English / 英語

RITE Today

2016 Vol.11

Annual Report

Research Institute of Inovative Tecnology for the Earth

RITE Today 2016 Vol.11

Contents

Significance of Paris Agreement

Director-General **Kenji Yamaji**
Research Institute of Innovative Technology for the Earth

2015 was a memorable year for Japan's energy and environmental policy. Japan's energy policy was thrown into confusion by the Fukushima nuclear accident in 2011. However, the Japanese government decided an energy mix plan for 2030 in July 2015, and drew up a global warming mitigation plan (Intended Nationally Determined Contribution (INDC)) for COP21 to be held at the end of 2015. The Paris Agreement was adopted at COP21 as an international framework in which all major countries participate. The Japanese government had advocated the establishment of such a framework for a long time.

The Paris Agreement requires each participating country to voluntarily set its global warming mitigation goal and implementation plan, which are to be reviewed every five years. In order to promote the effective implementation of global warming mitigation measures, all participating countries are required to report the status of implementation in a more transparent way according to a common method, and the status of implementation reported by each country is to be reviewed. This approach is similar to the pledge-and-review approach that has been proposed by Japan for more than 20 years.

The Paris Agreement also specifies a long-term goal to hold the increase in global average temperature to well below 2℃ above pre-industrial levels, and pursue efforts to limit the temperature increase to 1.5℃ above pre-industrial levels. In order to achieve the long-term goal, each participating country is required to aim to peak greenhouse gas emissions as soon as possible, and achieve net-zero greenhouse gas emissions by the latter half of the century. However, the above long-term goal may be problematic.

There are a number of scientific uncertainties about global warming, and there are a number of uncertain factors with regard to the forecast of the impacts of an increase in temperature and the feasibility of global warming mitigation measures. It is considered that it is necessary to take global warming mitigation measures in terms of risk taking account of such a number of uncertainties. Specifically, it is important to take effective long-term global warming mitigation measures on a global scale while flexibly dealing with various situations that may occur in the future, rather than setting the long-term goal using a specific numerical value. It is considered that it is appropriate to consider the long-term goal specified by the Paris Agreement to be a qualitative vision that represents the global warming mitigation measures to be taken in the future.

The Japanese government is scheduled to complete a "Global Warming Response Plan" that aims to implement the INDC by the spring of 2016 in view of the Paris Agreement. The "Innovation Strategy for Energy and Environment" that was proposed by Prime Minister Abe at COP21 will also be drawn up by the spring of 2016. This strategy aims at the development of innovative technologies and the application of these technologies all over the world so as to extend beyond the INDC for 2030.

It is important to conduct research and development from a global and long-term point of view, and provide enhanced measures in order to take global warming mitigation measures in terms of risk. The Paris Agreement points out the importance of innovation. In particular, the importance of research and development such as CCS technology is highlighted from a long-term point of view including the latter half of the 21st century.

RITE was established with the aim of contributing to the achievement of the New Earth 21 Plan proposed by Japan at the 1990 Houston summit. The basic roles of RITE are to tackle global warming from a long-term and global point of view, and contribute to widespread innovation as well as the development of policies. RITE will strive to enhance our activities to improve the future of the earth taking account of the significance of RITE that was reconfirmed by the Paris Agreement.

COP21 and Greenhouse Gas Emission Reduction Targets beyond 2020

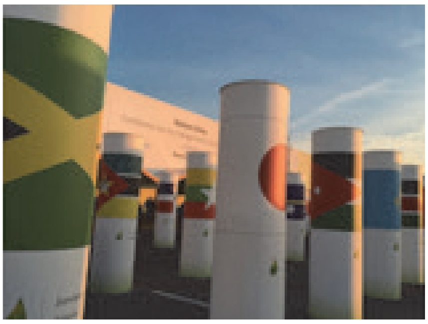
Keigo Akimoto
Group Leader, Systems Analysis Group

1. Introduction

A new epoch-making framework for climate change responses beyond 2020 (specifically, 2030 or 2025), the Paris Agreement, was agreed at the 21st Conference of Parties (COP21) of the United Nations Framework Conventions on Climate Change (UNFCCC) on December 12, 2015 in Paris. In this new framework, countries – almost all countries being represented – tackle greenhouse gas (GHG) emission reductions under an internationally legal force without disaggregation into developed and developing countries. I would like to express my highest appreciation to all the people in Japan and abroad who have made great efforts for such difficult negotiations.

The Kyoto Protocol, which was adopted in 1997 and took effect in 2005, requested developed countries to reduce their emissions bindingly, while having little power on developing countries to reduce the emissions. According to the Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2014, the increase rates of global greenhouse gas emissions after 2000 were higher than those before 2000 due to rapid emission growth in middle-high income countries, e.g., China, whose economies have developed rapidly. Although many nations made great efforts to reduce their emissions, they were not able to achieve effective reductions of global emissions.

In order to make a better framework for reducing GHG emissions effectively, the Japanese government has aimed to develop an international framework whereby all countries participate, and are required to reduce their emissions effectively. In the negotiation processes on the road to the Paris Agreement, the government refused to participate in the second commitment period (years of 2013–2020) of the Kyoto Protocol, as it still includes "developed and developing countries" as two fixed groups. The government then started developing a new framework in which each nation pledges their own emission reduction target and the international community reviews the targets: the so-called "pledge and review", and all countries participate in the elaboration of higher targets, instead of the framework that decides the global emission cap and allocates it to participating nations. The Paris Agreement was agreed as a "pledge and review" type framework. The agreement also has legal force internationally to require all member nations to submit their emission targets – same as the Kyoto Protocol – but is yet very different from that protocol which requires to achieve the decided emission reduction targets bindingly.



The entrance of COP21 grounds in Paris

This article briefly overviews the COP21 decision and the Paris

Agreement. It is important to develop a review system for Nationally Determined Contributions (NDCs) that include the emission reduction targets of each country in order to encourage continuous efforts on emission reductions, and therefore, the Systems Analysis Group of RITE has been evaluating the emission reduction efforts of NDCs. In this article, I would like to also discuss these evaluations.

2. Overview of the Paris Agreement

The COP15 held in Copenhagen, 2009, tried to agree on an emission reduction framework and targets toward 2020. The international community was not able to agree on a framework having legal force, but did agree on the Cancun Agreement at COP16 in Cancun, 2010. Towards COP21, the French government used strong determination and high flexibility to juggle different opinions among countries and stakeholders, and carefully built a consensus for the Paris Agreement. While the Paris Agreement has no binding targets for emission reductions (like the Cancun Agreement), it is one of the international treaties that have legal force followed by the descriptions in the agreement (which is different from the Cancun Agreement).

Article 2 of the Paris Agreement states that it “aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty” by “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C”, “increasing the ability to adapt to the adverse impacts of climate change”, and “making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development”. On the other hand, UNFCCC which is a treaty above the Paris Agreement intends “stabilization of greenhouse gas concentrations in the atmosphere to a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner”. The fact that the Paris Agreement described a specific target of global warming mitigation to be achieved for the world is a big change. In addition, it is also a big change that the target moves from atmospheric GHG concentration levels to temperature change levels. However, the relationship between greenhouse gas emissions and temperature change has a large uncertainty, and therefore, it should be noted that the required emission reduction levels have large uncertain ranges.

The Paris Agreement remains the UNFCCC’s “common but differentiated responsibility” which has been utilized for disaggregation into two groups, i.e., developed and developing countries. However, the Paris Agreement adds “in the light of different national circumstances” and avoids complete disaggregation into two groups. All member countries shall provide NDCs every five years, provide information including implementation and achievability of INDCs every two years, and undergo technical expert reviews. In this procedure, there is no differentiation between developed and developing countries. Good and fair reviews under the Paris Agreement will induce effective emission reductions, and it will be one of the most important results of the Paris Agreement.

Table 1 : Differences among Kyoto Protocol, Cancun Agreement, and Paris Agreement (Source: Mr. H. Mitsumata, METI, for the lecture at the symposium on innovative environmental technologies organized by RITE, 2015; translation to English by RITE)

	UNFCCC (1992), Kyoto Protocol (1997)	Cancun Agreement (2010) [without regal force]	Paris Agreement (2015) [with regal force]
Mitigation (emission reduction)	[Developed countries] economy-wide absolute emission reduction target (in Kyoto Protocol) [Developing countries] No specific targets of emission reductions	[Developed countries] economy-wide absolute emission reduction target [Developing countries] Mitigation action plans	[Both developed and developing countries] shall communicate NDCs every five years [Developed countries] should continue taking economy-wide absolute emission reduction targets [Developing countries] are encouraged to move over time towards economy-wide emission reduction or limitation targets
Finance	[Developed countries] requirements of finance supports to developing countries	[Developed countries] financial supports of 100 billion US$ per year for the developing countries conducting meaningful mitigation actions and transparency on implementation	[Developed countries] should provide financial resources to assist developing countries [Developing countries] are also encouraged to provide financial resources
Transparency of actions	[Developed countries] national inventory reports every years and national reports including policies and measures on mitigation, adaptation and finance supports every four years [Developing countries] national reports without deadline	[Developed countries] biennial reports on the progress in achieving emission reductions [Developing countries] biennial update reports containing updates of national greenhouse gas inventories	[Both developed and developing countries] - shall provide the information including the implementation and achievability of INDCs every two years - shall undergo technical expert review for the implementations and achievements

3. Evaluations on Nationally Determined Contributions of major economic countries from the viewpoint of emission reduction efforts

How to measure and evaluate emission reduction efforts of NDCs is crucial to increase the effectiveness of emission reductions. RITE attempted to undertake such an exercise. This article discusses evaluation results very briefly, and more details will be introduced in the part dealing with the research activity overviews of the Systems Analysis Group.

Several types of emission reduction targets were submitted for the INDCs: emission reduction rates from base year, reduction rates of emissions per GDP from base year, emission reduction ratios from baseline emissions, etc. In addition, the base years are also different. Such flexibility is important to encourage submissions of all countries under different national circumstances. However, the flexibility makes it all the more difficult to compare emission reduction efforts across nations. RITE has evaluated emission reduction efforts across countries by using multiple relevant indicators, and measuring them with the cooperation of Resources for the Future (RFF) in the U.S. etc. The indicators include both of the absolute values and improvement rates of GHG emissions per GDP, emission reduction ratios from baseline emissions, CO_2 marginal abatement costs, and emission reduction costs per GDP. However, each of these indicators has both strong and weak points, and they should be looked at by keeping their meanings and limits in mind.

The Japanese government submitted an Intended Nationally Determined Contribution (INDC) consisting of a 26% reduction by 2030 compared to 2013. In comparison, the INDCs of the U.S., EU and China are 26–28% reduction by 2025 compared to 2005, 40% reduction by 2030 compared to 1990, and 60-65% reduction of CO_2 emissions per GDP by 2030 compared to 2005, respectively.

Figure 1 shows the evaluations of emission reduction efforts for the indicators employed. Many of the indicators including CO_2 marginal abatement costs and emission reduction costs per GDP are ranking high for the INDCs of Switzerland and Japan. The marginal abatement costs for both are about 380 $/t$CO_2$. While Japan has achieved high energy efficiencies in many sectors, high improvements in energy efficiency are assumed for the INDC of Japan, and thus

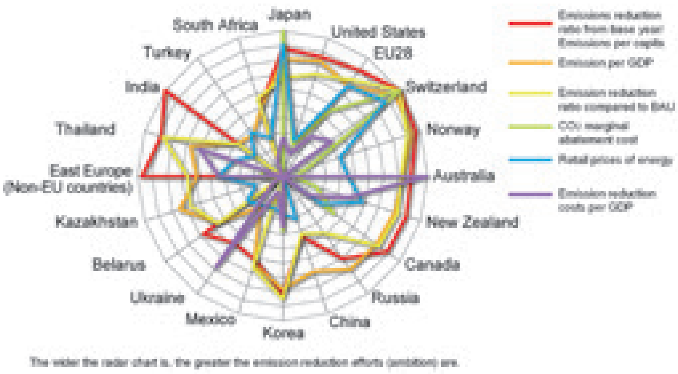


Figure 1 : Rankings of INDCs in terms of evaluation index for emission reduction efforts (Source: RITE estimates; Note: 119 countries and regions which submitted the INDCs by October 1, 2015 were estimated, but only 20 countries which the RITE model is able to evaluate in the mitigation costs were shown)

high marginal abatement costs are estimated. In Australia, the marginal abatement cost is not so high, but the emission reduction cost per GDP is significantly high.

These research studies were introduced as side-events of COP21, and had a favorable reception.

4. Expected global greenhouse gas emissions by aggregated Nationally Determined Contributions

RITE also estimated the expected global GHG emissions when all the submitted INDCs are achieved. According to the estimate, the global GHG emissions in 2030 are 59.5 GtCO_2eq. which would reduce emissions by 6.4 GtCO_2eq. from those in scenarios with only current policies in effect. The emission pathway is consistent with the temperature increase scenarios of +2 to +3 °C above pre-industrial levels. The range depends on the uncertainty of climate sensitivity and the achievability of deep emission reductions beyond the latter half of the 21st century thanks to possible developments and deployments of innovative technologies.

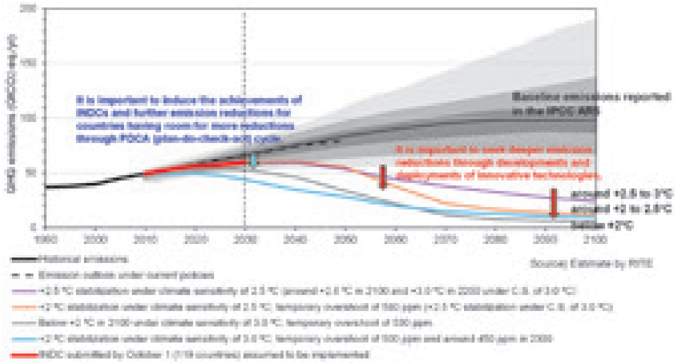


Figure 2 : Relationship between expected global greenhouse gas emissions submitted by October 1, 2015 as Nationally Determined Contributions, and the outlook for long-term emission reductions and temperature rise

Although emission reductions are expected in countries whose marginal abatement costs of INDCs are estimated to be high, emission increase is estimated in some of the countries whose marginal abatement costs are nearly zero, and part of the emission reductions could be offset.

At COP21, "Mission Innovation", which requires governments and private companies to expand investments in research and development on clean energies, was launched. The member countries aim at doubling government's expenditures on research and developments in clean energies. The Japanese government presented Japan's contributions, "ACE (Action for Cool Earth) 2.0," which consists of support for developments and more innovations in clean energies, and participation in "Mission Innovation".

5. Major future required items

The decision of COP21 requires IPCC to provide a special report on the impacts and GHG emission pathways to achieve below 1.5 °C above pre-industrial levels. It will be very challenging to achieve even 2 °C above pre-industrial levels, let alone the 1.5 °C target. In addition, all countries are required to submit long-term emission targets by 2020. It is necessary to reduce global emissions drastically in the long-term; however, if an emission reduction target with little chance to be achieved is set and persistently maintained, the framework relying on such targets will collapse in the future. In addition, excessively deep emission reductions could raise issues hindering broader sustainable development rather than climate change. It is necessary to conduct further quantitative research studies to come up with better solutions for climate change including such viewpoints.

Research & Coordination Group

Hideaki Tsuzuku
Group Leader

【Key members】
Masato Takagi, Deputy Group Leader, Expert Director
Satoshi Nakamura, Deputy Group Leader
Makoto Nomura, Chief Researcher
Kunio Sakuyama, Manager
Yoshinori Aoki, Manager
Yasuhide Nakagami, Planning Manager
Ichiro Saito, Vice Manager
Kohji Katsurahara, Vice Manager
Hiroyuki Azuma, Vice Manager
Jun-ichi Shimizu, Vice Manager
Sou Kuranaka, Vice Manager

Measures in Future for Deployment of CCS

1. Introduction

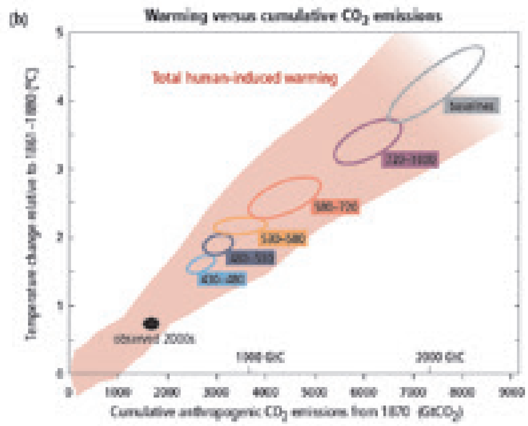
The Paris Agreement was adopted as the final outcome of COP21 in December 2015. “Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels”, “to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century” are set out in this agreement. “Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve”, “Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions” and “Each Party shall communicate a nationally determined contribution every five years” are also set out in this agreement. All countries including developing countries will take actions to address climate change and reviews will be conducted every five years in accordance with this agreement.

In this situation, Carbon capture and storage (CCS) is largely expected as one of the measures to reduce carbon dioxide which is one of greenhouse gases. There are, however, various concerns and challenges for deploying CCS on a full scale.

This report provides an outline of situation surrounding CCS, and the measures in future for the deployment of CCS on a full scale.

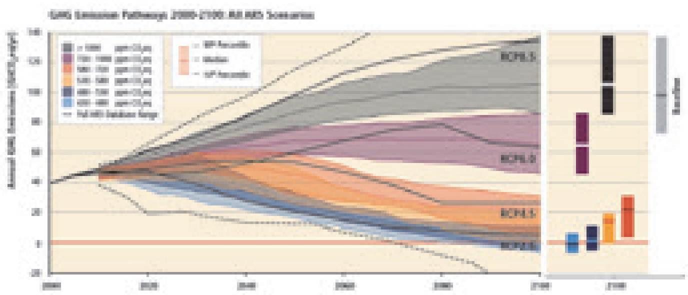
2. Implications of IPCC AR5

Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Synthesis Report Summary for Policymakers says “Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100". No matter what global mean surface temperature is, therefore, it is necessary to make incremental emission of CO_2, i.e. emission of CO_2 per annum, zero in order to stabilize global mean surface temperature (Figure 1). Also the Scenarios reaching atmospheric concentration levels of 430 to 480ppm CO_2eq by 2100, i.e. 2 °C Scenario claims that the global CO_2 emission per annum in 2100 is almost zero (Figure 2,3). Policymakers, companies emitting CO_2 and so on should better address climate change taking these points into account.



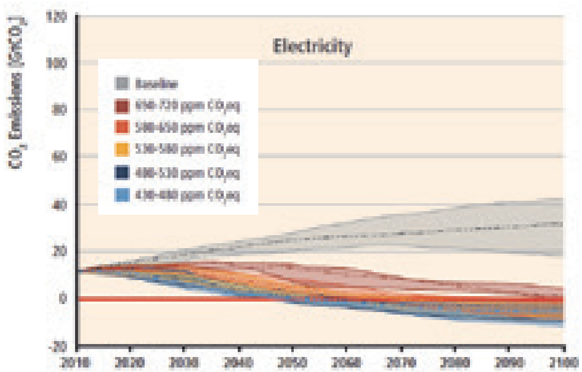
Source : Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Synthesis Report Summary for Policymakers, Figure SPM.5(b)

Figure1 : Relationship between cumulative CO_2 emissions and projected global temperature change



Source : Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) WGⅢ Report Summary for Policymakers, Figure SPM.5

Figure 2 : Pathways of global GHG emissions in baseline and mitigation scenarios for different long-term concentration levels from 2000 to 2100



Source : IPCC Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 7.9

Figure 3 : Representative concentration pathways in Electricity sector by 2100

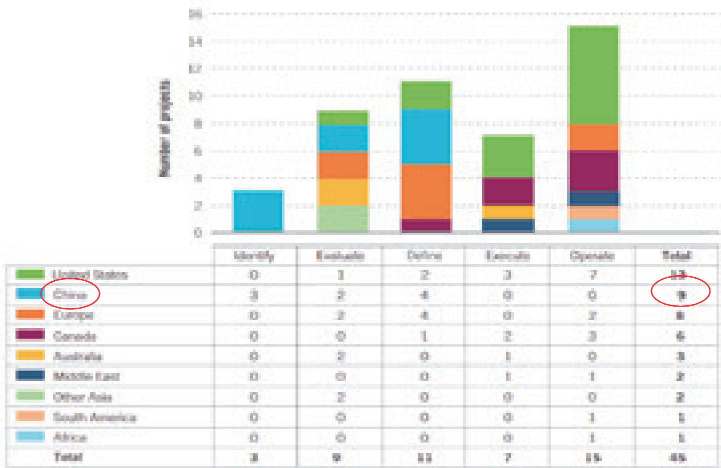
On the other hand, it takes considerable times to develop the infrastructure for CO_2 emission reduction. For example, it is said that lead-time in construction of thermal power station will be about 10 years. It means that more than several times of lead-time in construction will be required to develop all the infrastructures because all thermal power stations cannot be constructed at a time. If we take these points into consideration, therefore, we do not have much time until 2050 or even 2100. We have to commence implementing measures early.

There are limited measures for CO_2 emission reduction. We have to review all measures and implement these measures steadily. CCS is one of important measure options among these measures, and its deployment should be promoted. However, it takes considerable period of time and funds to deploy CCS on a full scale. It is pointed out, for example, that “It can take a considerable period of time, possibly up to ten years, to fully appraise a green field site ready for a final investment decision”. So making steady preparations is very important not to fall within moving second.

3. Overseas situations surrounding CCS

3.1 The current status of CCS large-scale projects in the world

According to “The Global Status of CCS: 2015”, there are 15 large scale integrated projects (LSIPs) listed in the Operate stage and 7 projects in the Execute stage. The number of LSIPs in the Operate stage increases by 2 projects, the number of LSIPs in Execute stage decreases by 2 projects. The number of total LSIPs including the planning stages of development amounts to 45, decreasing by 10 projects compared to those in last year (Figure 4).



Source : The global Status of CCS 2015 VOLUME 2

Figure 4 : Large Scale Integrated Projects of CCS in the world

The number of LSIPs in China amounts to 9 projects second to USA. Although China does not have LSIPs in the Operate and Execute stage, proceeding LSIPs with EOR and others in China in future is expected.

3.2 Trends in regulation on CCS in USA

The US Environmental Protection Agency (EPA) finalized two rules under Clean Air Act in August 2015 (Table1).

Table 1 : Trends in regulation on CO_2 emission in USA

Nation	Outline of regulation on CO2 emission
USA	**【regulation on CO2 emission for respective electric generating units】** ○Standards of Performance for Greenhouse Gas Emissions by EPA（went into effect on Oct. 23th 2015） ・The Environmental Protection Agency (EPA) is finalizing new source performance standards (NSPS) under Clean Air Act (CAA) section 111(b) ・The rate of CO2 emission from newly constructed coal-fired steam generating units is less than 640kg-CO2/MWh-gross（Implementing Partial CCS） ・The rate of CO2 emission from newly constructed natural gas-fired stationary combustion turbines is less than 450kg-CO2/MWh-gross or 470 kg-CO2/MWh-net **【state-specific regulation on CO2 emission 】** ○Regulation on CO2 emission for existing fossil fuel-fired electric generating units（went into effect on Dec. 22th 2015） ・Under the authority of Clean Air Act (CAA) section 111(d), the EPA is establishing CO2 emission guidelines for existing fossil fuel-fired electric generating units ・EPA is establishing ① Carbon dioxide (CO2) emission performance rates, ② state-specific emission performance rates and ③ state-specific CO2 goals reflecting the CO2 emission performance rates. ・Each state will establish and implement plans to meet the state goals. ・Heat rate improvement, Fuel switching to natural gas, Use of renewable energy together, Deployment of carbon capture and storage, Fuel switching to biomass, and Use of emission trade are set out in this rule as the examples of measures. ・Nationwide, by 2030, this final rule will achieve CO2 emission reductions from the utility power sector of approximately 32 percent from CO2 emission levels in 2005.

