and palladium. We succeeded in developing the Si-rich LTA-type zeolite membrane with improved hydrothermal stability compared to the conventional LTA-type zeolite membrane. We are also involved in the development of pore-filled Pd membranes and silica membranes with excellent hydrogen permselectivity. In the future, we will make the best use of the knowledge we acquired and strongly promote the development of inorganic membranes and membrane reactors applicable to FT synthesis. We then intend to unravel the science of inorganic membranes that we have left unattended.

4. Activities and efforts toward commercialization and industrialization

The core of the industrial collaboration department of the IMeRC is the Industrialization Strategy Council. A total of 18 separation membrane and support manufacturers and user companies (as of January 2021) participate on this council. Our goal is to establish an inorganic membrane industry that contributes to innovative environmental and energy technologies by promoting a common vision for manufacturers and user companies, as well as a joint research plan involving national projects and other initiatives.

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

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

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

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

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

e) Hosting exclusive technology seminars for council members

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

In 2020, because of the relationship with the COVID-19 virus, although there were some changes from the original plan, such as postponing the holding of workshops, a working group was established that would use the Web and promote studies as the CO_2 Separation Study Group and the Common Infrastructure (reliability evaluation, etc.) Study Group and subordinate organization. The group met a total of four times as the CO_2 Separation Study Group and a total of seven times as the Common Infrastructure (reliability evaluation, etc.) Study Group, and they further deepened the investigation. The Common Infrastructure Study Group aims to launch a government-sponsored project after 2021 by conducting a concrete preliminary test for accelerated deterioration of zeolite membranes and to acquire basic data for establishing long-term reliability. The CO_2 Separation Study Group studied the main theme of the applicability of inorganic membranes to natural gas fields containing high concentrations of CO_2.

In addition, seminars for council members were held on the Web (three times a year in FY 2020). In the future, we plan to give lectures on the latest R&D trends and needs, seeds, and practical development cases of membranes from advisory boards, member companies, and membrane-related companies, and there will be lively questions, answers, and discussions. It is done. In addition to gaining useful knowledge related to the practical application and industrialization of inorganic membranes, the seminars have been highly rated as meaningful places for interaction between member companies and front-line researchers.

Fig. 7 Lecture at the Seminar (April 2019)

5. In conclusion

In 2020, we constructed a membrane reactor (MR) in a project that directly decomposes methane and produces hydrogen, which was commissioned by NEDO, and confirmed the high conversion rate of the membrane reactor with this reaction system. We reported to the committee of NEDO. Regarding this project, a new project is scheduled to start in 2021, and we plan to work toward more practical use through this project.

Steadily achieved results in research and development made effective use of CO_2; in addition, NEDO's Moonshot research and development program was commissioned for the development of highly efficient direct air capture and carbon recycling technologies, and we conduct the research to develop the process on produce the liquid fuel from collected CO_2 from the atmosphere. With the acquisition of a long-term funded project, it will be possible to organize the IMeRC, and in the future, we would like to work diligently to become a core organization that leads the development and practical application of inorganic membranes in the world.

Click the link to open the RITE website

Press Releases

Events

Paper, Presentation and Publication

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

Other Activities

◆Environmental Education

Date	Participants	Number of partici-pants
27 Jan.	Fifth grade, Kizugawadai Elementary School	33
4 Feb.	Retired head teachers of Kyoto Yamashiro area	37
18 Feb.	First grade, Seikaminami Junior High School	4

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Research Institute of Innovative Technology for the Earth

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

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