The first rule is Carbon Pollution Standards for New, Modified and Reconstructed Power Plants. The final standards went into effect on Oct. 23rd 2015. The final standards for newly constructed fossil fuel-fired Electricity Generation Units (EGUs) apply to those sources that commenced construction on or after the date of publication of the proposed standards, Jan. 8th 2014. The standards require that the rate of CO_2 emission from newly constructed coal-fired steam generating units is less than 640kg-CO_2/MWh-gross and that the rate of CO_2 emission from newly constructed natural gas-fired stationary combustion turbines is less than 450kg-CO_2/MWh-gross or 470 kg-CO_2/MWh-net when units are operated above the unit-specific percentage electric sales threshold which is equivalent to a unit's net design efficiency. It is required to implement partial carbon capture and storage (CCS) on newly constructed coal-fired steam generating units in future.

The second rule is Clean Power Plan for Existing Power Plants with customized goals for states to cut the carbon pollution that is driving climate change. The rule went into effect on Dec. 22nd 2015. EPA is establishing ① Carbon dioxide (CO_2) emission performance rates, ② state-specific emission performance rates, and ③ state-specific CO_2 goals reflecting the CO_2 emission performance rates. Each state will establish and implement plans to meet the state goals. Measures in detail are required to be established by each state. Heat rate improvement, Fuel switching to natural gas, Use of renewable energy together, Deployment of carbon capture and storage, Fuel switching to biomass, and Use of emission trade are set out in this rule as the examples of measures.

United States of America has the strategies to reduce CO_2 emission by regulation for respective units and state-specific regulation. Nationwide, by 2030, this final rule will achieve CO_2 emission reductions from the utility power sector of approximately 32 percent from CO_2 emission levels in 2005.

3.3 International standardization for CCS

A Technical Committee (ISO/TC265) was established within International Organization for Standardization (ISO) and the international standards for CCS have been developed under this ISO framework. Six working groups are set up under the TC: Capture WG, Transportation WG, Storage WG, Cross-Cutting WG, Quantification & Verification WG and Enhanced Oil Recovery WG. For participating in this international framework, Japan set up the mirror committee of ISO/TC265 for the domestic discussion.

Each WG is developing International standards (IS) and Technical report (TR) (Table 2, Figure 5). TR on CO_2 capture has been finalized by WG1 and this TR is in the process of publication. Japan takes a lead of WG1 activity and this TR will be the first published document from TC265. WG1 has also started to develop IS for post combustion capture technology integrated with power plant. WG2 is developing IS on transportation by pipeline and this IS will be published this year. WG3 is developing IS on onshore and offshore CO_2 storage. WG4 is developing TR compiled with the information of quantification and verification. WG5 is developing IS on vocabulary and TR for life-cycle risk management. WG6 is developing IS for CCS-EOR.

A first TR and IS are expected to be published in 2016.

Table 2 : Summary of WGs activities

WG	Work items	Target date	Note
WG1 (Capture)	● DTR27912 was approved and in the process of the publication. TR 27912 ● WD is in the process of the development. IS 27919-1	TR:2015 IS:2018	TR27912 will be the first publication from TC265. The first publication of TC 265 initiated by Japan
WG2 (Transportation)	● DIS27913 is the process of voting. IS 27913	IS:2016	Transportation by ship will be the next project.
WG3 (Storage)	● CD27914 was approved and the development for DIS is started. IS 27914	IS:2017	Many comments to CD27914 should be solved.
WG4 (Q&V)	● WD is in the process of the development. TR 27915	TR:2015	DTR voting will be needed.
WG5 (Cross-Cutting Issues)	● Cross-cutting terms will be voted in second CD. IS 27917 ● WD of TR for Lifecycle risk management is in the process of the development. TR27918	IS:2017 TR:2017	The development period of IS 27917 was extended to 4 years.
WG6 (CO2-EOR)	● WD is in the process of the development. ISO 27916	IS:2018	CD voting is expected in 2016.

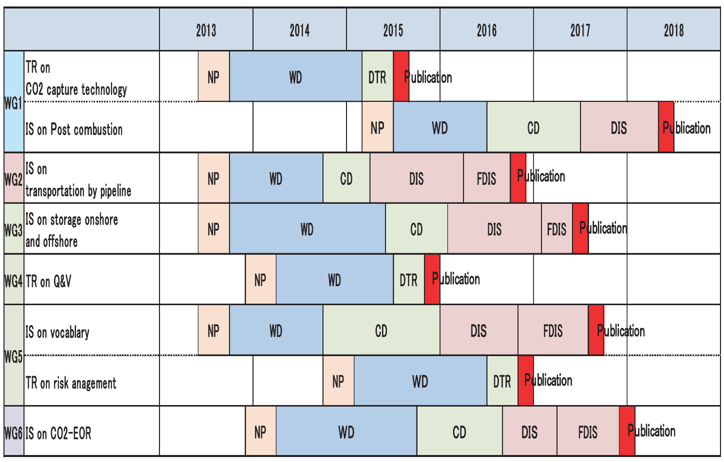


Figure 5 : Development schedule for standardization

4. Trends of measures for deployment of CCS steadily

4.1 Importance and challenges of CCS

The promotion of CCS deployment is very important as well as low carbon emission energy such as renewable energy, nuclear power and so on in order to reduce CO_2 emission drastically for restraining increase of global mean surface temperature because there are few options of measures. In the electric power generation sectors, load adjusting mechanism such as batteries or load adjusting power generation units is necessary because renewable energy like solar power, wind power and so on, or nuclear power cannot meet the variable load well. The thermal power generation equipped with CCS is a very important measure from this point of view.

There are some criticisms and anxieties about CCS in Japan. ① "There is no advantage in deploying CCS used only for addressing global warming problem which has an external diseconomy." ② "Are there places suitable for CO_2 storage in Japan where there are many faults and heterogeneous geological formations and earthquakes will occur?" ③ "No rules for the deployment of CCS are established as of now. Is the business of CO_2 storage feasible although there are many risks, for example, the risk that we cannot inject predicted amounts of CO_2?"

4.2 Things to tackle for deployment of CCS

Facilitating the deployment of CCS, reducing risks of CCS business and so on are necessary to deploy CCS on a full scale in future considering the criticisms and anxieties mentioned above.

The first thing to tackle for the deployment of CCS is the implementation of successive research and development (R&D) for cost reduction. It is extremely difficult that only private sectors implement R&D because CCS is expected to be deployed on a full scale in 2030. The government should lead successive implementation of R&D.

The second thing to tackle for the deployment of CCS is grasp and database compilation of quantity of CO_2 reservoirs. Grasp of quantity of CO_2 reservoirs is very important when the parties concerned like policymakers entities, company emitting CO_2 decide to deploy CCS on a full scale. On the other hand, "It can take a considerable period of time, possibly up to ten years, to fully appraise a greenfield site ready for a final investment decision." is pointed out. Early-stage storage site characterization is important for accelerating CCS deployment because it takes considerable period of time and fund to grasp and compile database of quantity of CO_2 reservoirs.

The third thing to tackle for the deployment of CCS is R&D of more economical and safer CCS technology suitable for geological formations in Japan. There are many faults and heterogeneous geological formations. It is necessary to develop more economical and safer CCS technology to secure CO_2 reservoirs. RITE proposes a next-generation CO_2 storage system which has advantageous effects by extracting water from the aquifer.

The fourth thing to tackle for the deployment of CCS is to establish mechanisms, legislative system and so on. It is very difficult to deploy CCS by market mechanism because CCS is a countermeasure only for global warming which has an external diseconomy. It is necessary to establish some mechanisms including incentive such as subsidy and tax reduction, emissions trading, and regulations.

The final thing to tackle for the deployment of CCS is to promote understanding of CCS. CCS is not familiar to public although it is critical technology for addressing global warming. There is anxiety about leak of CO_2 stored underground. It is important to make efforts to explain the accurate information plainly for promoting understanding of CCS.

4.3 Image of deploying CCS

It is important to implement R&D of CO_2 capture and storage successively and storage site characterization. Implementing a large scale demonstration project is necessary before CCS deployment on a full scale. Successive promotion of understanding of public on CCS is necessary because there are anxieties about leak of CO_2 stored underground and inducing earthquakes. It can take a considerable period of time for storage site characterization, environmental impact assessment, and construction of facilities when it comes to operating CCS. Considering the indication that “It can take a considerable period of time, possibly up to ten years, to fully appraise a greenfield site ready for a final investment decision.”, it is necessary to prepare for seven to ten years before operating CCS on a full scale in 2030 on the premise that legislative system and mechanisms facilitating CCS deployment will be established. Figure 6 indicates image of deploying CCS.

As mentioned above, it is necessary to prepare systematically and steadily toward CCS deployment.

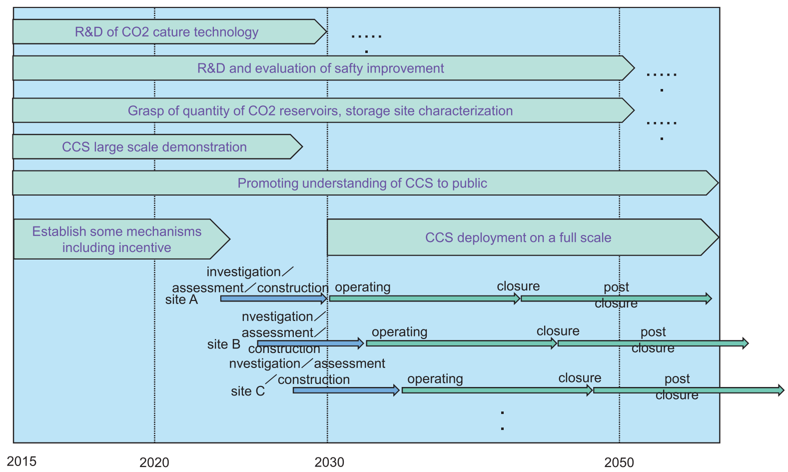


Figure 6 : Image of deploying CCS

5. More economical and safer CCS technology (SUCCESS)

5.1 Secure quantity of CO_2 stored by Multi-Well System

In Japan, geological formations often contain many faults and impermeable layers. Thus, there is a possibility that we cannot inject enough amount of CO_2 actually. We have to take into account the above stated points when we plan to store CO_2 underground. "SUCCESS" (Storage & Utilization of CO_2 for Coexistence of Economical & Safe System) has been proposed as one of the next-generation CO_2 storage system which has three advantageous effects which are utilization of geothermal heat, relax of formation pressure, and realization of injection rate by extracting water from the reservoir with pressure relief wells. This system is also expected to secure enough amounts of stored CO_2 in a reservoir of closed system which is surrounded by faults and impermeable layers. A CO_2 reservoir of open system which has open boundary can secure enough amounts of stored CO_2. However, the CO_2 reservoir of closed system cannot secure it. The reason is that CO_2 injection induces an increase of formation pressure to be unable for water to flow throughout the reservoir in the closed system. On the other hand, by setting the pressure relief well and extracting water from the reservoir, inherent storage capacity of the reservoir can be fulfilled. In this way, CO_2 reservoir of closed system can secure enough amounts of stored CO_2 by setting pressure relief wells in addition to the injection wells (Figure 7).

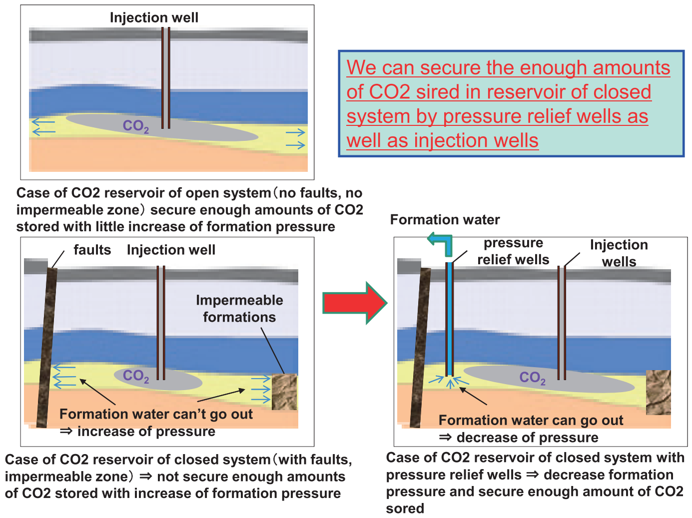


Figure 7 : Image of capacity improvement of CO_2 reservoir by multi-well system

5.2 Examination of effects of Multi-Well System by the numerical value simulation

RITE has conducted numerical value simulation of Multi-Well System with injection wells and pressure relief wells using an actual geological model at a certain site. Figure 8 indicates the results. W-1 is an injection well; W-2 and W-3 are pressure relief wells in Figure 8. They all are set at high permeable zones. The amount of injected CO_2 prepared for the simulation is one million ton per annum. We calculate three cases i.e. case of setting no pressure relief well, case of setting pressure relief well at W-2 and case of setting pressure relief well at W-3. As a result, we cannot inject CO_2 after 4 years duration in the case of setting no pressure relief well due to increase of the formation pressure. On the other hand, we can inject CO_2 for more than 12 years in the case of setting pressure relief well at W-2. However, we cannot inject CO_2 after 4 years duration in the case of setting pressure relief well at W-3. From these calculated results, we recognize that the setting of pressure relief well cannot produce the effects in the case of no continuity (conductivity) of the three-dimensional high permeable zone between W-1 and W-3. As mentioned above, setting pressure relief wells is extremely effective on CO_2 reservoir of closed system, but appropriate arrangement of the wells should be considered because some cases that setting of pressure relief wells cannot produce the effects exist in some wells arrangement and geological conditions.

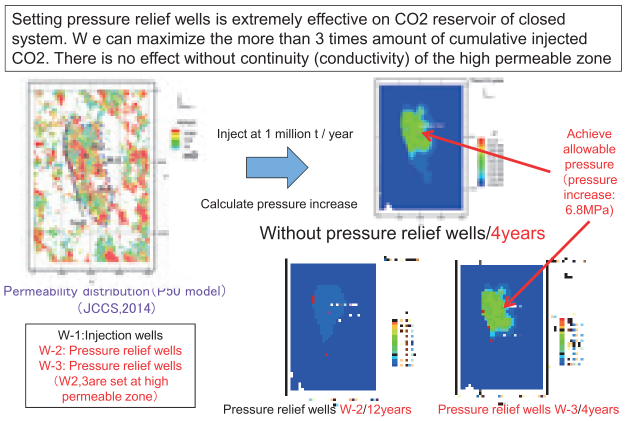


Figure 8 : Examination of effects of Multi-Well System by the numerical value simulation

As mentioned above, the storage capability of reservoir varies depending on the location of injection well and pressure relief wells. Therefore, it is necessary to clarify the best locations where we can maximize the amounts of cumulative injected CO_2 by setting pressure relief wells. Actually we calculated 3,450 cases using Differential Evolution (DE) method as a method to optimize the wells arrangement. The amount of cumulative injected CO_2 (up to 25 years) in the maximized case is about 15.6 million ton which is 3.3 times in comparison with minimum (Figure 9). It is essential to improve the methods like this for injecting CO_2 effectively into complicated geological formations.

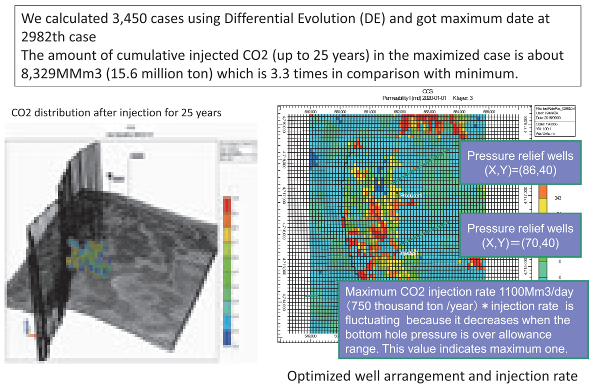


Figure 9 : Optimized well arrangement and result of calculation

The method of setting pressure relief wells causes increase of the cost due to drilling new wells and treating the produced water. It is also necessary to review and calculate considering trade-off relationship between the increase of cost and the increase of reservoir capacity.

6. Conclusion

It is finally necessary to make annual CO_2 emission zero in order to stabilize global mean surface temperature. ① the global CO_2 emission per annum in 2100 is almost zero and ② CO_2 emission per annum from power generation sector in 2050 is almost zero in, what we call, 2°C Scenarios. CCS is one of important measure options and the deployment of CCS should be promoted because there are limited measures for CO_2 emission reduction.

In order to deploy CCS on a full scale in future, the following measures should be taken; ① implementation of successive research and development (R&D) for cost reduction, ② grasp and database compilation of quantity of CO_2 reservoirs, ③ R&D of more economical and safer CCS technology suited to geological formations in Japan, ④ establishing mechanisms, legislative system and so on, and ⑤ promoting understanding of CCS. Especially, it is necessary to develop more economical and safer CCS technology suitable for geological formations in Japan because there are many faults and heterogeneous geological formations in Japan. The next-generation CO_2 storage system (SUCCESS), which RITE proposes, is extremely effective in geological formations of closed system by setting pressure relief well. It is important to develop the methods of optimizing well arrangement in future.

References

1) Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Synthesis Report Summary for Policymakers, 2015, IPCC

2) Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) WG Ⅲ Report Summary for Policymakers, 2015, IPCC

3) IPCC Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2015, IPCC

4) The global Status of CCS 2015 VOLUME 2, 2015, GCCSI

5) Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units, 2015, US EPA

6) Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, 2015, US EPA

Systems Analysis Group

Keigo Akimoto
Group Leader

【Key members】

Toshimasa Tomoda, Chief Researcher
Kenichi Wada, Senior Researcher
Miyuki Nagashima, Senior Researcher
Takashi Homma, Senior Researcher
Fuminori Sano, Senior Researcher
Junichiro Oda, Senior Researcher
Ayami Hayashi, Researcher
Kohko Tokushige, Researcher
Yosuke Arino, Researcher
Bianka Shoai Tehrani, Researcher
Keii Gi, Researcher

Research Activities in Systems Analysis Group

The Systems Analysis Group provides valuable information about measures on global warming and energy issues, both in and outside Japan by thinking them systematically and through systems analyses. We present here three research topics out of our research activities conducted in 2015; 1) our evaluation on the required efforts to achieve the greenhouse gas (GHG) emission reduction targets beyond 2020 (Intended Nationally Determined Contributions: INDCs), 2) the assessment of energy efficiency of power plants in India, as it is important to conduct effective emission reduction measures in developing countries, and 3) an evaluation of hydrogen systems as one of the key innovative technologies for effective mitigations on climate change. Our group contributes to better climate change policies and measures through such analyses and evaluations.

1. Evaluations on emission reduction efforts of the INDCs

The Paris Agreement was adopted at COP21 as described in the feature part. Appropriate reviews are important to make effective GHG emission reductions on a global level. This section introduces the evaluation of the INDCs submitted by Japan and other major nations in terms of emission reduction efforts.

1.1 Evaluations on the Japan's INDC

In July 2015, the Japanese government decided the official outlook of energy supply and demand for 2030 and a corresponding GHG emission target of 26% reduction compared to 2013. Then they submitted the INDC including the emission reduction target to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC). In this decision, the government assumed 17% of energy savings from the baseline, and aimed at decreasing electricity costs. On the other hand, the price elasticity of electricity is low (which means that price increases induce only small savings of electricity). As a matter of fact, there surely is potential fora certain of energy savings in residential and commercial sectors as the government assumed. However, one must notice that such large savings have not been achieved in the past due to multiple barriers to effective energy savings in these sectors – sometimes called “hidden costs” – which are not considered in this simple estimate of energy saving potentials.

According to the estimates by RITE energy and global warming mitigation assessment model DNE21+, the marginal abatement cost for the 26% reduction target of GHG emissions is about 380 $/tCO_2$ and that for the 22% reduction contribution in energy-related CO_2 emissions is about 260 $/tCO_2$. Both marginal costs are significantly high because the reduction target was developed assuming considerable energy savings. Before the government made these decisions, RITE realized several cost assessments including the economic impacts for different scenarios in electricity supply by source, GHG emission reduction levels, etc. in order to provide valuable information as decision support. In these estimates, the economic impacts under several scenarios with different shares of renewable energies and nuclear powers, and different intensities of GHG emissions were provided quantitatively. According to RITE global energy and economic model DEARS, which can estimate the economic impacts including spillover effects across sectors in the whole economy, GDP loss is 2.5% which corresponds to about 18 trillion JPY per year. Such large impacts depend little on the decided electricity mix (renewables: around 22−24%, nuclear: around 20−22%, coal: around 26%, LNG: around 27%) but do largely on the assumed high amounts of energy savings. The electricity mix is considered to be relatively well balanced taking account of the actual constraints on electricity in Japan. On the other hand, the energy savings assumed here are too large and can have huge impacts on the economy. While the target for energy savings is too stringent, achieving it would require a good environment on whole economy inducing wide capital investments in private sectors to ensure smart measures on energy savings.

1.2 Evaluations of the INDCs of major economic nations

The Systems Analysis Group, together with Resources for the Future (RFF) in the U.S. and the Fondazione Eni Enrico Mattei (FEEM) in Italy, has conducted an evaluation of emission reduction efforts of INDCs employing multiple indicators enabling to measure the levels of efforts.

The appropriate indicators include both absolute levels and improvement rates of GHG emissions per GDP, emission reduction ratios from baseline emissions, CO_2 marginal abatement costs, and emission reduction costs per GDP. However, no silver bullet indicator exists, and each indicator has good and bad points as shown in Table 1. Therefore, the indicators should be used while acknowledging their meanings and limits.

Figure 1 shows GHG emissions per capita, GHG emissions per GDP, and

CO_2 marginal abatement costs for twenty nations/regions of INDCs (in 2025 for the U.S. and in 2030 for other nations). The emission per capita of the INDC of China in 2030, for example, is much higher than that of EU and Japan.

The GHG emissions per GDP of the INDC of Japan is evaluated to be at an excellent level when the INDCs of Switzerland and Norway where hydro power contribute greatly to the electricity supplies are excluded.

Table 1 : Indicators employed for measuring emissions reduction efforts

Indicators for emission reduction efforts	Overview and notes
Emissions reduction ratio from base year	When baseline emissions are expected to stagnate, it is more relevant to simply compare the projected reduction rates and the estimate of BAU with uncertainties can be avoided.
Emissions per capita	As it is highly dependent on the country's level of economic activity and situation in general, it can be difficult to assess emissions reduction efforts through this indicator.
CO_2 intensity (GHG emissions per GDP)	Reveals what level of CO_2 emissions corresponds to what degree of economic activity. However, it depends on the country's industry structure that has less relations with emission reduction efforts.
Emissions reduction ratio compared to BAU	While it allows taking into account the difference of economic growths, etc., it puts aside past efforts in energy savings and abatement potential of renewables.
CO_2 marginal abatement cost (carbon price)	This is a particularly relevant indicator to assess reduction efforts as it contains countries' differences in terms of economic growth, energy savings efforts, abatement potential of renewables. Uncertainties are high as this is a model-based estimation.
Retail prices of energy (electricity, city gas, gasoline, diesel)	While marginal abatement costs show the additional effort to be made, this indicator also includes the efforts made in the baseline. Market data is available for ex-post evaluation, but for ex-ante evaluation, only model-based estimates are available which makes uncertainties rather high.
Emission reduction costs per GDP	As marginal abatement costs do not take into account the economy's ability to bear such an effort, this indicator does. Uncertainties are high as this is a model-based estimation.

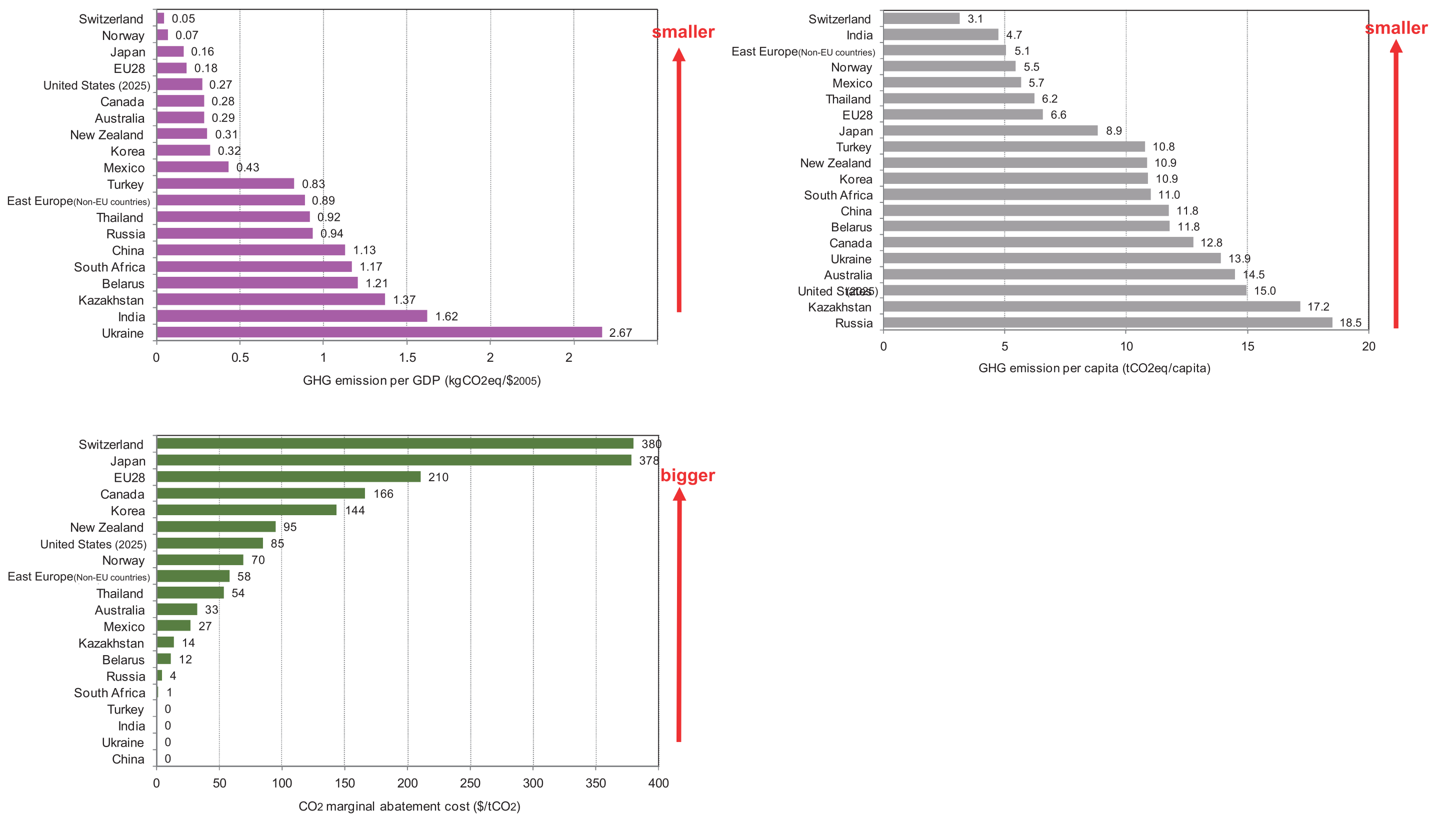


Figure 1 : Example evaluations on emission reduction efforts of INDCs (GHG emissions per capita, GHG emissions per GDP, and CO_2 marginal abatement costs; in 2025 for the U.S. and in 2030 for other nations)

For the estimations of marginal abatement costs, climate change mitigation models are required. The models need to assume the estimates of current energy efficiency levels by sector, cost reductions of renewable energies etc. and therefore the estimated costs have uncertain ranges across models. Figure 2 shows the marginal abatement costs estimated not only by RITE model DNE21+ but also by other models. The WITCH model developed by FEEM cannot evaluate the Japan separately. RITE participates in an international model comparison project for evaluations of the INDCs, MILES, which funded by European Commission, and evaluates the Japan's INDC with National Institute of Environmental Studies (NIES). Figure 2 also shows the cost estimate for the Japan's INDC by the AIM model developed by NIES, which is about 186 \$/tCO_2. While these estimates have a certain levels of uncertainty, they are considered to be comparable for major countries.

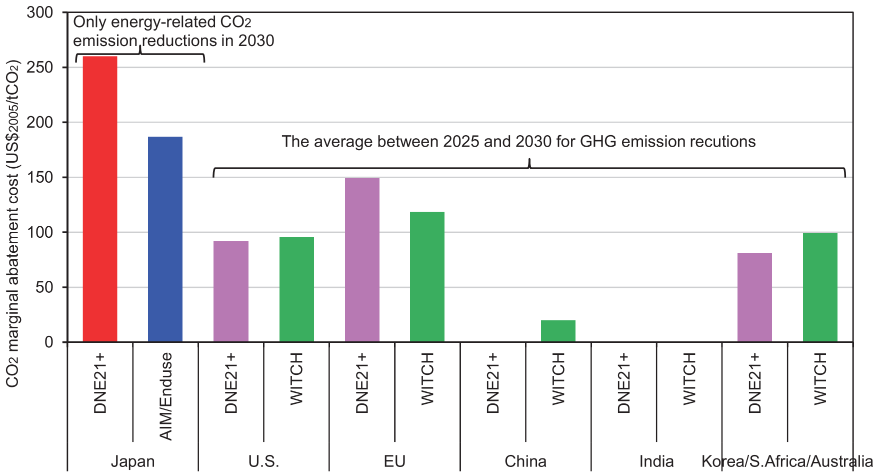


Figure 2 : Estimates of CO_2 marginal abatement costs of INDCs (Comparison between RITE DNE21+ and NIES AIM/Enduse and FEEM WITCH)

Many indicators of Switzerland, Japan and EU were evaluated to have high rankings and the INDCs to require large emission reduction efforts and to be ambitious. On the other hand, the INDCs of Turkey, Kazakhstan, China etc. were evaluated to be relatively inferior in terms of emission reduction effort. The U.S. was in the middle; however, this result should be interpreted with care because the U.S.'s target year is 2025 while many other nations' are 2030. The CO_2 marginal abatement costs of China, India etc. are almost zero and the INDCs of these nations can be realized only by following the Business as Usual (BAU), while the estimates depend slightly on the uncertainty ranges in GDP outlook.

These evaluations can provide the opportunities for all the countries considering the rooms of further emission reductions, and it is important that good PDCA (Plan-Do-Check-Act) cycles are established for effective emission reductions.

1.3 The relationship between the INDCs and the long-term goal

The Intergovernmental Panel on Climate Change (IPCC) published the Fifth Assessment Reports (AR5) between 2014 and 2015. There are still large uncertainties while scientific studies on climate change issues have improved. One of the typical uncertainties is climate sensitivity. The equilibrium climate sensitivity (the equilibrium temperature rise levels when atmospheric CO_2 concentration is double and stabilized) had been evaluated likely to be 1.5–4.5 °C and 2.5 °C as the best estimate since the Third Assessment Report (TAR) of IPCC. The climate sensitivity was evaluated likely to be 2.0–4.5 °C and 3.0 °C as the best estimate in the Fourth Assessment Report (AR4) published in 2007. However, according to the latest report of AR5, the climate sensitivity was evaluated likely to be 1.5–4.5 °C (there was no consensus on the best estimate), in which the lowest range was smaller than that of AR4 and the same as that before AR4. Although the change is only 0.5 °C, the impact on allowable global emission reductions for a certain level of temperature target is very large. Figure 3 shows the multiple GHG emission pathways for certain levels of temperature target such as +2 °C target with the assumptions of climate sensitivity not only of 3.0 °C but also of 2.5 °C. There are large gaps between global GHG emissions in 2030 expected by the submitted INDCs and the required emission pathways for +2 °C target with assumption of 3.0 °C of climate sensitivity. However, the expected emissions by the INDCs are almost consistent with the emission pathways for +2 °C target with assumption of 2.5 °C of climate sensitivity, although the achievability depends strongly on the realization of deep emission reductions in the latter half of the 21st century.

There are also larger uncertainties on global warming damages than climate sensitivity. In addition, there are large uncertainties in global warming mitigation costs. A better climate change response measures under such several kinds of large uncertainties are required in order to minimize the total risks. Systems Analysis Group also conducts such studies on climate change response strategies under uncertainties including these analyses on the impacts of uncertainties in climate sensitivity.

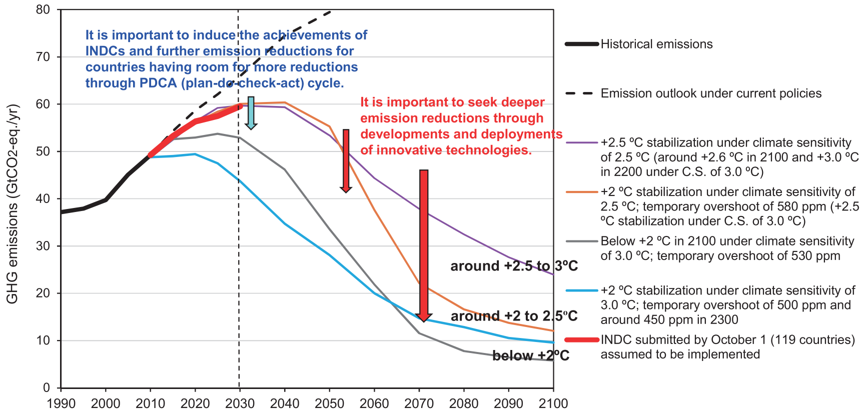


Figure 3 : Expected global GHG emissions of the aggregated INDCs submitted by October 1, 2015 and the GHG emission pathways corresponding to temperature change levels

2. Technology diffusion in developing countries: an analysis of coal power plant in India

2.1 Introduction

Technology diffusion of low-carbon technologies is one key measure for CO_2 emission reductions, and it is important to investigate concrete measures particularly for early CO_2 emission reductions. In this section, we focus on Indian coal power plants and indicate the CO_2 emission reduction potential of high-standard operation and maintenance (O&M) technologies.

2.2 Thermal efficiency of Indian coal power plant

Before we focus on CO_2 emission reduction potential, we investigate the current state of Indian coal power plants. The collected data covers 74 power stations (68.5 GW), which accounts for 83% of installed coal power capacity in India. Figure 4 shows net thermal efficiency by station[1) 2)]. The horizontal axis indicates the commission year of power station.

There are various types of power producers, such as national owned, state owned, and private owned stations. In Figure 4, NTPC is the largest (national owned) company in India, and NLC (national owned) operates brown coal power stations. Figure 4 reveals that recent stations have higher thermal efficiency compared to aged stations, and NTPC has more efficient power stations compared to other producers.

We also conducted a multiple linear regression analysis. The regression analysis indicates that (1) larger capacity of power stations have higher thermal efficiency, (2) newer stations have higher thermal efficiency, (3) higher capacity factor of power stations have higher thermal efficiency, and (4) NTPC and private owned stations are higher by 1.2% point compared to other stations[2)].

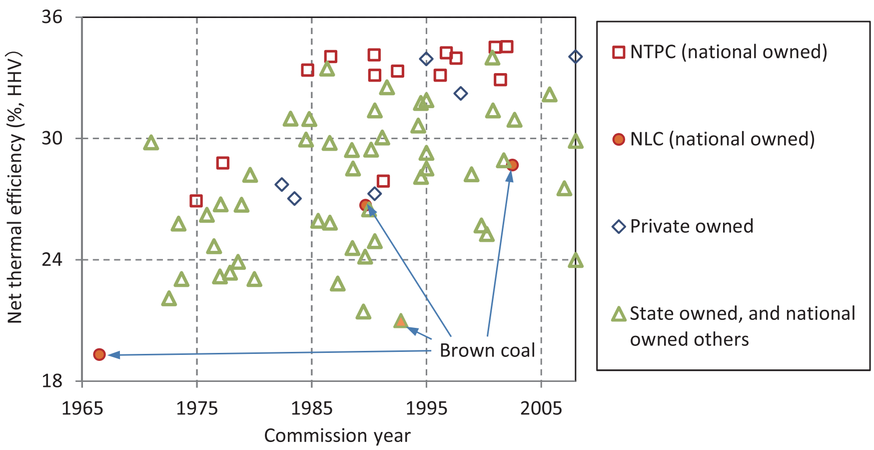


Figure 4 : Thermal efficiency of Indian coal power station during the period from FY2007–FY2009[1) 2)]

In order to improve the thermal efficiencies of existing coal power stations, diffusing high-standard operation and maintenance (O&M) technologies are important. Concrete measures can be (1) efficient soot blowers inside the boiler, (2) burning optimization (decreasing of unburnt combustible content, NOx reducing), (3) plant operation optimization (main steam temperature / pressure stabilization).

2.3 Particulate matter (PM) concentration of exhaust gas from Indian coal power plant

CO_2 emission reductions are basically a long-term global concern; however, PM reductions are receiving attention as a local need. high-standard operation and maintenance (O&M) technologies could have a synergy effect on PM reductions. We investigate PM concentration of exhaust gas from Indian coal power plant (Figure 5) [3]. The Air Act 1981 set the upper limit to 150 mg/Nm^3 for coal power plant with a capacity over 210 MW. Most stations comply with the standard value of PM concentration (less than 150 mg/Nm^3); however, some stations report PM concentration exceeding the limit.

High-standard O&M technologies could reduce the PM concentration from Indian coal power plant[2]. Japanese PM concentration reported is below 10 mg/Nm^3. Concrete measures can be electrostatic precipitator improvement (capacity expansion, operating time expansion, dust collection efficiency improvement through practical effort against high resistivity of fly ash).

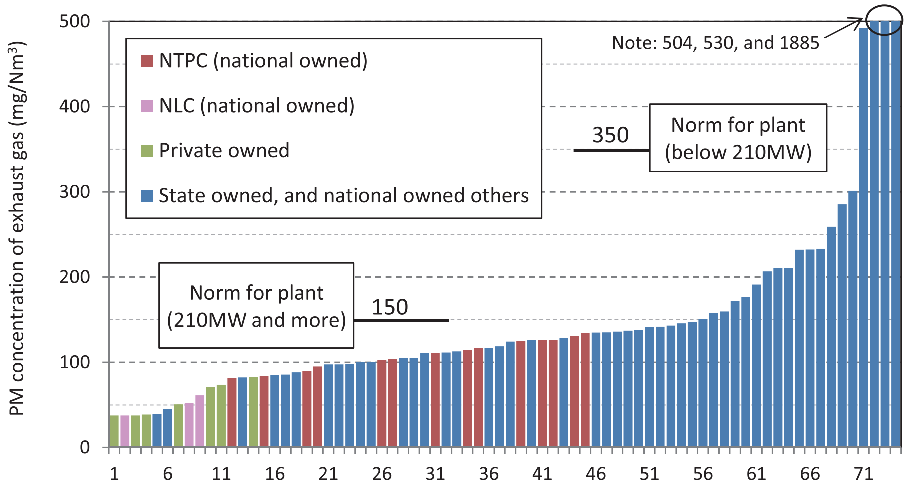


Figure 5 : PM concentration of exhaust gas from Indian coal power station during the period from FY2007–FY2009[2) 3)]

2.4 CO_2 emission reduction potentials from Indian coal power station

We assessed the improvement potential for thermal efficiency, capacity factor, PM concentration of exhaust gas, using a method named directional distance function that is used in environmental economics. This method explicitly considers the difference of given condition (commission year, capacity of power station) by station. The results indicate that net thermal efficiency could improve from 30.1% to 32.6%. This corresponds to a 36 million tCO_2/yr emission reduction, which accounts for 7.5% of the CO_2 emissions[2].

2.5 Summary

High-standard operation and maintenance (O&M) technologies could improve thermal efficiency of Indian coal power stations from 30.1% to 32.6%. This corresponds to a 36 million tCO_2/yr emission reduction. High-standard O&M technologies could also have synergies with PM emission reductions. In addition to new construction of state-of-the-art power plant, we conclude that high-standard O&M technology diffusion is of key importance.

References

1) Ministry of Power, Perform, Achieve and Trade (PAT), (2012)

2) J. Oda, K. Akimoto, M. Nagashima, Analysis of Coal Power Plant Performance by Station in India, 36(6), pp.17-26, (2015)

3) Central Electricity Authority, Ministry of Power, Performance Review of Thermal Power Station 2011-12, (2014)

3. Evaluations on hydrogen systems as one of the innovative technologies

3.1 Introduction

A drastic reform of Japan's energy policy is required in order to overcome the challenges the country has faced since the Great East Japan Earthquake and the Fukushima nuclear accident. As stated in Japan's energy strategic plan[1)], hydrogen is expected to be an important upcoming technology: "As for future secondary energy, hydrogen is expected to play the central role, as well as electricity and heat".

This section presents an assessment of hydrogen systems development under long-term CO_2 emission reduction scenarios by using the global energy systems model DNE21+ developed by the Systems Analysis Group.

3.2 Assumptions of hydrogen systems for model analysis

Regarding hydrogen production technologies, DNE21+ model considers coal gasification, natural gas reforming, biomass gasification, and water electrolysis in a bottom-up fashion (capital cost, energy efficiency, and lifetimes of technologies are modeled). Application of CCS (CO_2 capture and storage) is also considered for coal gasification, natural gas reforming, and biomass gasification. However, conventional byproduct hydrogen in the industrial sector (e.g., oil refinery, iron and steel sector) is not explicitly considered.

Pipeline and tanker with liquefied hydrogen are assumed as the two transportation technologies for hydrogen among regions (the world is divided into 54 regions in the DNE21+ model). For hydrogen distribution within the regions, several technologies (e.g., tank lorry, pipeline) are likely to be mixed according to distribution of hydrogen supply and demand, etc. However, in this analysis, since DNE21+ model does not consider the distribution of hydrogen supply and demand, such technology options mix for hydrogen distribution within regions are not explicitly evaluated.

Hydrogen power generation, hydrogen reduction ironmaking, and fuel cell vehicle are explicitly modeled as hydrogen-use technologies. In addition, the substitution options of hydrogen are considered for natural gas supply with top-down fashion (e.g., heat demand in commercial and industrial sector).

For fuel cell vehicle, two vehicle price cases are assumed as shown in Table 2. In the standard case, although fuel cell vehicle price decreases over time, it is still higher than that of battery electric vehicle even in 2050. In the advanced FCV case, the prices of fuel cell vehicle and battery electric vehicle are assumed to be the same in 2050. The assumed prices of fuel cell vehicle from previous studies[2)] are usually higher than that of battery electric vehicle in the standard case of this study. Therefore, the advanced FCV case is considered as the case expecting high technological progress for the fuel cell vehicle.

Table 2 : Assumed vehicle price and vehicle efficiency for small passenger cars (2020-2030-2050)

Technology	Vehicle price [Ten thousand JPY/vehicle]	Vehicle efficiency [km/L-gasoline eq.]
Internal combustion engine vehicle (Low Eff.)[*1]	170-170-170	13.0-13.5-14.1
Internal combustion engine vehicle (High Eff.)[*1]	200-200-200	23.8-24.8-25.8
Hybrid electric vehicle[*1]	227-224-203	33.7-38.2-42.2
Plug in hybrid electric vehicle[*1]	328-307-209	53.5-60.6-82.9
Battery electric vehicle	584-439-220	73.0-78.7-96.1
Fuel cell vehicle	Standard case: 862-602-233 Advanced FCV case: 585-430-220	44.6-50.5-61.7

*1 Assumptions for gasoline engine vehicle

3.3 Evaluations on hydrogen systems by using the DNE21+ model

DNE21+ model assesses CO_2 emission reduction measures until 2050 for several emission reduction levels. In the model evaluation, emission reduction is estimated for each region and sector by minimizing world total emission reduction costs. The above mentioned hydrogen-use technologies are cost-efficient emission reduction measures under 550 ppm CO_2eq levels (which corresponds to an estimated CO_2 marginal abatement cost of 150 \$/tCO_2 in 2050).

As hydrogen is mostly produced from fossil fuels (coal and natural gas) with CCS, regions with large potentials of fossil fuels and CO_2 storage, such as the Middle East, Russia, and the United States, are evaluated as important hydrogen producers.

Under 550 ppm CO_2eq levels, hydrogen power generation is cost-efficient in the countries without cost efficient potential in other competitive power generation technologies for CO_2 emission reduction (e.g., CCS for fossil-fueled power plant is difficult in countries with little CO_2 storage potential). The evaluated world total hydrogen power generation in 2050 is about 900 TWh/yr (Share in electricity generation: 2%) in ALPS-CP3.0 (+2 °C target is expected to be achieved in this scenario. The estimated CO_2 marginal abatement cost is 400 \$/tCO_2 in 2050).

Other available hydrogen-use technologies are not cost-efficient emission reduction measures under 550 ppm CO_2eq levels, but they are cost-efficient in ALPS-CP3.0. The estimated world total hydrogen consumption in 2050 is about

25 EJ/yr (share in final energy consumption: 5%). As shown in Figure 6, fuel cell vehicle is not cost-efficient in the standard case, because battery electric vehicle and plug-in hybrid electric vehicle have more favorable costs. However, fuel cell vehicle has advantages in the advanced FCV case, resulting in 100 million fuel cell vehicles being used worldwide.

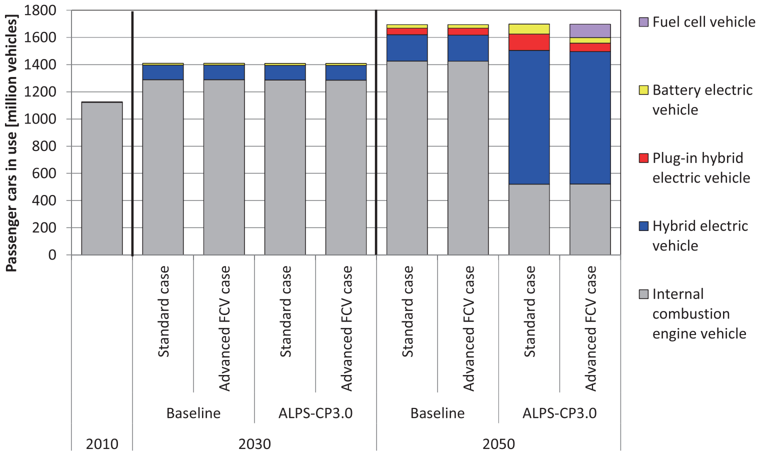


Figure 6 : Passenger cars in use by technology (world total)

3.4 Conclusion

Hydrogen systems are expected to play an important role to achieve deep CO_2 emission reduction. R&D on hydrogen systems and construction of hydrogen infrastructures from a longer-term perspective will be important for the diffusion of hydrogen system.

References

1) Agency for Natural Resources and Energy, “Japan’s Strategic Energy Plan”, (2014)

2) IEA, “Energy Technology Perspective 2012”, (2012)

Molecular Microbiology and Biotechnology Group

Masayuki Inui
Acting Group Leader

【Key members】

Akemi Sasaki,
Deputy Group Leader, Associate Chief Researcher
Ken-ichi Inatomi, Associate Chief Researcher
Haruhiko Teramoto, Associate Chief Researcher
Toru Jojima, Associate Chief Researcher
Kazumi Hiraga, Associate Chief Researcher
Takanobu Watanabe, Senior 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
Takahisa Kogure, Senior Researcher
Akira Watanabe, Senior Researcher
Hiroshi Kosugi, Senior Researcher
Takeshi Kubota, Researcher
Shinichi Oide, Researcher
Naoki Saruya, Researcher
Ryoma Hashimoto, Researcher
Junya Ishida, Researcher

Global Biorefinery Trends and Research Overview of the Molecular Microbiology and Biotechnology Group

1. Introduction

A major focus of our research is on development of technologies to produce biofuels and green chemicals from non-food biomass (Fig. 1). In this section, we provide an overview of global biofuel and green chemical production.

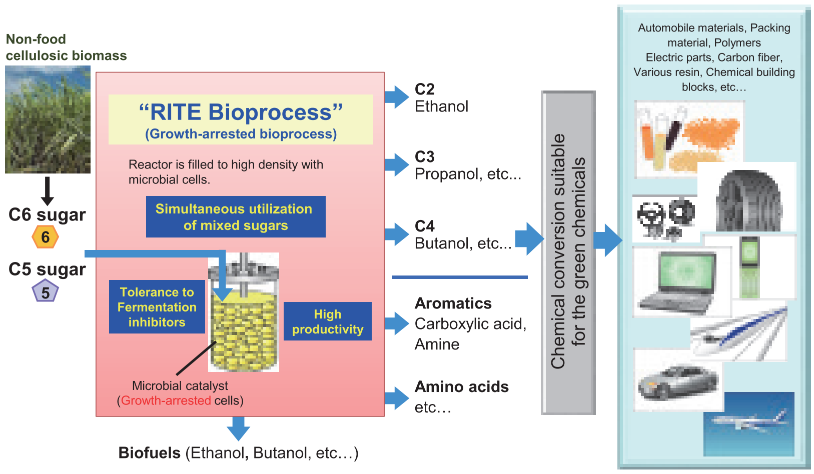


Fig. 1 : Concept of Biorefinery

Biofuels

Biofuels such as bioethanol and biodiesel are fuels produced from biomass through biological processes, and their global production and consumption have been increasing. In 2014, 24.6 billion gallons (94 million KL) of bioethanol and 7.9 billion gallons (30 million KL) of biodiesel were produced in the world. Over 80% of global bioethanol is produced in the U.S. and Brazil, while a large volume of biodiesel is consumed in Europe. As the negative impact of biofuels on food supply has been pointed out during the past several years, intense efforts are being made for development and commercialization of technologies to produce these biofuels from non-food biomass.

The U.S. Environmental Protection Agency (EPA) has been putting effort into promoting the use of biofuels, and set a target for the 2016 annual biofuel consumption of 18.1 billion gallons, of which the second generation biofuel cellulosic bioethanol accounts for 0.23 billion gallons. Cellulosic biofuels are produced from agricultural wastes such as corn stover, and their production does not affect food supply. They are more promising alternative for petroleum-based fuels than the food-based biofules, as they can reduce carbon dioxide emissions from agricultural waste burning as well as fuel consumption. In the U.S., Brazil, and Europe, large-scale commercial plants that produce over 100,000 KL cellulosic ethanol per year are in operation, and DuPont started running the world's largest commercial cellulosic ethanol plant in Iowa last November.

Green chemicals

Like the biofuel market, the market for green chemicals including biomaterials and biopolymers is expanding in the world. According to an estimate by a German private company, annual bioplastics production is expected to hit 17 million tons per year, more than triple the current production level, and account for 4% of the plastics produced in the world by 2020.

In addition to the conventional green chemicals such as poly lactic acid and poly amber, commercial use of bio-polyethylene terephthalate (Bio-PET) and bio-polyethylene (Bio-PE) is expanding. Bioplastics with improved physicochemical properties are also in use now. For examples, heat-resistant poly lactic acid is used to produce textile fibers and films, and high-impact polyamide with enhanced chemical resistance is used for automobile parts. The current status of bioplastic production from non-food biomass is similar to that of cellulosic ethanol production. Intense efforts are being made to develop technologies to mass-produce bioplastics from non-food biomass at a reasonable cost.

2. Feature of RITE Bioprocess (Growth-Arrested Bioprocess)

RITE has developed an efficient biomass utilization technology based on an inherent feature of *Corynebacterium glutamicum*, namely, it retains major metabolic pathways active while its growth is arrested under anaerobic conditions. "RITE Bioprocess", the growth-arrested bioprocess we developed has so far enabled cost-efficient production of biofuels and green chemicals, and we gained global recognition for our achievement.

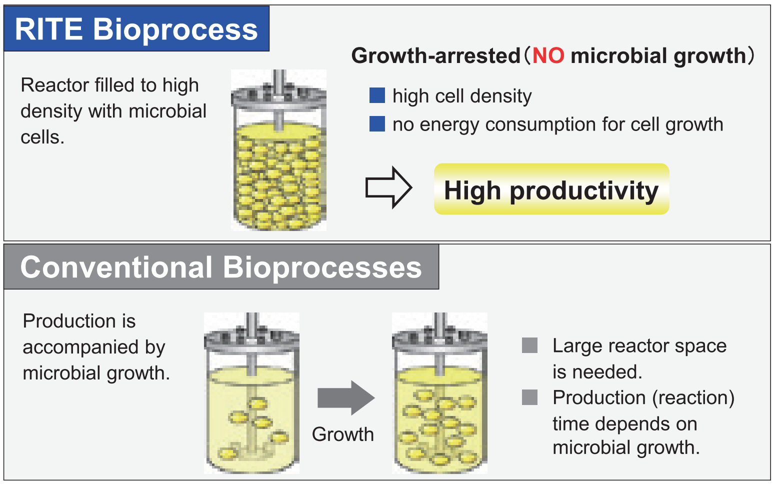


Fig. 2 : Features of RITE Bioprocess

In RITE Bioprocess, cells of a *C. glutamicum* strain engineered to have an optimal metabolic pathway for a particular target chemical are grown on a large scale, packed to very high densities in a reactor, and allowed to produce the target metabolite under anaerobic conditions (Fig. 2). The key of our process is the unique property of *C. glutamicum* mentioned above. Bioconversion of feedstocks to target products proceeds without microbial cell growth, achieving higher efficiency and productivity compared to conventional fermentative processes, in which formation of products and biomass inevitably occurs in parallel. Metabolic engineering enabled our microbial catalyst to utilize C6 & C5 sugars simultaneously, and we found that *C. glutamicum* is highly tolerant to fermentation inhibitors included in cellulosic hydrolysates such as furans, demonstrating that RITE Bioprocess is compatible with cellulosic non-food biomass (see RITE Today 2013-2014).

Through RITE Bioprocess, we have achieved production of ethanol, lactic acids, and various amino acids with remarkably high yields. We are currently applying the technology to microbial production of butanol, biojet fuels, and aromatic compounds like phenol. In the following sections, we describe recent progress in our research on biofuels and green chemicals production.

3. Development of biofuels production technologies

3.1 Biobutanol

Technologies to produce butanol from biomass, especially from non-food cellulosic biomass, have attracted growing attentions recently. Butanol is a more suitable for gasoline additive than ethanol due to its physicochemical properties (Table 1), and it can be a starting material for biojet fuel production via conventional chemical reactions. A downside of butanol is its strong cytotoxicity to microbial biocatalysts, and it is this cytotoxicity that hampers progress in development of cellulosic butanol production technologies.

Table 1 : Comparison of butanol with ethanol as a gasoline additive

	Ethanol	Butanol
Corrosion	High	Low
Water solubility	Fully miscible	Limited miscible
Blend vapor pressure	High	Low

Using a transgenic strain metabolically optimized for butanol production, biobutanol productivity comparable to the world's highest standards has been attained through RITE Bioprocess (see RITE today 2014-2015). In 2015, we launched a new research project on cellulosic butanol production, which is funded by Ministry of Economy, Trade and Industry (METI) (See Topics). One of the major goals of the project is to further improve cellulosic butanol productivity of our process by ameliorating the microbial biocatalyst with cutting-edge breeding technologies. The other goal is to establish a bioprocess to convert cellulosic hydrolysates derived from non-food biomass to butanol with economy and efficiency, collaborating with the U.S. National Renewable Energy Laboratory (NREL) expert at lignocellulose saccharification.

3.2 100% Green jet fuel

Petroleum-based jet fuels are mixtures of hydrocarbons, consisting mainly of cyclic and branched acyclic saturated hydrocarbons with 10-15 carbon atoms and aromatic compounds. All these hydrocarbons are necessary to possess physical properties favorable for aviation fuels such as low freezing and flash points. In contrast to the petroleum-based fuels, fuels produced from biomass lack aromatic compounds, and thus biojet fuels currently in use are a blend of petroleum-based fuels and biofuels, of which the latter constitutes at most 50% of the total. With funding from New Energy and Industrial Technology Development Organization (NEDO), we have been working on development of a technology to produce all different types of hydrocarbons required for jet fuels, including aromatic compounds, from biomass. The goal of the project is to establish a 100% biojet fuel production process (Table 2, and see Topics of RITE Today 2015).

Our strategy is to confer the ability to catalyze a reaction that has never been observed in microbes to our microbial workforce by functionally expressing organocatalysts in its cells. The microbe equipped with organocatalysts is able to generate an array of hydrocarbons, and it is possible to develop a 100% biojet fuel production process using this "hybrid" microbe. In contrast to the biofuels generated with the existing technologies, polymerization and isomerization of fermentative products are unnecessary for the biojet fuel produced through this bioprocess. Therefore, our process is superior to the other processes in terms of manufacturing cost (Table 2). We think that our strategy is applicable to production of diverse chemicals whose production through a bioprocess has never been achieved. We are currently putting effort into improving productivity of our process to speed up industrialization of this technology.

Table 2 : Comparison of various biojet fuels production technologies

	FT-SPK (FT-synthetic paraffinic kerosene)	Bio-SPK (Bio-synthetic paraffinic kerosene)	DSHC (Direct sugar to hydrocarbon)	ATJ (alcohol to jet)	RITE technology
Feedstock	Biomass (low cost / abundant)	Plant oil (High cost / limited supply	Sugar cane (Limited supply)	Biomass (low cost / abundant)	Lignocellulosic biomass (low cost / abundant)
Composition	Paraffins	Paraffins	Paraffins	Paraffins	Paraffins Aromatics
Polymerization	Required	NR	NR	Required	NR
Isomerization	Required	Required	NR	NR	NR
Hydrogen supply	Required	Required	Required	Required	NR
Blend limitation	50%	50%	10%	50%	Up to 100%

NR; not required

3.3 Biohydrogen

Hydrogen is considered as the ultimate clean energy because its combustion with oxygen generates only water. The existing hydrogen production technology, however, relies on fossil resources and emits CO_2 during the hydrogen production process, making hydrogen less attractive as an alternative for fossil fuels. Microbes can produce hydrogen without generating CO_2, and development of a bioprocess for hydrogen production has long been anticipated. Despite the intense efforts made by a number of research groups around the world, attempts to establish a cost-efficient biohydrogen production process are so far unsuccessful, due mainly to insufficient productivity.

In collaboration with SHARP Corporation, our group has developed a novel biohydrogen production process using a facultatively anaerobic bacterium *Escherichia coli*. In our process, a recombinant *E. coli* strain strongly expressing a hydrogen-producing enzyme complex is exploited as a whole cell catalyst, and bioconversion of formate to hydrogen proceeds in a reactor densely packed with the microbial catalyst (Fig. 3). The process is unique in the sense that hydrogen production proceeds independently of cell growth. Consequently, the volumetric hydrogen production rate (300L H_2/L·hr) achieved by this process is two orders of magnitude higher than that of conventional fermentation processes. Collaborating with NREL, we are starting a new research project, which is funded by METI, on development of a biohydrogen production process from non-food cellulosic biomass. In this project, we optimize the microbial catalyst for hydrogen production through genetic engineering, aiming at improvement in hydrogen productivity from non-food biomass (See Topics).

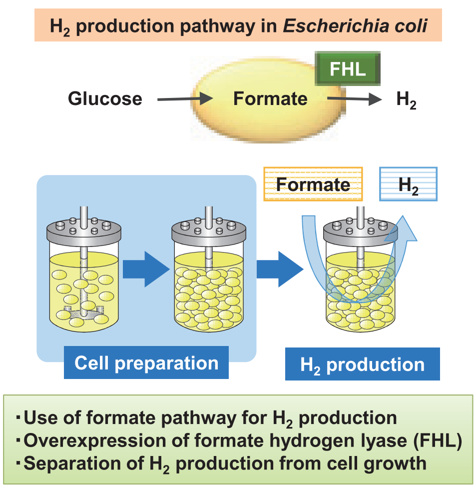


Fig. 3 : High-density microbial cell catalyst for high-speed production of H_2

4. Development of green chemicals production technology

4.1 Biomass-derived phenol

Phenol currently generated from fossil resources has been widely used as raw materials for phenol resins, polycarbonates, and so on. Replacing the petroleum-based phenol with that produced from renewable biomass can greatly reduce CO_2 emission. According to an estimate, it is possible to reduce 26 million metric tons of CO_2 emission in the world and 2.6 million metric tons of CO_2 emission in Japan in 2030 by producing 50% of phenol from biomass (Fig. 4).

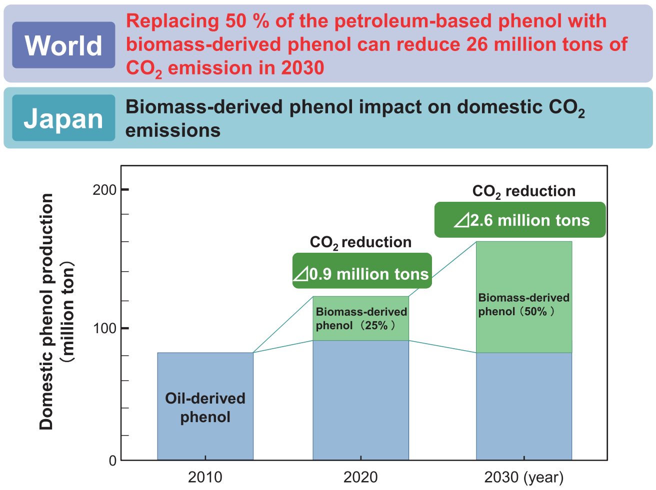
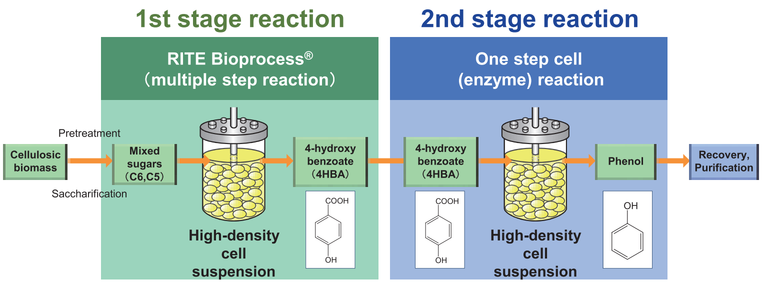


Fig. 4 : Impact of biomass-derived phenol on CO_2 emissions.

Due to its strong cytotoxicity, however, microbial production of phenol has been considered difficult. To overcome the hurdle, we developed a two-stage bioprocess for phenol production (Fig. 5). In the first stage, 4-hydroxybenzoate (4-HBA), a precursor of phenol, is generated through RITE Bioprocess. 4-HBA is subsequently converted to phenol by a single step reaction catalyzed by the microbial whole cell catalyst. Rationale of the strategy is our finding that 4-HBA is approximately 10-fold less toxic to our microbial workforce. Our process achieved higher phenol titers compared to the published data, demonstrating the advantage of the two-stage bioprocess over conventional fermentation processes. We propose that the strategy is applicable to production of other toxic chemicals of industrial importance.



IC_{50} ratio

	Growth inhibition	Inhibitory effect on growth-arrested bioprocess (RITE Bioprocess®)
Phenol	1	1／ 3
4-HBA	1／10	1／20

Fig. 5 : Phenol production by the two-stage bioprocess

4.2 Aromatic compounds

Aromatic compounds have been used as raw materials for a wide variety of products including pharmaceuticals, agrochemicals, cosmetics, flavors, flagrance, and fuels. In microbial cells, aromatic compounds are produced mainly through the shikimate pathway, and over 30 reactions are involved in their biosynthesis from glucose. This pathway complexity, along with their cytotoxicity, creates a hurdle for development of a cost-efficient bioprocess for aromatic compounds production.

Nevertheless, we succeeded in achieving high productivities of various aromatic compounds through RITE Bioprocess. Combining forefront genetic and metabolic engineering technologies, we are currently trying hard to ameliorate the microbial catalysts in order to further improve our bioprocess (see RITE Today 2015).

We have received recognition for our achievement from different private companies, and are planning to launch collaborative research projects with some of them, aiming at commercialization of our bioprocess.

5. Towards industrialization of our technologies

5.1 Cellulosic ethanol

"Simultaneous utilization of C6 and C5 mixed sugars" and "tolerance to fermentation inhibitors derived from lignocellulose" are the two major challenges for processing non-food biomass to target products. Under the laboratory condition, our ethanol- producing bioprocess succeeded in overcoming these challenges (Fig. 6), and we have started working towards industrialization of the technology. In 2011, we established a venture capital firm, Green Earth Institute Co., Ltd. (GEI) to commercialize the bioprocess for cellulosic ethanol production. Studies to scale up the bioprocess are in progress at GEI's research institute (Green Earth Research Center) in Kisarazu, Chiba prefecture. GEI is actively searching for partnership opportunities with domestic as well as foreign private companies, in order to expand its business internationally.

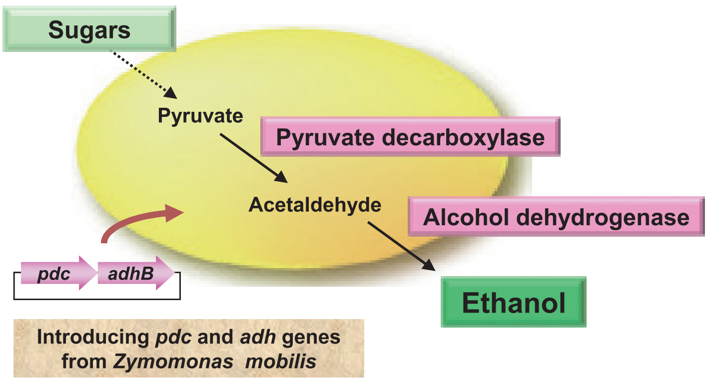


Fig. 6 : Metabolic engineering of *C. glutamicum* for ethanol production

5.2 Biomass-derived phenol

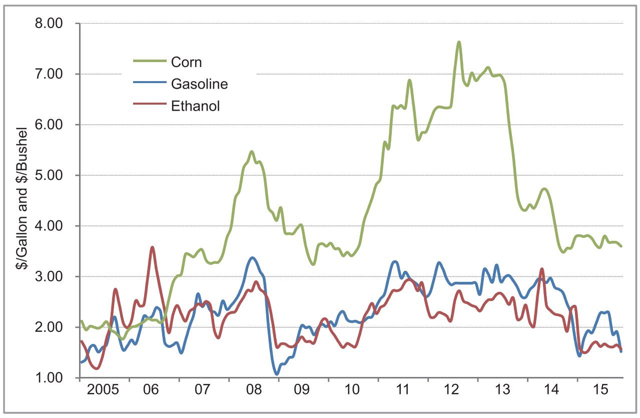
In 2014, Sumitomo Bakelite Co., Ltd. and RITE established Green Phenol Development Co., Ltd to accelerate industrialization of our biomass-derived phenol producing technology (see RITE Today 2015). We set up a target of starting commercial mass production of phenol by 2018.

With the financial supports from NEDO, we started scale-up studies of our bioprocess from 2014, and were able to demonstrate that the two-stage phenol production process is applicable to a 500-liter pilot plant scale (Fig. 7). The next hurdle is to integrate the phenol production process with concentration and purification processes at the pilot plant scale. To work on this, we started a new project funded by NEDO. The goal of the project is to establish a manufacturing process, through which pure phenol is produced from non-food biomass.

Fig. 7 : Pilot plant for biomass-derived phenol production

6. Closing remarks

Crude oil prices keep declining and hit $35 per barrel, the lowest price since 2008, in last December. Decline in oil prices is expected to continue, because of the end of the 40-year-old ban on U.S. crude oil exports. The bioethanol price also dropped last year due most likely to low oil prices (Fig. 8).



Source: USDA Economic Research Service (http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30041)

Fig. 8 : U.S. bioethanol price (2005-2015)

Nonetheless, the U.S. bioethanol production in 2015 was estimated to be 15 billion gallons equivalent to that of the preceding year, indicating the limited influence of crude oil prices on the biofuels market.

Our group continues to put effort into developing technologies to produce the next generation biofuels including cellulosic ethanol, butanol, hydrogen, and biojet fuels. We also move forward with industrialization of our technologies like the two-stage bioprocess for phenol production. Through our research activities, we would like to contribute to environmental protection and establishing an energy- and carbon-efficient society.

Chemical Research Group

Shin-ich Nakao
Group Leader

【Key members】

Yoshinobu Sato, Deputy Group Leader, Chief Researcher
Naotsugu Ito, Chief Researcher
Ryoichi Nishida, Chief Researcher
Takayuki Higashii, Chief Researcher
Katsunori Yogo, Associate Chief Researcher
Shigenobu Okajima, Senior Researcher
Teruhiko Kai, Senior Researcher
Tsuguhiro Kato, Senior Researcher
Kazuya Goto, Senior Researcher
Firoz Alam Chowdhury, Senior Researcher
Satoshi Mikami, Senior Researcher
Hidenao Yamada, Senior Researcher
Shin Yamamoto, Senior Researcher
Fuminori Ito, Researcher
Kouji Kida, Researcher
Shuhong Duan, Researcher
Ryohei Numaguchi, Researcher
Junpei Fujiki, Researcher
Emi Matsuyama, Researcher

Challenges in the Advanced Industrialization of CO_2 Capture Technologies and the Development of Inorganic Membranes and Membrane Reactors for H_2 Energy Production

1. Technologies for CO_2 capture and hydrogen energy

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

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

In this regard, we have developed chemical absorbents that allow CO_2 capture at an energy consumption rate of 2.0 GJ/t-CO_2 and from which the CO_2 may be released at temperatures below 100 °C. One such chemical absorbent with particular promise was selected for application in a commercial CO_2 capture plant owned by a private Japanese company that became operational in the fall of 2014.

Molecular gate membrane modules are also being developed to selectively capture CO_2 from H_2-containing pressurized gases, such as those generated in the integrated coal gasification combined cycle (IGCC), with a CO_2 capture cost target of 1500 JPY/t-CO_2.

We have developed dendrimer/polymer hybrid membranes that show excellent CO_2/H_2 separation performance. RITE, together with three private companies, has established a joint research association to develop these membranes along with membrane modules and separation systems for practical applications. Recently, we succeeded in achieving the project's targets under high-pressure conditions of 2.4 MPa using laboratory-scale membranes composed of modified materials. We plan to develop the membrane module system by examining the separation performance and robustness of the membrane modules in field tests.

Using our technologies, including the developed RITE-solvents, we are also investigating solid sorbents for CO_2 capture to efficiently reduce energy consumption. We are currently examining the synthesis of novel solid sorbents capable of achieving 1.5 GJ/t-CO_2 for regeneration energy. We have successfully developed a RITE-solvent-based solid sorbent that can be regenerated at low temperatures. Its evaluation for practical use is now underway in collaboration with a private company.

Recently, there has been a significant emphasis on the use of CO_2-free, hydrogen-based energy, generated by either renewable sources or fossil fuels combined with CCS. To realize this, it is necessary to develop efficient processes for the dehydrogenation of chemical hydrides such as methylcyclohexane or ammonia to allow for the ready storage and transportation of hydrogen. In response to this requirement, our group is developing silica and zeolite membranes for the processing of methylcyclohexane, as well as a palladium membrane for use with ammonia. Moreover, membrane reactors incorporating these membranes are also under development and steady gains are being made.

As noted above, our aim is to promote innovative CO_2 capture technologies as well as other new processes to reduce CO_2, thereby laying the foundations for next generation technologies while developing practical processes that are acceptable to industry.

2. Development of CO_2 capture technology using chemical absorption systems

CO_2 capture by chemical absorption is a prospective technology for CO_2 separation from CO_2-containing gas, in which CO_2 is absorbed in an amine-based solution and dissociated with thermal energy. Over the last decade, we have developed highly efficient CO_2 absorbents capable of reducing the energy consumption associated with CO_2 separation.

During the project ″COURSE 50, Step 1″, we achieved the target energy consumption rate for CO_2 capture of 2.0 GJ/t-CO_2 with a CO_2 regeneration process temperature of less than 100 °C (Figs. 1, 2). One of the developed absorbents with the highest performance was selected for application in a commercial plant owned by a private Japanese company, operational in the fall of 2014.

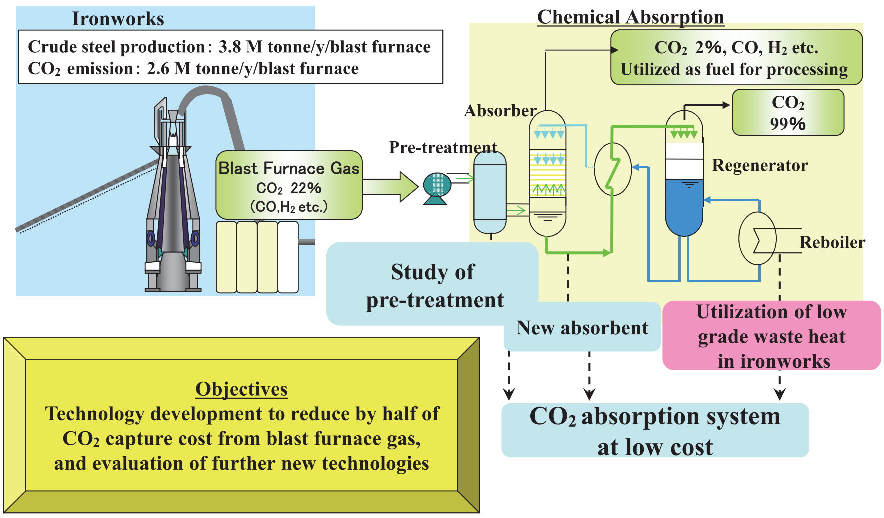


Fig. 1 : A cost-saving CO_2 capture system scheme

CAT: Chemical Absorption Test plant

Fig. 2 : Photographic images of a technology demonstration plant

We have been conducting the project "COURSE 50, Step 2" since 2013, in which higher performance chemical absorbents are being developed.

Additionally, we have advanced the development of chemical absorbents for CO_2-containing high-pressure gases with excellent CO_2 absorption and dissociation performances. The purpose of this study has been the development of highly efficient absorbents that enable CO_2 dissociation while maintaining the high CO_2 partial-pressure of the CO_2-containing gas, called "High-Pressure Regenerable Absorbents". With these novel absorbents, the energy consumption for the CO_2 compression process after the capture is significantly reduced owing to the high-pressure of the captured CO_2.

The novel solvents developed previously exhibit high CO_2 recovery and excellent CO_2 absorption and desorption rates with relatively low reaction-heat under the high-pressure conditions above 1 MPa (Fig. 3). The total energy consumption rate using this process for CO_2 separation and capture, including the energy required for compression, has been estimated to be less than 1.1 GJ/t-CO_2.

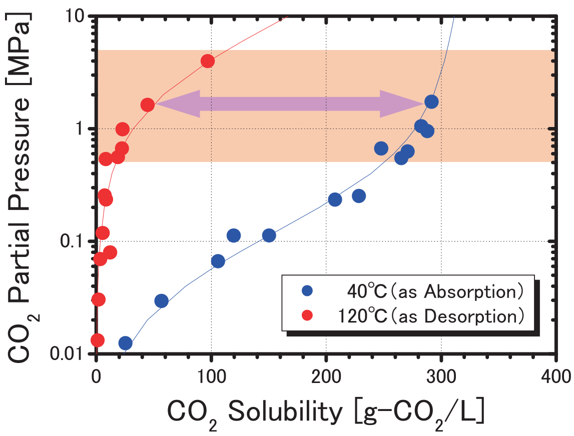


Fig. 3 : CO_2 pressure-solubility relationships of "High-Pressure Regenerable Absorbents"

3. CO_2 and H_2 separation using polymeric membranes

Under the project "Cool Earth 50," the government of Japan has announced its intention to reduce the country's CO_2 emissions to half of the current emission levels by 2050. One promising means of reducing CO_2 emissions is the development of a joint integrated coal gasification combined cycle (IGCC) with CO_2 capture by CO_2 selective membranes (Fig. 4). Our group is currently developing molecular gate membrane modules that effectively separate CO_2 during the IGCC process.

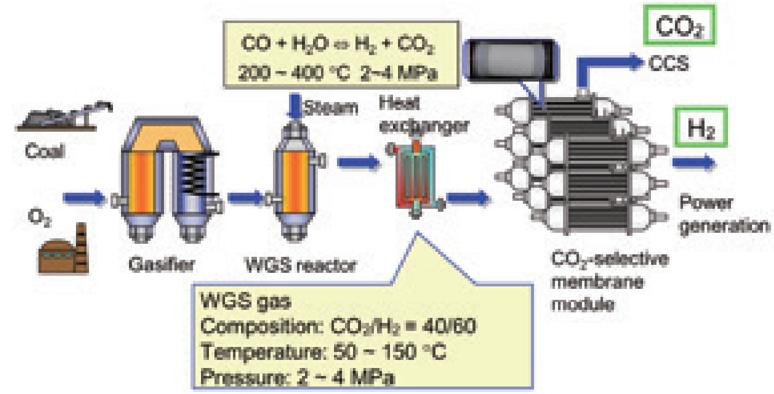


Fig. 4 : Schematic of the IGCC process with CO_2 capture by CO_2 selective membranes

Fig. 5 shows a schematic illustration of the working principles of a molecular gate membrane (dendrimer/polymer hybrid membrane). Unlike conventional CO_2 selective membranes, molecular gate membranes show exceptionally high CO_2 separation over H_2. In the molecular gate membrane, CO_2 reacts with amino groups to form either carbamate or bicarbonate, which acts as a gate to block the passage of H_2. Consequently, the amount of H_2 diffusing to the other side of the membrane is greatly reduced and high concentrations of CO_2 can be obtained.

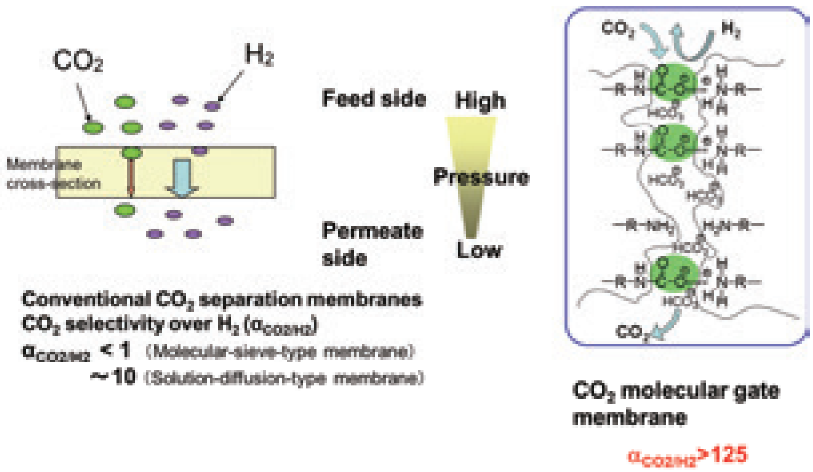


Fig. 5 : Schematic of conventional CO_2 separation membranes and CO_2 molecular gate membrane

Our group has developed new types of dendrimer/polymer hybrid membranes that show excellent CO_2/H_2 separation performance in the separation of CO_2/H_2 gas mixtures.

Based on these materials, RITE, Kuraray Co., Ltd., Nitto Denko Corporation and Nippon Steel & Sumikin Engineering Co., Ltd. have established the Molecular Gate Membrane module Technology Research Association for the purpose of researching new membranes, membrane modules and separation systems (Fig. 6). Recently, we succeeded in improving the separation performance of such membranes through the modification of poly(vinyl alcohol) (PVA)-based materials, and the target CO_2 separation performance was obtained under high-pressure conditions of 2.4 MPa using laboratory-scale membranes (Fig. 7). We plan to develop the membrane module system further by examining the separation performance and robustness of membrane modules in field tests.

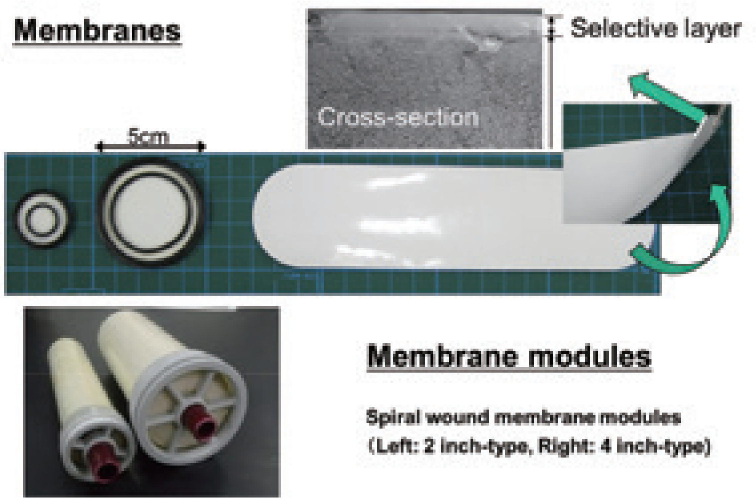


Fig. 6 : CO_2 molecular gate membranes and membrane modules

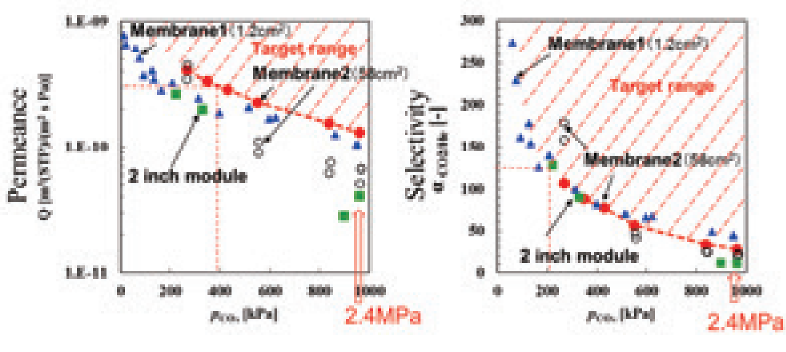


Fig. 7 : Separation performance of CO_2 molecular gate membranes
(Feed gas pressure: 0.1~2.4MPa)
(Membrane area: 1.2cm^2 (Membrane1), 58cm^2 (Membrane2))

The development of these CO_2 molecular gate membrane modules is being performed under a project recognized by the Carbon Sequestration

Leadership Forum (CSLF), a ministerial-level international climate change initiative focused on the development of improved, cost-effective technologies for the separation and capture of CO_2 for transport and long-term safe storage.

4. Advanced development of CO_2 capture by solid sorbents

Solid sorbents prepared from amines and porous supports exhibit similar CO_2 sorption characteristics to those of liquid amine solvents. Additionally, solid sorbents have the advantage of a lower expected heat duty for regeneration processes. The relationship between amine structures and their CO_2 desorption performances was explored by computational chemistry. Our findings led to the fabrication of a more efficient solid sorbent in terms of desorption performance and sorption capacity (Fig. 8). RITE conducted simulation studies to accurately estimate the energy and cost of CO_2 capture from coal-fired power plants. The CO_2 capture process was modeled based on amine–CO_2 chemical reactions. The energy efficiency of a power plant with a CO_2 capture system was estimated to improve by about 2% when a solid sorbent was used instead of an advanced liquid amine solvent.

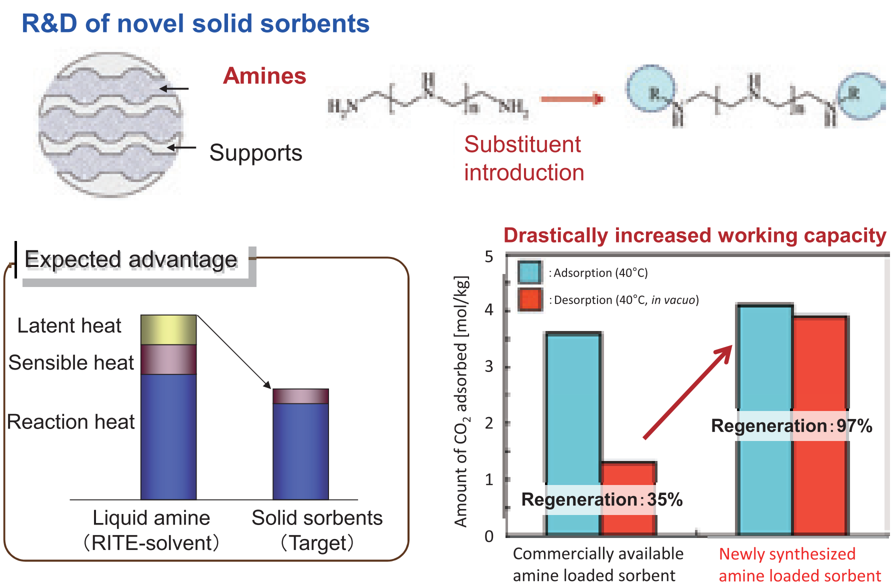


Fig. 8 : RITE solid sorbents

Currently, we are evaluating the solid sorbent process using a lab-scale adsorption/regeneration test apparatus. We have found that the steam desorption process (SA-VSA: Steam-aided vacuum swing adsorption) is suitable for CO_2 recovery using the RITE sorbent. The RITE sorbent recovered CO_2 with high purity (98%) and high recovery yield (93%) from a simulated flue gas. To date, the regeneration energy of the RITE solid sorbent has been estimated to be 1.5 GJ/t-CO_2, as shown in Fig. 9.

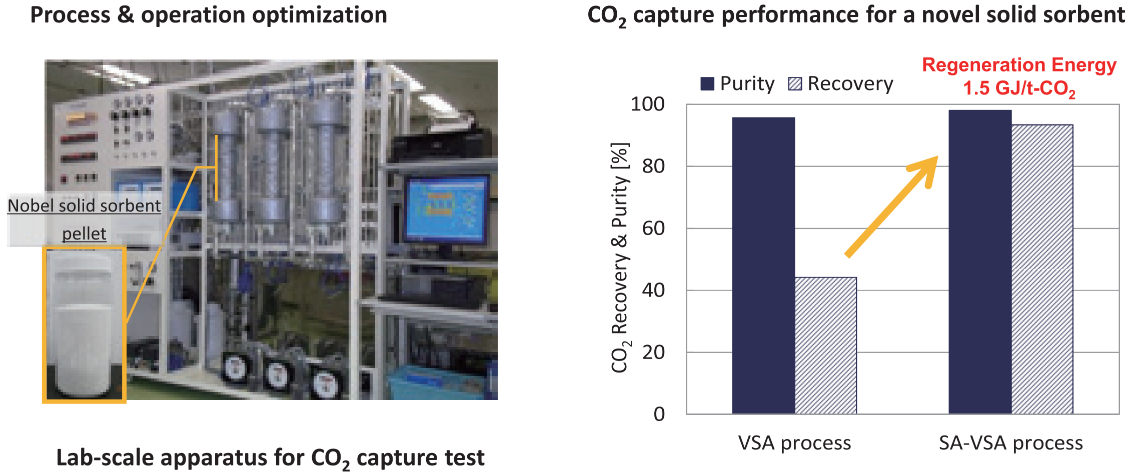


Fig. 9 : CO_2 capture process using RITE sorbent

Based on these findings, examination of the practical use of the RITE-developed solid sorbent is underway. Since last year, RITE has conducted a project (phase II) with a private company funded by the Ministry of Economy, Trade and Industry (METI). The research objective is to develop of a novel solid sorbent system that is applicable to CO_2 capture from coal-fired power plants. The R&D road map of solid sorbent systems is shown in Fig. 10. Material optimization, process evaluation and a large scale CO_2 capture testing is planned to be carried out until 2020.

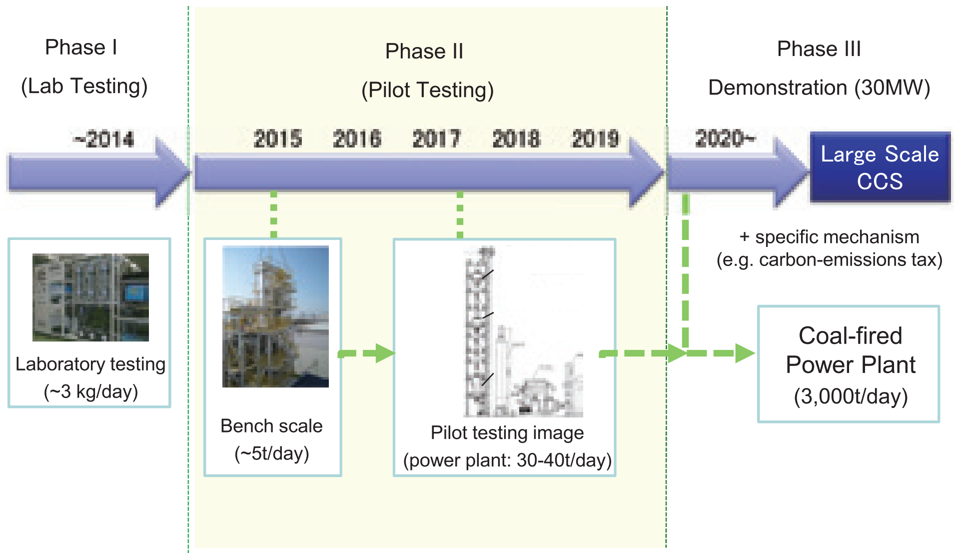


Fig. 10 : R&D Road map of solid sorbent system

5. Development of inorganic membranes for H_2 energy production

It is necessary to develop efficient means of dehydrogenating chemical hydrides such as methylcyclohexane or ammonia to establish new energy systems based on CO_2-free hydrogen. This topic was extensively addressed during the 4th Strategic Energy Plan endorsed by the Japanese Cabinet in April 2014.

In 2013, our group began a project funded by NEDO. In this work, RITE has been collaborating with the Chiyoda Corporation to develop membrane reactors for compact, lower-temperature H_2 generation systems using methylcyclohexane prepared using a counter-diffusion chemical vapor deposition (CVD) apparatus. The goal of this project is to fabricate a hydrogen generator with decentralized power for small-to-medium sized customers such as commercial establishments and office buildings. Thus, our group is developing single-type membrane reactors and modular hydrogen generators for the dehydration of methylcyclohexane.

At first, we confirmed that we can use an outer-catalyst type membrane reactor (Fig. 11) without any protecting membrane, which efficiently supplies enough heat to the catalyst. In dehydrogenation experiments using such single-type membrane reactors, it was confirmed that the membrane reactor can be operated at a reaction temperature lower than those of conventional dehydration reactions with post-separation (Fig. 12). A longer catalyst life and reduction in reaction impurities are therefore expected.

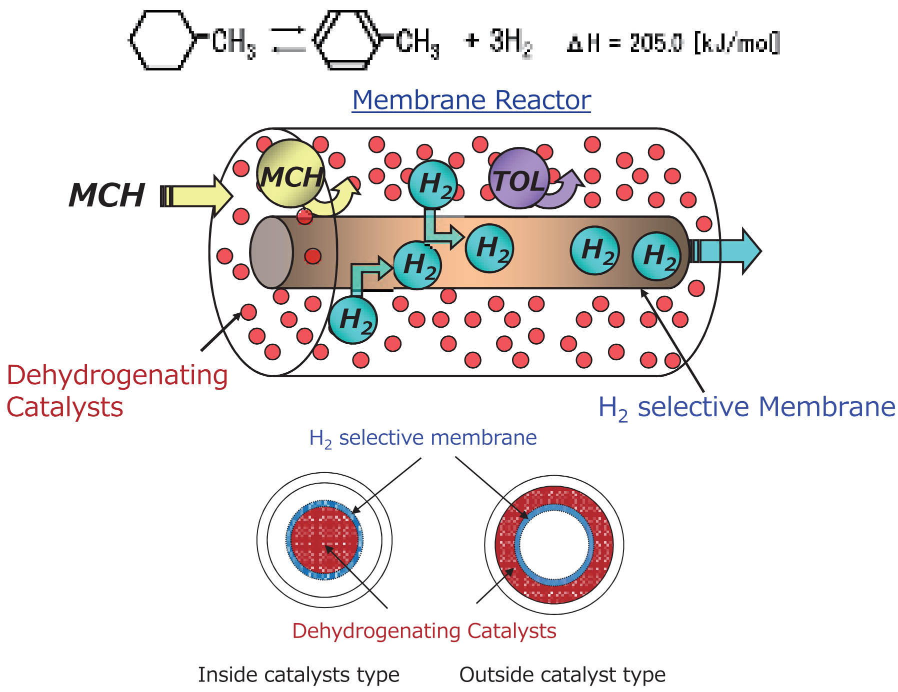


Fig. 11 : Membrane reactor for dehydrogenating MCH

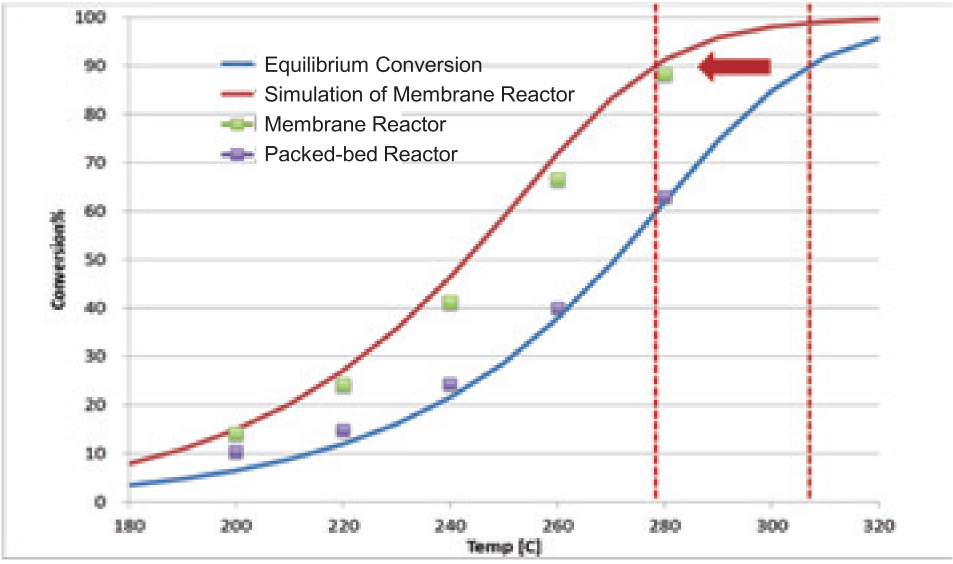


Fig. 12 : Experimental and simulated results of dehydrogenating reaction of MCH with a packed-bed reactor and a membrane reactor

We also developed a bench-scale dehydrogenating apparatus consisting of seven membrane reactors with silica membrane, the first in the world (Fig 13). We started operating tests of this apparatus for gathering engineering data from November 2015.

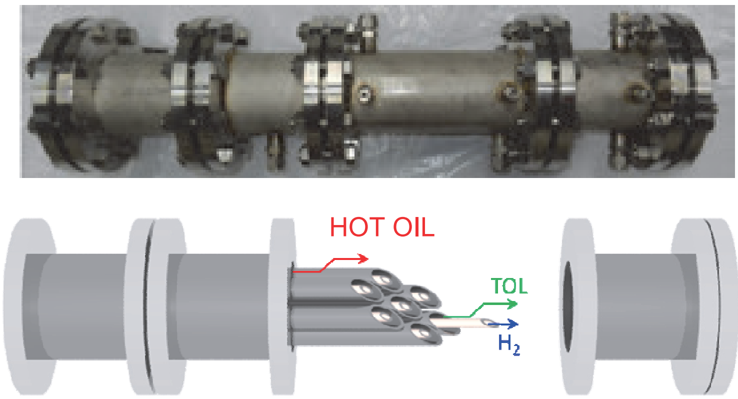


Fig. 13 : Dehydrogenating reactor consists of Seven membrane reactors

Pd membranes are also under research and development for the dehydrogenation of ammonia or steam reforming of natural gas. Our membranes, pore-fill type Pd membranes (Fig. 14), are anticipated to greatly improve the durability of the associated generation devices and reduce their cost, both of which are presently serious challenges for Pd membranes. We have already confirmed that our Pd membranes have excellent hydrogen separation performance and good durability. Additionally, we can expect cost reduction because the amount of Pd used in our membrane is about one third of that used in other membranes.

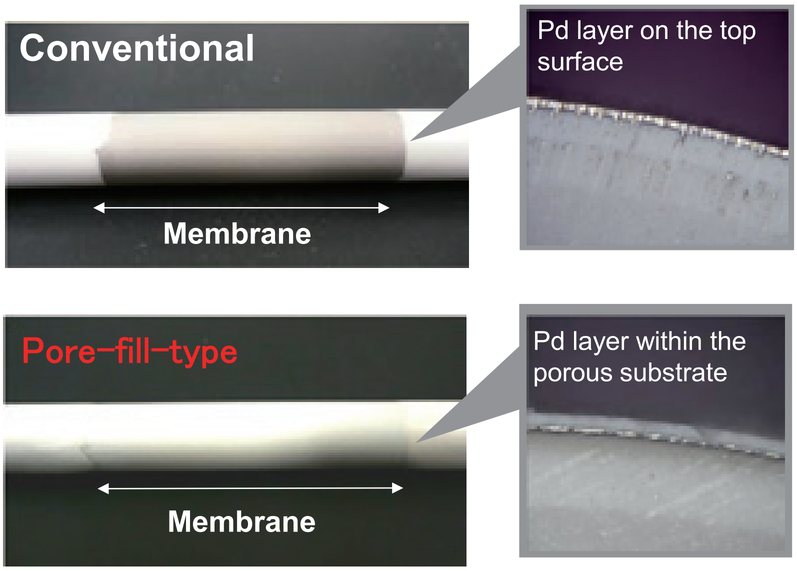


Fig. 14 : Pore-fill-type Pd membrane

Finally, in the COURSE 50 Step 2 project, CVD-based silica membranes have been developed as membrane reactors that employ the water gas shift reaction and H_2 separation to allow H_2 generation from blast furnace gases. We succeeded in developing innovative silica membranes having both excellent hydrogen separation performance and durability against water.

CO_2 Storage Research Group

Kenji Yamaji
Group Leader

【Key members】

Satoru Yamasaki, Deputy Group Leader, Chief Researcher
Makoto Nomura, Chief Researcher
Ziqiu Xue, Chief Researcher
Nobuo Takasu, Associate Chief Researcher
Masaki Tajima, Associate Chief Researcher
Jun Kita, Senior Researcher
Takahiro Nakajima, Senior Researcher
Ryozo Tanaka, Senior Researcher
Keisuke Uchimoto, Senior Researcher
Michimasa Magi, Senior Researcher
Saeko Mito, Senior Researcher
Tetsuma Toshioka, Senior Researcher
Tsutomu Hashimoto, Senior Researcher
Osamu Nishizawa, Senior Researcher
Tamotsu Kiyama, Senior Researcher
Atsushi Ibusuki, Senior Researcher
Hironobu Komaki, Senior Researcher
Makoto Nishimura, Senior Researcher
Osamu Takano, Senior Researcher
Hironori Izumi, Senior Researcher
Yasuhiro Okabayashi, Senior Researcher
Yi Zhang, Researcher
Kazuhiko Nakano, Researcher
Hyuck Park, Researcher
Takuma Ito, Researcher
Takamichi Nakamura, Researcher
Lanlan Jiang, Researcher
Makiko Takagishi, Research Assistant
Kaoru Kanamori, Pranning Manager

Installing and Utilizing CO_2 Geological Storage Technologies on Site

1. Overview

Reducing the emissions of carbon dioxide (CO_2), a dominant component of greenhouse gases (GHG), is an imminent issue to be addressed. Carbon capture and storage (CCS) is a series of technologies for separating and capturing CO_2 emitted from a large-scale emission source, such as a thermal power station and a steel mill, and storing the captured CO_2 geologically. CCS is considered as one of the effective CO_2 mitigation options, together with conversion efficiency improvement, fuels switching and renewables expansion.

According to the 5th Assessment Report compiled by the Intergovernmental Panel on Climate Change (IPCC) in 2014, scenarios where CO_2 concentrations in 2100 are set at a level of 430-480 ppm (so-called 2 degree scenarios) are characterized by near zero annual emissions in 2100 and near zero emissions in the power sector in 2050. In these analyses, CCS is positioned as an important mitigation option.

In this context, Japan launched a large-scale CCS demonstration project in Tomakomai, Hokkaido. Currently, Japan CCS Company advances drilling works and other preparations. The demonstration project will be operational in the fiscal year of 2016 – more than 100 thousand tonnes of CO_2 will be captured from a hydrogen plant in a refinery annually, injected into two geological formations (Moebetsu formation at a depth of 1,100 to 1,200 meters and Takinoue formation at a depth of 2,400 to 3,000 meters), and then monitored for watching its behavior.

RITE carries out a program of research and development on a wide range of safety assessment technologies for CO_2 geological storage, collaboration with international organizations and a global CCS development survey. These activities, interconnecting with the Tomakomai demonstration project, are aimed at commercializing safety assessment technologies for CO_2 geological storage and improving public confidence in CCS.

2. Research and Development of CO_2 geological storage

There are a number of types in CO_2 underground injections: injection into oil fields to enhance oil recovery (EOR); injection into coal seams to enhance methane recovery (ECBM); injection in depleted gas fields to sequestrate CO_2; and injection in deep saline aquifers to store CO_2. The deep saline aquifer CO_2 storage site has, as shown in Fig. 1, an impermeable caprock formation (a mudstone layer) with high sealing properties above the aquifer (a sandstone layer). Thus, once injected, CO_2 can be stably and safely stored for a long period of time.

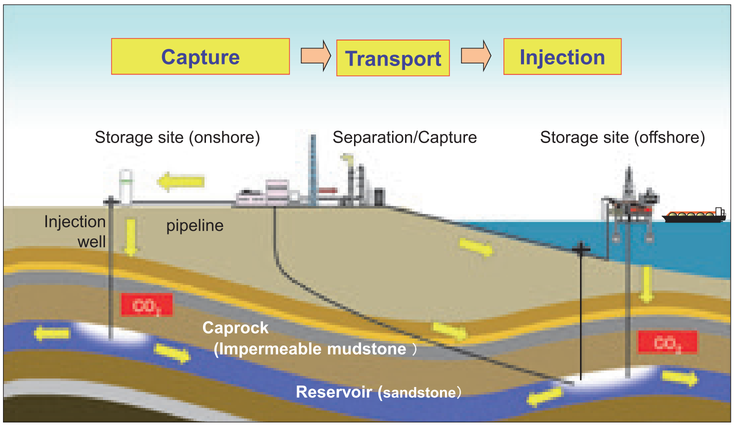


Fig. 1 : Concept of CO_2 geological storage

A framework of RITE's research works on CO_2 geological storage is shown in Fig. 2: evaluating storage performance (building geological models), analyzing CO_2 behavior in a reservoir (monitoring and numerical simulation of CO_2 behavior), and analyzing CO_2 migration from a reservoir (numerical simulation of CO_2 migration and developing methods for offshore environmental impact assessment). Furthermore, RITE is compiling best practice manuals based on our works and lessons we have learned from the projects in and out of Japan.

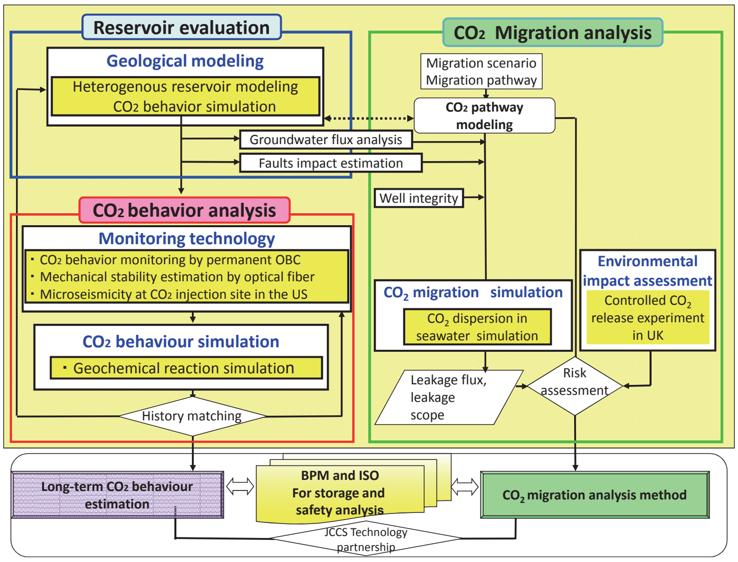


Fig. 2 : R&D on CO_2 geological storage technologies

2.1 Development of techniques of evaluating storage performance

RITE is developing methodologies of evaluating storage performance under two programs: “development of a geological modelling methodology” and “development of a groundwater flow analysis methodology”.

The Analysis of the behavior of CO_2 injected in a reservoir requires a highly-reliable geologic modelling that takes heterogeneity into account. On the other hand, not so many geological data such as those from boring core samples and physical logging are available because in CO_2 geological storage projects have a limited number of exploration wells from the viewpoint of avoiding leaks of stored CO_2 as much as possible. To make the best use of data acquired under such restriction, it is required to develop a methodology to integrate various data from boring cores, physical logging and 3D seismic surveys for geological modelling. RITE conducted reservoir characterization of the Nagaoka storage site, as a case study, and clarified its depositional environment. Building on this analysis, we are developing a highly reliable modelling methodology by integrating geological data, including porosity and permeability obtained from physical well logging and core samples, and 3D seismic data through the GDI (Geology Driven Integration) approach. We are also studying an optimal layout of multiple wells and an optimal combination of well functions for future CO_2 injection in a larger reservoir.

In the development of a methodology of groundwater flow analysis, we assess the impacts of CO_2 injection on regional groundwater flow in the case of storing CO_2 in a coastal area. The analysis of this kind requires us to develop a hydrogeological model that covers both the land and the sea by combining onshore and offshore geological data. In such a way, RITE has been building a model suitable for the Tomakomai demonstration site. It is critical in the precise evaluation of groundwater flow to utilize not only data in literatures but also hydrological data such as porosities and permeability acquired by taking and analyzing core samples at the storage site and to understand the state of groundwater before CO_2 injection.

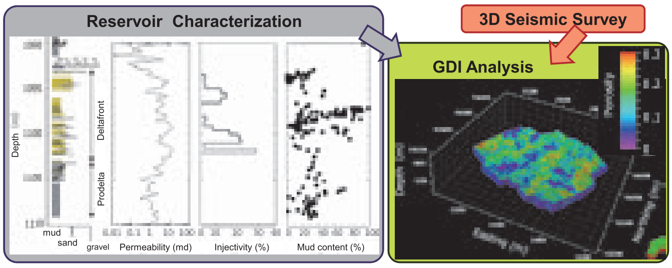


Fig. 3 : An example of porosity distribution by an analysis of integrating geological data and 3D seismic data

2.2 Analysis of CO_2 behavior in reservoir

For wider deployment of CO_2 geological storage, it is important to monitor CO_2 injected in a deep reservoir and demonstrate that the CO_2 is retained stably there. For this purpose, RITE is comprehensively analyzing data acquired at the Nagaoka site, including time-lapse physical logging data, to clarify the mechanisms of storing CO_2 and to improve techniques to simulate long-term CO_2 behavior. In addition, RITE is actively developing other technologies for the safety of CO_2 geological storage, including a methodology to assess micro-seismicity induced by CO_2 injection and fiber-optic sensing for monitoring the deformation of geological formations.

— Development of a methodology of evaluating microseismicity induced by CO_2 injection

RITE, in co-operation with the US Lawrence Berkeley National Laboratory, conducted monitoring of microseismicity induced by CO_2 injection with an observation system installed in shallow boreholes at a CO_2 injection site in the USA by FY2014. We analyzed the relation between observed microseismicity and CO_2 injection by examining monitoring data acquired so far. We also worked on a basic design of a Traffic Light System (TLS) for CO_2 injection management, based on microseismicity monitoring.

— Development of a technology to monitor the stability of geological formations during CO_2 injection

To evaluate the stability of geological formations during CO_2 injection, it is desired to monitor not only the deformation of the reservoir and caprock in details but also the deformation of all other layers from the reservoir to the surface. There is a commercialized technology for continuous measurement from the surface to subsurface in the oil and gas development sector – a technology to measure temperature along a depth direction with an optic fiber (DTS: Distributed Temperature Sensing). Building on the optic fiber sensing technology, RITE has been developing a technology to measure the deformation (strain) of formations continuously in a depth direction.

In FY2012 and FY2013, RITE conducted a pilot test where we installed optic fibers at the outside of the casing of a 300-meter-deep well. With the optic fibers, we successfully measured gradual deformation of formations in the injection zone in response to CO_2 injection and changes in strain of the casing due to a step-by-step release of a well packer (Fig. 4). In FY2014, we conducted various tests with an 880-meter-deep well, establishing a way of installing optic fibers in a deep well and confirming that the way of installation realized negligible signal loss even for long-length fibers. In FY2015, we carried out other various tests, including a monitoring of the deformation of formations due to water pumping at near wells (Fig. 5), detection of leak in formations and sonic survey with DAS (Distributed Acoustic Sensing). These tests were aimed at investigating the stability of the measurement system during long-term monitoring, on-site capability of strain measurement and optic fiber measurement of other than the deformation of formations.

Its future commercialization requires optic fiber cables to have a higher strength and a higher sensitivity in order to make it installable in deep wells. RITE has been developing and improving this kind of ground burial optic fiber cables.

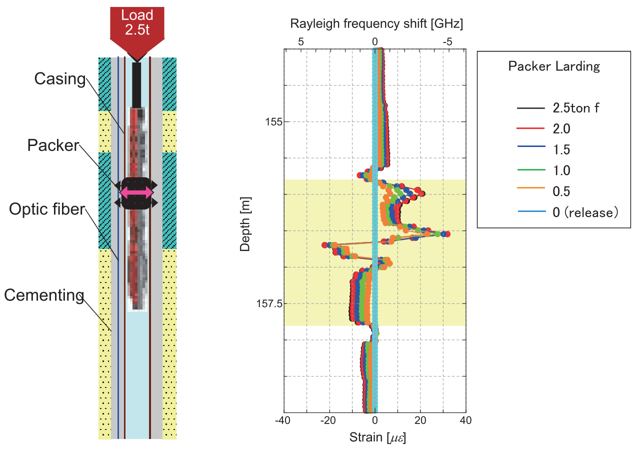


Fig. 4 : On-site Rayleigh measurement sensitivity

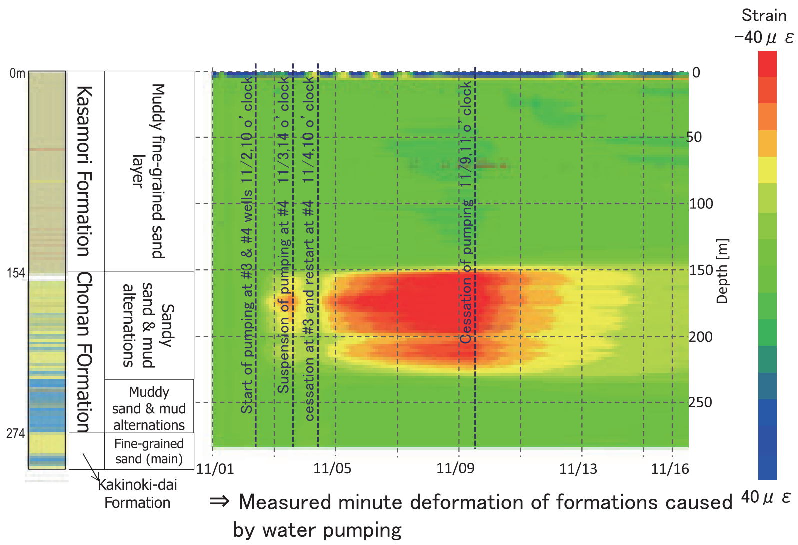


Fig. 5 : Deformation of formations caused by a water-pumping test on 2 to 9 November

— Analysis of CO_2 behavior with an X-ray CT scanner and up-scaling

To evaluate long-term integrity of CO_2 injected in a deep reservoir, it is essential to reveal the mechanisms of replacement between CO_2 and formation brine in the reservoir rock. Affected by its depositional environment,

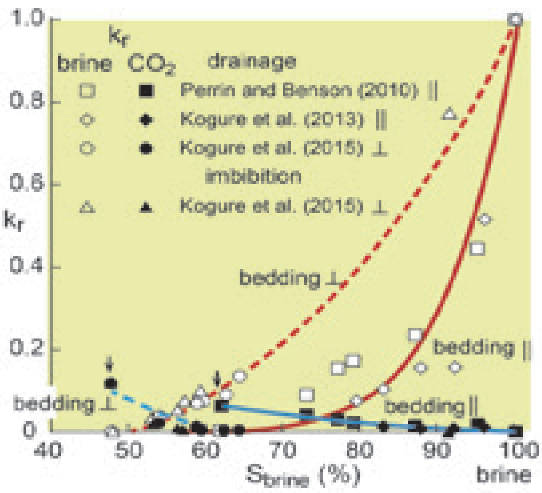


Fig. 6 : Relative permeability of CO_2 and brine in parallel and perpendicular directions with subtle heterogeneity orientation

the characteristics of pore space such as size and continuity have variation. By analyzing a heterogeneous core sample with an X-ray CT scanner from the viewpoint of relation between CO_2 distribution and permeability of each of brine and CO_2, it was clarified that the relative direction of CO_2 flow against the heterogeneity orientation is largely influential in permeability and also that CO_2 flow pattern is dependent on flow rate (Fig. 6). CO_2 horizontal flow and vertical migration are dominated by minute heterogeneity and the finding will contribute to clarification of flow mechanism in scaling-up.

— CO_2 behavior at Nagaoka site

RITE conducted a CO_2 injection test in Nagaoka, Niigata from July 2003 to January 2005, injecting 10,400 tonnes of CO_2 into a saline aquifer at a depth of 1,100 meters. Building on the injection project, RITE has developed methodologies for monitoring the status of CO_2 underground and a simulator for predicting CO_2 behavior in a reservoir. There have been a number of overseas storage projects but it is only the Nagaoka site where the behavior of CO_2 has been monitored in detail for more than 10 years continuously after its injection cessation. Outcomes from the monitoring, therefore, attract close attention in the world.

In the development of methodologies for monitoring CO_2 behavior, we repeatedly carried out physical loggings, formation water sampling, and cross-well seismic tomography and evaluated CO_2 distribution and its state – whether to be in a supercritical phase or be dissolved in formation water. In FY 2015, RITE conducted neutron, sonic, and induction loggings again and made sure that CO_2 has been stored safely by verifying that CO_2 has stayed nearly at the same place after injection. We also made certain that CO_2 dissolution into formation water has been in progress, shifting to safer trapping.

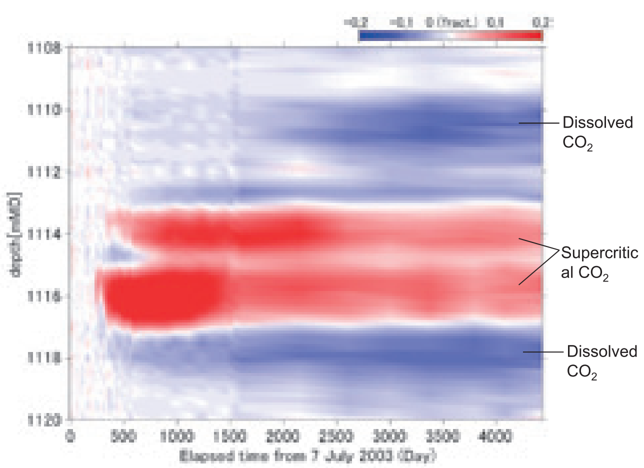


Fig. 7 : CO_2 behavior monitoring with resistivity logging at the Nagaoka site

In the development of CO_2 behavior simulator, we have verified it precisely with monitoring data acquired at the Nagaoka site. We updated the geological model through history matching with observation data and then executed a long-term prediction in 1,000 years with the highly reliable geological model. As a result, it was confirmed that the injected CO_2 will stay within a limited area of the reservoir, not migrating so farther.

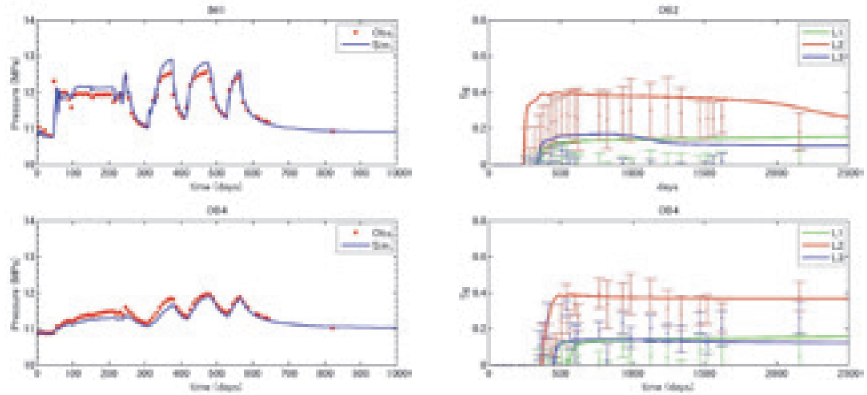


Fig. 8 : Comparisons between the monitoring and the CO_2 behavior simulation results. (Left: Bottom hole Pressure, Right: CO_2 saturation)

2.3 Analysis of CO_2 migration from reservoir

In the case of storing CO_2 in a sub-seabed reservoir, it is required to monitor the CO_2 not seeping from the reservoir to the sea from the viewpoint of marine environment protection. As a CO_2 seepage detection if CO_2 is seeped, we propose a methodology of monitoring CO_2 dissolved in seawater: to measure a carbonate system in seawater (e.g. pH, total carbonic acid and total alkalinity) and then to compare them with background data. Analyzing publically available long-term observational data in the Osaka Bay as a case study, RITE demonstrated that anomalous values caused by seepage are detectable by measuring the carbonate system together with dissolved oxygen. As a next step, RITE measured a carbonate system (CO_2 partial pressure) and amount of insolation continuously in an actual sea to grasp natural fluctuation in a carbonate system and then examined whether anomalous values are extracted from the natural fluctuation. The analysis implied that a carbonate system in a coastal area can be varied significantly due to several factors, including photosynthesis and microorganisms' activities such as respiration and degradation but that the measurement of the variation of dissolved oxygen can make it possible to recognize a range of natural fluctuation in a carbonate system and to detect anomalous values with a high accuracy.

CO_2 seeped as gas bubbles can be monitored effectively with acoustic equipment because they reflect and scatter sonic wave in seawater. We examined the capability of side-scan sonars through trial detection of gas blowout at an offshore natural site and of controlled release bubbles. These tests led us to a conclusion that the side scanner can detect relatively small amounts of bubbles and quantify the volume of seepage.

RITE is developing computational models for simulations to understand in which area CO_2 seeped into seawater is spread at what concentration. Since CO_2 is considered to seep from the seabed as bubbles, we are working on incorporating in our ocean model a process where CO_2 bubbles is dissolved as moving upward in seawater. CO_2 dissolved in seawater is spread by seawater flow, which is generated by wind blowing directly above around the area and possibly other factors, in particular, wind blowing above distant water. We are therefore attempting to enable more accurate simulations to be performed by integrating a wide area model capable of simulating at a scale of hundreds km and a high-resolution narrow area model which has bubble simulation functions.

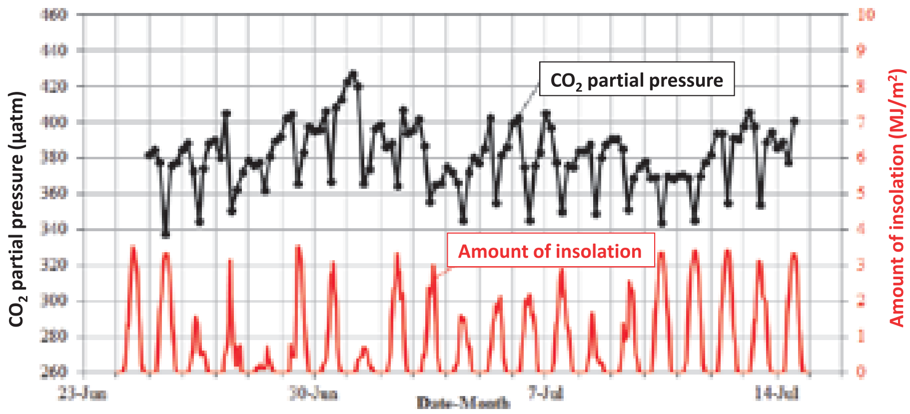


Fig. 9 : Relation between CO_2 partial pressure and amount of insolation on a seabed in a coastal area (50 m deep)

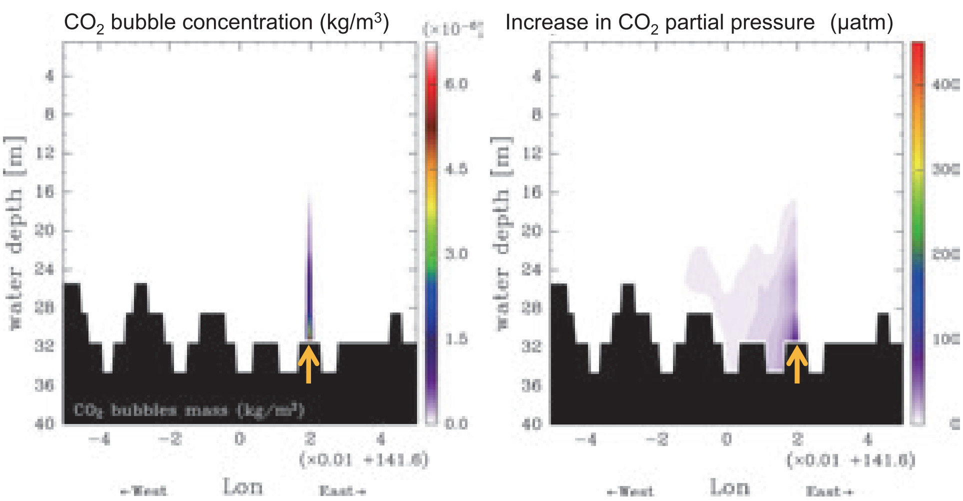


Fig. 10 : Results of a CO_2 seepage diffusion simulation (The arrows show the seepage point)

2.4 Compilation of CCS Best Practice Manuals toward CCS commercialization

Since the world-first CO_2 geological storage project became operational in Sleipner in the North Sea in 1996, a number of CO_2 geological storage project have been launched. With an aim to promote CCS, institutions in major countries in North America and EU have been compiling general guidebooks, guidelines and best practice manuals.

Foreseeing domestic and global CCS deployment in future, RITE has been compiling “CCS Best Practice Manuals” as a technical reference for Japanese companies to carry out CCS projects. As best practices in Japan, we have been summarizing mainly various technical aspects of the CO_2 injection test carried out in Nagaoka, Niigata from 2003 to 2005. We have also been collecting and sorting out overseas best practices in the U.S. Regional Carbon Sequestration Partnerships (RCSPs) and Europe.

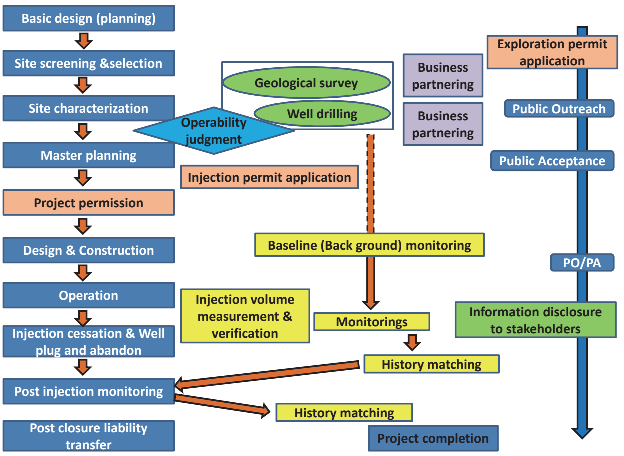


Fig. 11 : CCS project flow

We will finalize Chapter 1 “basic planning” to Chapter 4 “master planning” by the end of FY 2015. We plan to complete Chapter 5 “designing and construction” to Chapter 8 “post-closure management” by FY 2020, incorporating outcomes from the large-scale CCS demonstration project in Tomakomai.

3. Survey of Global CCS Activities and Co-operation with International Organizations

Through co-operation with international organizations, RITE contributes to accelerating CCS deployment and monitors CCS-related activities in the world. Summarized below are highlights in the global CCS community in FY2015 and major activities in a couple of international bodies to which RITE contributes—the IEA Greenhouse Gas R&D Programme (IEAGHG) and the Carbon Sequestration Leadership Forum (CSLF).

3.1 Highlights in CCS

Highlights in FY2015 include the initiation of operation in the Quest project in November in Canada. In the project, CO_2 is captured in its hydrogen production process and is stored in a saline aquifer. The project was incentivized by public funding and also carbon credits equivalent to a double level of carbon tax. With the Quest becoming operational, there are 15 large-scale CCS projects in the world, including four saline aquifer storage projects.

In the power sector, following the Boundary Dam project, which came into operation in October 2014 for the first time in the world, two CCS coal-fired power projects will become operational in the USA in 2016. In addition, it has come to be more likely that the final investment decision is to be made in 2016 for the so-called ROAD project in the Netherlands, which has been in danger of cancelation. In the situation where expectation has been growing for operational experiences to be increased in the power sector, the UK Government made announcement of abandoning a one billion-pound funding to CCS fossil power plant demonstration projects in November 2015. Since the UK has been one of the most proactive countries to promote CCS deployment, it has brought concerns of giving adverse impact on future deployment of CCS technology.

A highlight in regulations is CO_2 emissions performance standards for fossil-fired power plants enforced in the USA. The standard for new coal-fired power plants was set out at a level where around 20% of CO_2 emissions need to be captured. But it is widely thought that what the implementation of the regulation will promote is the construction of combined cycle gas turbines, not that of coal-fired power plants with CCS.

3.2 IEAGHG and CSLF Update

With the year of 2015 being the 10th anniversary of the IPCC's CCS Special Report, IEAGHG publicized a special issue of an international journal in September. The special issue consists of 17 papers with a focus on CCS progress in the past 10 years, covering capture, storage, economics, bio-CCS, policies and public acceptance. It concludes that science and technology underpinning CCS has been well advanced in the 10 years and that CCS has come to be ready for large-scale projects.

CSLF now has 25 members, welcoming Rumania and Servia as a new member in the ministerial meeting in November. The both new members, in the momentum of strengthening climate change countermeasures globally, have great expectation on CCS as a measure of making the best use of their abundant ignite resources. In the ministerial, it was agreed to launch an international network among large saline aquifer storage projects, which creates expectation of progress in knowledge sharing in this area. After about two year activities, the taskforces on 2nd and 3rd generation capture technologies and offshore CO_2 storage publicized a report respectively. Information collated by the former taskforce is supposed to be sorted out and opened on the CSLF web site. For the latter activity, a workshop with the aim of exploring future international co-operation is slated for 2016. The new taskforce activities agreed are effective use of pore space in storage formations (improvement of storage efficiency), offshore EOR and bio CCS.

Research & Coordination Group

Publication of Technical Report on CO_2 Capture technology(ISO/TR27912)

Toward practical applications of CCS, developments of international standard documents on CCS have been in progress respectively by each technology area (Capture, Transportation, Storage, Quantification and Verification, Cross-Cutting Issues and CO_2-EOR) under Technical Committee 265 (TC265) in International Organization for Standardization (ISO). Among these activities, Working Group led by Japan, WG1 (capture), has developed Technical Report, ISO/TR27912. This document has been already approved by TC265 and in the process of publication. It will be released as the first document from TC265 in the near future.

In capture of CO_2 generated by the use of fossil fuel, there are capture processes such as Post-Combustion capture, Pre-Combustion capture and Oxyfuel combustion mainly. Capture technologies for them such as chemical absorption, physical absorption, adsorption, membrane separation are well-known and actively developed. These technologies could be applied to power and industrial areas such as power generation, iron and steel making industry, cement industry and gas production industry. The status for practical application of each technology is currently diverse.

This TR widely covers the latest information regarding CO_2 capture technologies, equipment and processes. A good relationship among members from related countries has been established through discussion of the priority of the standardization in the process of the development of TR prior to the development of a series of International Standard (IS) for CO_2 capture in CCS.

For the actual work of the development, a base document was first prepared by member companies of Capture WG organized in Japan. It was drafted with experts from each country who joined WG1 through discussion in six WG1 meetings since the first meeting in Beijing in September, 2013. The draft was approved through voting by participating countries in TC265 and now it is officially in the process of publication by ISO central secretariat.

This TR consists of 13 chapters which covers Scope, Terms and definitions, various CO_2 capture system such as Post-combustion capture and Pre-combustion capture in the power industry, cement, iron & steel, industrial gas production processes, and discussion on possible future direction for standardization. It includes comprehensive information of capture technologies with over 200 pages. WG1 agrees to revise this TR when needed by the development of capture technologies in the future.

Innovative Environmental Technology Symposium 2015 -Toward realization of low-carbon society-

This symposium is an annual event that RITE hosts to present our research progress and achievements to all the parties concerned. This year we were honored to invite Mr. Mitsumata, Deputy Director-General for Technology and Environment, METI, who had just attended COP21, to deliver a speech on the outcomes of the conference including the Paris Agreement. Also, Prof. Yamaji, Director-General of RITE, gave a keynote speech on the milestones and challenges toward the fulfillment of Japan's INDC, and the role of RITE as well as the importance of CCS. The latest achievements and the future outlook of our research and development activities were introduced from each research group not only by the presentations but also through the poster session, which brought an active dialogue between the participants and the researchers.

Date 18 December 2015
Venue Ito Hall (Tokyo)
Organized by RITE
Supported by the Ministry of Economy, Trade and Industry (METI), the Chemical Society of Japan, the Society of Chemical Engineers, Japan Society for Bioscience, Biotechnology and Agrochemistry, Japan Society of Energy and Resources, and the Japan Institute of Energy
The number of participants 360
Program

- Guest speech: COP21 and the current status of the international negotiations on climate change
  Hiroki Mitsumata, Deputy Director-General for Technology and Environment, Industrial Science and Technology Policy and Environment Bureau, METI
- Keynote speech: Future energy environment policy and the role of RITE
  Kenji Yamaji, Director-General
- Lecture1: Assessment of Japan's and other countries' efforts to mitigate GHG emissions contained in the INDCs
  Keigo Akimoto, Group Leader, Systems Analysis Group
- Lecture2: Measures in future for deployment of CCS
  Hideaki Tsuzuku, Group Leader, Research & Coordination Group
- Coffee break, Poster session
- Lecture3: Current status and future prospects of the development of Biorefinery technology
  Masayuki Inui, Acting Group Leader, Molecular Microbiology and Biotechnology Group
- Lecture4: Approach of the Chemical Research Group toward low-carbon society
  Shinichi Nakao, Group Leader, Chemical Research Group
- Lecture5: Development of CCS safety assessment technologies – Latest trend of overseas projects and researches in RITE -
  Ziqiu Xue, Chief Researcher, CO_2 Storage Research Group

Systems Analysis Group

ALPS International Symposium Assessing effective initiatives to tackle climate change —Towards COP21

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) alerted international communities about climate change with higher confidence than previous reports. For example, it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. At such an important time both for energy and climate policy decisions, FY2014 ALPS International Symposium was held to disseminate the research achievements of the project and also to present relevant lectures by speakers invited from both abroad and Japan that are eminent scholars active in this field. The speakers pointed out that the required emission reduction efforts for achieving the target below 2 °C above pre-industrial levels depended strongly on the uncertainty of climate sensitivity. In addition, there were suggestions on review methods for Intended Nationally Determined Contributions (INDCs) which were expected to be discussed at the COP21. We had valuable lectures and discussions by excellent scholars.

Date 27 February 2015
Venue Otemachi Sankei Plaza (Tokyo)
Organized by RITE
Co-organized by Ministry of Economy, Trade and Industry
The number of participants 212
Program

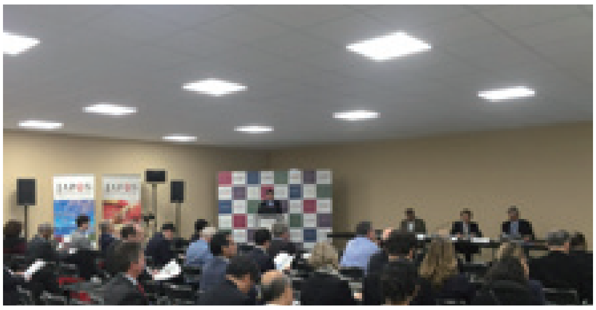
- Japanese Perspective to the Nationally Determined Contributions for Global Climate Change Response
  Kenji Yamaji, Director-General, RITE
- Re-Examination of Emission Paths Considering Uncertainties of the Climate Sensitivity
  Yoichi Kaya, President, RITE
- The Road to Paris: From Global Commitments to National Pledges and Co-Benefits
  Nebojsa Nakicenovic , Deputy Director General, IIASA
- Assessment of Restrictions on Public Financing for New Coal-Fired Power Plants Overseas
  Miyuki Nagashima, Senior Researcher, Systems Analysis Group, RITE
- Risk Management Strategy of Climate Change
  Taishi Sugiyama, Senior Researcher, Central Research Institute of Power Industry
- Comparability of Effort in International Climate Policy Architecture
  William A. Pizer, Professor, Duke University
- Reviewing Emission Mitigation Contributions
  Joseph E. Aldy, Harvard Kennedy School
- Evaluations on Emission Reduction Efforts of the Nationally Determined Contributions for the Post-2020 Periods
  Keigo Akimoto, Group Leader, Systems Analysis Group, RITE

COP21 Side Event New Methods for Comparing Levels of Efforts and Evaluations of INDCs -Transparency, Policy Surveillance, and Levels of Effort-

A side event at COP21 in Paris was held research studies on the evaluations on emission reduction efforts of Intended Nationally Determined Contributions (INDCs) which were determined by each country before the COP21 were introduced and discussed. In the discussions, it was pointed out that the emission reduction efforts should be measured by using multiple indicators that are comparable, measurable, replicable and universal. In addition, the speakers presented that high marginal abatement costs of the INDCs are observed for Japan and other developed countries, but those of many developing countries are nearly zero according to the quantitative evaluations.

Date 9 December 2015
Venue COP21 Japan Pavilion (Paris)
Organized by RITE
Collaborating research institutes
Resources for the Future (RFF), Fondazione Eni Enrico Mattei (FEEM)
The number of participants 45
Program

- Transparency, Policy Surveillance, and Levels of Effort: Assessing and Comparing INDCs
  Raymond Kopp, Senior Fellow, RFF
- Assessment and Comparison of INDCs: Effectiveness vs Fairness?
  Carlo Carraro, Professor, Ca' Foscari University of Venice
- RITE's Evaluations on Emission Reduction Efforts of the INDCs and the Expected Global Emissions
  Keigo Akimoto, Group Leader, RITE
- A Model Based Assessment of the INDCs
  Massimo Tavoni, Deputy Coordinator, FEEM

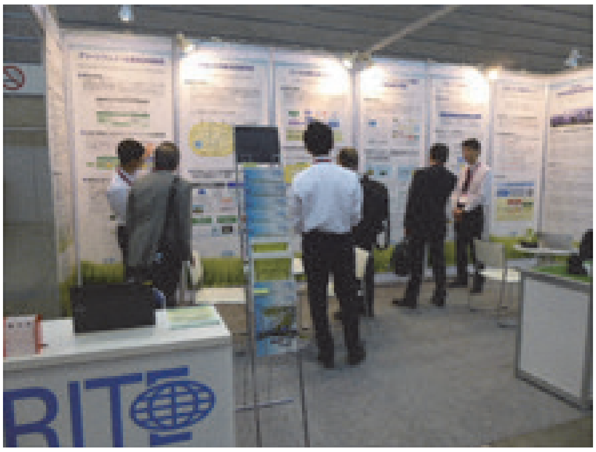


Molecular Microbiology and Biotechnology Group

BioJapan 2015

World Business Forum "BioJapan 2015" was held at PACIFICO Yokohama on October 14-16, 2015. RITE attended the forum as a member of the organization committee, and gave an exhibition of our works based on the key technology RITE Bioprocess, the "growth-arrested" bioprocess we developed. We reported about the recent progress of our projects on aromatic green chemicals and biofuels, including biojet fuel, biobutanol, and biohydrogen. In collaboration with Green Phenol Development Co., Ltd. (GPD) established by RITE and Sumitomo Bakelite Co., Ltd. in May 2014, we also described our plan for industrialization of the biophenol production technology.

Once again, we thank all visitors including government officials and parties from the related industry.



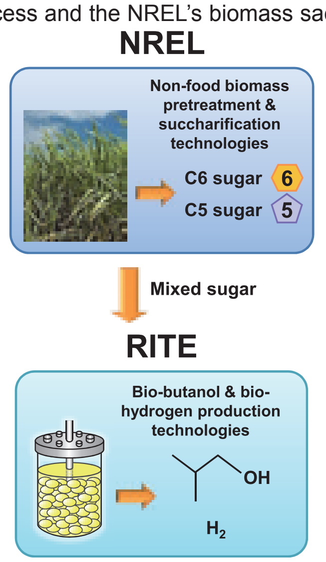
RITE/GPD exhibition booth

Introduction of new projects

As a part of Japan's efforts to tackle global warming and climate change, Ministry of Economy, Trade and Industry (METI), Japan, set up "A program for international joint research and development of innovative energy technology" in order to strongly encourage research institutes in Japan to collaborate with the leading-edge research institutes abroad, and to facilitate innovations in the field of energy technology.

Molecular Microbiology and Biotechnology group is involved in this program and works on two projects, "Research and development of a highly efficient biohydrogen production process" and "Research and development of a biobutanol production process with high carbon yield from cellulosic biomass", over the next 5 years in collaboration with the U.S. National Renewable Energy Laboratory (NREL). Established in 1977, NREL has been on the cutting-edge of renewable energy technologies such as solar energy, wind-power energy, and bio-energy. It has a mission to facilitate commercialization of renewable energy technologies, and therefore is proactive in supporting applied as well as fundamental studies. Since a memorandum of understanding, "Japan-US Clean Energy Technologies Action Plan" was signed between METI and the U.S. Department of Energy, NREL has been carrying out collaborative studies on renewable energy technologies with the research institutes in Japan. As a front runner in the area of biomass energy technology, NREL has been putting effort into studies on cellulosic biofuels production technologies, and established a cellulosic biomass pretreatment and saccharification process most cost-efficient in the world.

In this collaboration, RITE and NREL work together to establish innovative bioenergy production technologies by integrating the strong points of each institutes, namely RITE Bioprocess and the NREL's biomass saccharification technology.



Framework of the collaboration between RITE and NREL

CO_2 Storage Research Group

CCS Technical Workshop 2015 —The current status of CCS and global advanced projects-

CCS – which captures CO_2 from large emission sources and stores it in a saline aquifer – has been seen as an important option in the reduction of CO_2 emissions. To promote CCS deployment, it is inevitable to improve the safety of CO_2 geological storage and gain public confidence. With this in mind, RITE organized the workshop, inviting experts on leading-edge CCS demonstration projects and reporting up-to-date achievement in our safety evaluation technology development.

Through presentations delivered by four domestic and overseas experts, moderated by Prof. Kozo Sato (Graduate School of Engineering, The University of Tokyo), we made useful information dissemination and communication with audience to foster better understanding on CCS.

Date 9 October 2015
Venue Hotel Grand Palace (Tokyo)
Organized by RITE
Co-organized by Ministry of Economy, Trade and Industry
The number of participants 296
Program

- Presentation 1: World CCS: Current Status, Challenges and Future Directions
  John Gale, General Manager, IEA GHG
- Presentation 2: Pressure Monitoring, Contingency Planning, and Mitigation of Leakage from CO_2 Storage Projects
  Sally Benson, Professor, Stanford University
- Presentation 3: Research and Development of Safety Assessment Technology for CO_2 Storage in Deep Saline Aquifer
  Ziqiu Xue, Chief Researcher, CO_2 storage research group, RITE
- Presentation 4: The Boundary Dam Project — It's First Year —
  Mike Monea, President, Carbon Capture and Storage Initiatives, SaskPower
- Wrap-up: Kozo Sato, Professor, the University of Tokyo

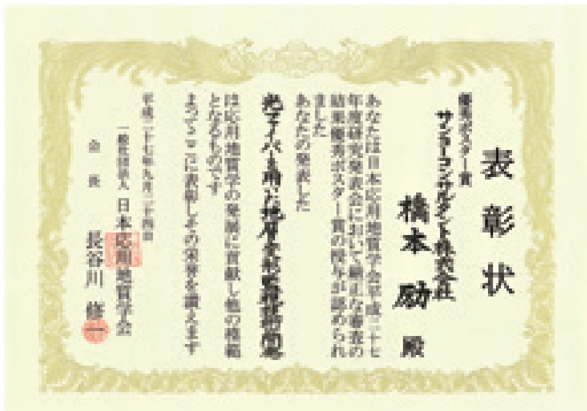
Won an outstanding poster award at the Japan Society of Engineering Geology conference 2015 —Development of technology to monitor deformation of geological formations with optic fibers—

In the Japan Society of Engineering Geology conference 2015 held on 24 and 25 September, Tsutomu Hashimoto, senior researcher in RITE (seconded from Suncoh Consultants) won an outstanding poster award for his "development of technology to monitor deformation of geological formations with optic fibers".

RITE has been conducting research and development on measuring the deformation of geological formations continuously from surface to subsurface along a depth direction with optic fibers installed as distributed sensors outside of a well for safety assessment for CO_2 geological storage.

The award came together with brief remarks – The thoughtful sequence of onsite works is plainly explained, including creative installation of sensors to a depth of 300m and the verification of detectability of formation deformation caused by CO_2 injection and well casing deformation caused by increase and decrease in loads on a packer; and in addition the development is highly valued from the viewpoint of applicability to other areas.

We will continue lab tests and onsite experiments to put it into a practical level as a tool to monitor the stability of geological formations in CO_2 storage projects.



Chemical Research Group

5th Symposium for Innovative CO_2 Membrane Separation Technology Recent trends in membrane separation technology contributing to the prevention of global warming

The purpose of this symposium was threefold. First, to report recent research trends in CO_2 separation membrane technologies that the Association has been developing. Second, to gain an overview of overseas research and development in this technology area. Third, to provide interested parties with the background to understand the required public and private R&D activities for CO_2 emission reductions.

Date 2 October 2015
Venue Ito Hall (Tokyo)
Organized by Molecular Gate Membrane Module (MGM) Technology Research Association
Co-organized by Ministry of Economy, Trade and Industry
Supported by Japan CCS Co., Ltd., Global CCS Institute and Japan Association for Chemical Innovation
Co-sponsors The Membrane Society of Japan, The Society of Chemical Engineers, Japan, The Society of Polymer Science, Japan and The Chemical Society of Japan
The number of participants 242
Program

- Keynote speech: Latest trends in global warming mitigation and role of CCS
  Yoichi Kaya, President, RITE
- Keynote speech: Current status and future prospects of polymeric membranes for gas separation
  Hiroyoshi Kawakami, Tokyo Metropolitan University Faculty & Graduate School of Urban Environmental Sciences
- Keynote speech: Latest trends in coal gasification technology and IGCC
  Hiroshi Sasatsu, Electric Power Development Co., Ltd.
- Lecture: Development of CO_2 molecular gate membrane modules
  Shin-ichi Nakao, Senior Managing Director of MGM Technology Research Association
- Lecture: Latest trends of CO_2 capture technologies in overseas
  Teruhiko Kai, MGM Technology Research Association

Participation in the second annual meeting of the Innovation for Cool Earth Forum (ICEF)

The second annual Innovation for Cool Earth Forum (ICEF) was held on 7th & 8th October 2015, and several researchers from RITE participated to make a presentation.

ICEF is an international conference which started in 2014 with the Prime Minister Abe's proposal in order to establish a platform to discuss the importance of addressing climate change through innovation. It is organized by the Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO), and Prof. Kaya, President of RITE, acts as a chairperson of the steering committee.

In this year's meeting, Prof. Yamaji, Director-General of RITE, chaired the Energy Systems Session, and the researchers from the institute delivered a presentation on the latest achievements in each related session as follows.

Session Iron and Steel
Keigo Akimoto
Group Leader, Systems Analysis Group
"Role of iron and steel sector in responding to global warning"

Session Advanced Liquid Biofuels
Masayuki Inui
Acting Group Leader,
Molecular Microbiology and Biotechnology Group
"Current Trends and Emerging Technologies for Biojet Fuel Production in Japan"

Session CCS
Shinichi Nakao
Group Leader, Chemical Research Group
"CO_2 Capture Technologies for cost reduction"

Session International Framework for Complementing UN
Mitsutsune Yamaguchi
Special Advisor
"International/regional schemes complementing the UN"

Preparatory Office for Inorganic Membranes Research Center

Foundation of Inorganic Membranes Research Center

Inorganic Membranes Research Center will be founded as the fifth research organization of RITE in April, 2016. This research center will cope with not only research and development but also the promotion of the industrialization of innovative energy and environmental technologies using inorganic membranes.

Expectations for inorganic membranes

Development of efficient hydrogen production, storage, and transportation methods is essential for building a “Hydrogen-based Society”. Chemical hydrides, ammonia, and liquefied hydrogen have high potential as effective media for these methods. Membrane reactors using inorganic membranes such as silica, zeolite, or palladium are expected to be efficient dehydrogenating apparatus for chemical hydrides or ammonia because they usually provide greater compactness, higher efficiency, and lower cost compared with those of existing methods.

Inorganic membranes are also expected to be used in improved methods of separating CO_2 from CO_2 and CH_4 mixtures, so they have received much attention as innovative energy and environmental technology.

What is the Inorganic Membranes Research Center?

Inorganic Membranes Research Center consists of the Research Section and the Industry Cooperation Section. The Industry Cooperation Section has company members from both manufacturing companies and user companies of inorganic membranes. The Research Center also has an advisory board of leading researchers from several universities. The Research Center will promote open innovation to produce synergistic outcomes.

Efforts of the Research Section

The Research Section will tackle innovative research and development for constructing a ‘Hydrogen-based Society’, carbon capture, and so on. For example, the research and development of highly efficient fuel cells or hydrogen supplying stations with methyl-cyclohexane as fuel will be conducted.

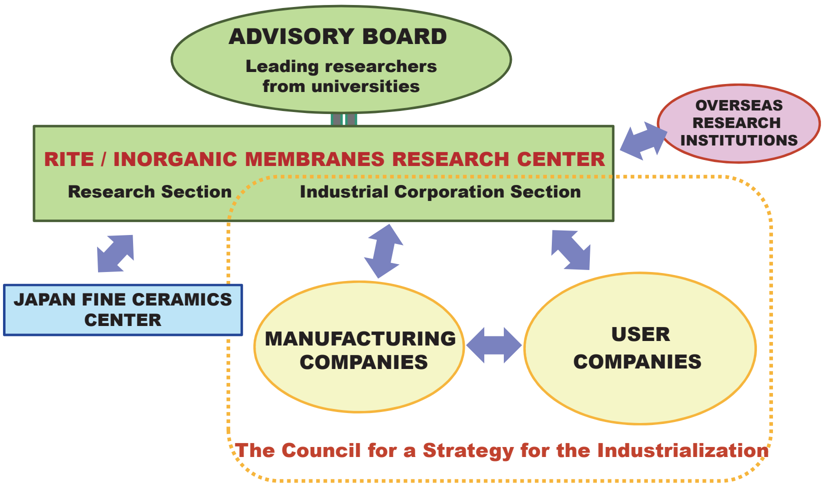
For CO_2 separation, we intend to conduct research and development on methods of refining biogas or methods of separating and extracting natural gas from wells.

In addition, the Research Section will accept researchers from member companies, and the highest level technologies will be transferred to them from the leading researchers of our advisory board.

Actions of the Industrial Cooperation Section

In the Industrial Cooperation Section, various efforts will be made toward the industrialization of inorganic membranes in cooperation with manufacturing companies and user companies.

For example, we intend to formulate a roadmap of the industrialization of innovative technologies based on inorganic membranes, propose and set up joint research with member companies, and hold seminars for member companies.



Framework of Inorganic Membranes Research Center and its Cooperating Partners

Directors

Original Paper

1. Y. Kaya, M. Yamaguchi, K. Akimoto, The uncertainty of climate sensitivity and its implication for the Paris negotiation, Sustainability Science, 10.1007/s11625-015-0339-z, 2015

Books

1. Kenji Yamaji, Issues of HLW Disposal in Japan, pp.279-287, In K. Nakajima(ed.), Nuclear Back-end and Transmutation Technology for Waste Disposal, Beyond the Fukushima Accident, Springer Open, 2015
2. Y. Kaya, K. Yamaji, K. Akimoto, Climate Change and Energy, Japanese Perspectives on Climate Change Mitigation Strategy, ICP Series on Climate Change Impacts, Adaptation, and Mitigation – Vol.4, Imperial College Press, 2015
3. M. Yamaguchi and K. Akimoto, The view from different parts of the world: A view from Japan, pp.115-129, In S. Barrett, C. Carraro and J. de Melo(eds.), Towards a Workable and Effective Climate Regime, CEPR Press, 2015

Systems Analysis Group

Original Paper

1. F. Sano, K. Wada, K. Akimoto, J. Oda, Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro- and sectoral decomposition analyses, Technological Forecasting & Social Change, Vol.90 Part A pp.153-165, January 2015
2. K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longdon, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D. P. van Vuuren, K. Wada, V. Bosetti, P. Capros, Locked into Copenhagen pledges - Implications of short-term emissions targets for the cost and feasibility of long-term climate goals, Technological Forecasting & Social Change, Vol.90 Part A pp.8-23, January 2015
3. E. Kriegler, K. Riahi, N. Bauer, V. J. Schwanitz, N. Petermann, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, S. Rao, T. Arroyo-Currás, S. Ashina, J. Bollen, J. Eom, M. Hamdi-Cherif, T. Longden, A. Kitous, A. Méjean, F. Sano, M. Schaeffer, Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy, Technological Forecasting & Social Change, Vol.90 Part A pp.24-44, January 2015
4. E. Kriegler, N. Petermann, V. Krey, V. J. Schwanitz, G. Luderer, S. Ashina, V. Bosetti, J. Eom, A. Kitous, A. Méjean、L. Paroussos, F. Sano, H. Turton, C. Wilson, D. van Vuuren, Diagnostic indicators for integrated assessment models of climate policy, Technological Forecasting & Social Change, Vol.90 Part A pp.45-61, January 2015
5. N. Bauer, V. Bosetti, M. Hamdi-Cherif, A. Kitous, D. McCollum, A. Méjean, S. Rao, H. Turton, L. Paroussos, S. Ashina, K. Calvin, K. Wada, D. van Vuuren, CO_2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies, Technological Forecasting & Social Change, Vol.90 Part A pp.243-256, January 2015
6. J. Arakawa, K. Akimoto, Assessments of the Japanese energy efficiency standards program, Journal of Sustainable Development of Energy, Water and Environment Systems, Vol.3 No.1, pp.66-78, March 2015
7. A. Hayashi, K. Akimoto, F. Sano, T. Tomoda, Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios, Journal of the Japan Instituted of Energy, Vol.94 No.6 pp.548-554, 2015
8. E. Kriegler, K. Riahi, N. Bauer, V. J. Schwanitz, N. Peterman, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, S, Rao-Skirbekk, T. A. Curras, S. Ashina, J. Bollen, J. Eom, M. Hamdi-Cherif, T. Longden, A. Kitous, F. Sano, A. Mejean, M. Schaeffer, K. Wada, P. Capros, D. van Vuuren, O. Edenhofer, C. Bertram, R. Bibas, J. Edmonds, N. Johnson, V. Krey, G. Luderer, D. McCollum, J. Kejun, A short note on integrated assessment modeling approaches: Rejoinder to the review of "Making or breaking climate targets - The AMPERE study on staged accession scenarios for climate policy", Technological Forecasting & Social Change, Vol.99 pp.273–276, 2015
9. K. Tokushige, K. Akimoto, J. Oda, T. Homma, Analysis on Emission Reduction Efforts of GHG Emissions in Japan for the First Commitment Period of the Kyoto Protocol, Journal of Japan Society of Energy and Resources, Vol.36 No.2, pp.1-9, 2015
10. J. Oda, K. Akimoto, M. Nagashima, Analysis of Coal Power Plant

Performance by Station in India, Journal of Japan Society of Energy and Resources, Vol.36 No.6 pp.17-26, 2015

11. K. Lessmann, U. Kornek, B Bosetti, R. Dellink, J. Eyckmans, M. Nagashima, H.P. Weikard, Z. Yang, The stability and effectiveness of climate coalitions: A comparative analysis of multiple integrated assessment models, Environmental and Resource Economics, Vol. 62 No.4 pp.811-836, December 2015

12. Y. Kaya, M. Yamaguchi, K. Akimoto, The uncertainty of climate sensitivity and its implication for the Paris negotiation, Sustainability Science, 10.1007/s11625-015-0339-z, 2015

13. J. Aldy, B. Pizer, K. Akimoto, Comparing emission mitigation efforts across the countries, Climate Policy, in press

14. F. Sano, K. Akimoto, T. Homma, K. Tokushige, Evaluation of the Japan's greenhouse gas emission target for 2030, Journal of Japan Society of Energy and Resources, in press

Other Paper

1. K. Akimoto, Energy mix and climate change mitigation, Monthly Keidanren, May 2015

2. K. Akimoto, Nuclear power from the view point of climate change issues, Online Media Politas, May 26, 2015

3. F. Sano, K. Akimoto, Analysis of long-term emission reduction targets, Electrical Review, June 2015

4. J. Oda, K. Akimoto, International comparison of power generation efficiency: Effects of operation and maintenance improvement, Electrical Review, Special Summer Issue 2015

5. K. Wada, Negotiations and technology transfer under UNFCCC, Electrical Review, July 2015

6. K. Akimoto, Estimates for the nation's economic value of nuclear power, Journal of Public Utility Economics, Vol.67 No.1 pp.31-33, July 2015

7. K. Tokushige, K. Akimoto, Evaluation of the Voluntary Action Plan on the environment, Electrical Review, August 2015

8. K. Akimoto, Japan's energy mix development and efforts toward reductions of GHG emissions, Bulletin 'Kozan', Vol.68 No.8, October 2015

9. K. Akimoto, The government's energy mix is reasonable as a balance of S + 3E, Weekly Economist, December 22, 2015

10. K. Akimoto, DNE21+: A global energy and climate change mitigation model, Journal of Japan Society of Energy and Resources, in press

Oral Presentation

1. K. Akimoto, Quantitative analyses on emission reduction efforts under the voluntary action plan in Japan , Technical Workshop on Policy Approaches for Industrial Sector in the Climate-Energy Interface, France, January 16, 2015

2. K. Akimoto, J. Oda, F. Sano, Electricity generation costs by source, and costs and benefits by substitutions of generation sources, The 31st Conference on Energy, Economy, and Environment, January 27, 2015

3. T. Homma, K. Akimoto, Economic impacts of electricity price increases on industry by region, The 31st Conference on Energy, Economy, and Environment, January 27, 2015

4. A, Hayashi, K. Akimoto, F. Sano, T. Homma, Global analyses on conditions for bioenergy and CO_2 fixation in forest to be introduced, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

5. B. Shoai Tehrani, Assessment of low carbon investments in Europe: Two methodological approaches, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

6. J. Oda, K. Akimoto, M. Nagashima, Analysis of coal power plant efficiency by station in India, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

7. K. Tokushige, K. Akimoto, J. Oda, T. Homma, Analysis for reviews of intended nationally determined contributions addressing the post-2020 emissions reductions, The 31st Conference on Energy, Economy, and Environment, January 28, 2015,

8. K. Wada, K. Akimoto, M. Nagashima, The diversity and potentiality of technology transfer under UNFCCC, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

9. Y. Arino, K. Akimoto, F. Sano, T. Homma, J. Oda, An analysis on the option values of geoengineering under uncertainties in future climate change, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

10. M. Nagashima, T. Homma, F. Sano, K. Akimoto, J. Oda, T. Tomoda, K. Wada, Assessment of U.S. restrictions on public financing for new coal-fired power plants overseas and proposed regulation, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

11. F. Sano, K. Akimoto, H. Torii, J. Oda, B. Shoai Tehrani, A scenario developing of introduction of hydrogen system by using a world energy systems model, The 31st Conference on Energy, Economy, and Environment, January 28, 2015

12. K. Akimoto, RITE's analyses and assessments of energy mix and climate change targets, Society for Environmental Economics and Policy Studies 20th Anniversary Symposium, Meiji University, May 8, 2015

13. Y. Arino, K. Akimoto, F. Sano, T. Homma, J. Oda, T. Tomoda, An analysis on the option values of geoengineering under uncertainties in climate change, 21st Annual Conference of the European Association of Environmental and Resource Economists, Helsinki, Finland, June 25, 2015

14. T. Homma, K. Akimoto, The economic impacts of climate policies under the shared socioeconomic pathways, 18th Annual Conference on Global Economic Analysis, Melbourne Convention Center, Melbourne, Australia, Jun. 17-19, 2015

15. K. Wada, Scaling up technology transfer through the UNFCCC Technology Mechanism, Our Common Future under Climate Change (CFCC) Conference, Paris France, July 30, 2015

16. B. Shoai Tehrani, K. Akimoto, Measuring the impacts of climate change on human well-being through life quality index, The Fifth Congress of the East Asian Association of Environmental and Resource Economics, Taipei, Taiwan, August 18, 2015

17. K. Akimoto, F. Sano, T. Homma, K. Tokushige, Evaluations of Japan's INDCs from the viewpoint of equity among countries and of long-term emission pathways, Society for Environmental Economics

Systems Analysis Group

and Policy Studies 20th Annual Meeting, September 18, 2015

18. J. Oda, K. Akimoto, Analysis of global average energy efficiency in power and steel sectors, Society for Environmental Economics and Policy Studies 20th Annual Meeting, September 18, 2015

19. K. Wada, K. Akimoto, F. Sano, Economics of energy efficiency for mitigating CO_2 emissions, Society for Environmental Economics and Policy Studies 20th Annual Meeting, September 20, 2015

20. F. Sano, K. Akimoto, T. Homma, K. Tokushige, B. Shoai Tehrani, Evaluation on the Japan's INDC in comparison with other nations', and in the context of achieving 2℃ target, Eighth Annual Meeting of the IAMC 2015, Potsdam, Germany, November 16, 2015

Non Journal Publications

1. B. Shoai Tehrani, Current conditions of energy and climate mitigation policies in Japan & the analyses with RITE model, MILES Kick-off Meeting, France, January 15, 2015

2. K. Wada, F. Sano, K. Akimoto, Heterogeneity of technology adoption in the transportation sector, ADVANCE Meeting, The Netherlands, January 22, 2015

3. K. Akimoto, The future of energy and environment, Regional Energy Seminar in Hiroshima, January 30, 2015

4. K. Akimoto, Overview of Strategic Energy Plan, Workshop on Energy Policy, Aomori Prefecture Association of Villages and Towns, February 2, 2015

5. K. Akimoto, Electricity generation costs by source - Towards the development of the future energy mix-, Meeting for Energy Public Relations, February 5, 2015

6. K. Akimoto, Climate change policies and trends of Japan and the world: Challenges for COP21, Keynote Lecture, Aichi Pref. Environment Prize Ceremony, February 19, 2015

7. K. Akimoto, The current situation and the future of electricity supplies, Japanese Association of Metal, Machinery, and Manufacturing Workers (JAM) Symposium, February 21, 2015

8. K. Akimoto, The trend of mitigation efforts response to global warming and outlook for COP21, Lecture on Current Affairs / Situation, Japan Foreign Traders Association, INC., March 4, 2015

9. K. Akimoto, Toward the development of Japan’s energy mix and INDC, Joint Meeting of Global Environmental Strategy WG / Climate Change Strategy WG, Keidanren, March 5, 2015

10. K. Akimoto, Consideration towards the development of energy mix, Symposium for Consideration of Japan's Energy Mix, March 6, 2015

11. K. Wada, Progress on co-benefits research, International Workshop, Bridging Atmospheric Science and Policy in Asia: Identifying Areas for Collaborative Research, IIASA-IGES, March 10, 2015

12. K. Akimoto, Estimates for the nation’s economic value of nuclear power, Academic Study Group, Society of Public Utility Economics, March 17, 2015

13. K. Wada, The trend of technology negotiation and the study on CTCN, The 42nd TESCUE Study Meeting, March 18, 2015

14. K. Akimoto, The INDCs prospects, the relationship of INDCs with the 2 degree C target and implications for international exchange, The Fourth Case Study Meeting, Green Forum 21, March 23, 2015

15. K. Akimoto, Electricity generation costs by source, focusing on nuclear power cost, The 8th Exchange Meeting of Mass Media, Atomic Energy Society of Japan, March 30, 2015

16. Y. Arino, K. Akimoto, F. Sano, T. Homma, J. Oda, T. Tomoda, Estimating the option value of solar radiation management under uncertain climate sensitivity, Ireland-Japan International Energy Modeling Workshop, April 16, 2015

17. K. Akimoto, Estimate for electricity generation costs by source, Research Commission for the Nuclear Energy Policy and Supply and Demand, Liberal Democratic Party of Japan, April 23, 2015

18. K. Akimoto, Part III, Model analysis for climate change mitigation strategy, Climate Change and Energy, Japanese Perspective on Climate Change Mitigation Strategy, Imperial College Press, June 2015

19. K. Wada, Implications of INDCs, The 44th TESCUE Study Meeting, May 20, 2015

20. J. Oda, F. Sano, K. Akimoto, Analysis of diffusion of next-generation cars under global CO_2 emissions reduction scenarios, Technical Meeting for Information and Systems Electronics: Rare Metal Resource Restrictions and Next-generation Energy technology, The Institute of Electrical Engineers of Japan, May 27, 2015

21. K. Akimoto, Trends towards COP21 and the future strategies to reduce CO_2 emissions, Environmentally Friendly Case Study Meeting, The Japan Machinery Federation, June 5, 2015

22. K. Akimoto, Japan’s energy mix and strategies to reduce GHG emissions after 2020, Special Lecture for On-site Representative of Mines and Refineries, Japan Mining Industry Association, June 10, 2015

23. K. Wada, The status of technology transfer negotiations, The 45th TESCUE Study Meeting, June 24, 2015

24. K. Wada, Technology transfer negotiations in the context of UNFCCC, Mechanisms Study Meeting, June 26, 2015

25. K. Akimoto, Comparing emission mitigation effort, Duke Environmental and Energy Economics Working Paper Series, June 2015

26. K. Akimoto, Domestic and international policy trends and issues of renewable energy with a focus on solar power, Science Council of Japan, July 2, 2015

27. K. Akimoto, Energy mix and GHG emission reduction targets, RITE Alumni Association, July 3, 2015

28. K. Akimoto, B. Shoai Tehrani, Overview and assessment of Japan’s energy mix and INDCs, MILES Project meeting, Paris France, July 8, 2015

29. K. Akimoto, CO_2 marginal abatement costs of each country, Meeting of Global Environmental Strategy WG, Keidanren, July 17, 2015

30. K. Akimoto, Evaluation of INDCs from a perspective of international equity, 2015 CIGS Symposium on Climate Change, Canon Institute for Global Studies, July 23, 2015

31. K. Wada, K. Akimoto, Y. Arino, RITE's approach to uncertainty analysis for mitigation / geoengineering strategies, EMF Snowmass

Workshop, July 24, 2015

32. A. Hayashi, Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios, International Forum & The Tenth Renewable Energy Exhibition 2015, July 31, 2015

33. K. Akimoto, Evaluation of energy mix and the future issues related to energy policy, Meeting of Fukui Atomic Energy Council for Peaceful Uses, August 6, 2015

34. K. Akimoto, Toward the realization of the energy mix and reduction of GHG emissions, Committee on Environment, Limestone Association of Japan, September 4, 2015

35. K. Akimoto, Evaluation of energy mix and the future issues related to energy policy, Energy Social Meeting, Japan Society of Energy and Resources, September 7, 2015

36. M. Yamaguchi, Economics of climate change, Asia Europe Economic Forum, Paris France, September 15, 2015

37. K. Akimoto, Assessment of relationships between climate change and energy security in the RITE ALPS Project, CD-Links Kick-off Meeting, IIASA, Vienna, Austria, September 29, 2015

38. K. Akimoto, Japan's strategic energy plan, including energy security, The 16th Senior Network (SNW) Symposium, Atomic Energy Society in Japan, October 3, 2015

39. K. Akimoto, Role of iron and steel sector in responding to global warming, Iron and Steel Session, Innovation for Cool Earth Forum (ICEF), October 7, 2015

40. K. Akimoto, Energy mix in 2030, Workshop Organized by Safety and Security Academy of Sciences, 'Is the future energy good enough? ', October 14, 2015

41. K. Wada, How to promote low-carbon investment for mitigation actions in developing countries -The role of the Climate Technology Center and Network-, on the website of Graduate School of Public Policy, The University of Tokyo, October 2015

42. K. Akimoto, GHG emissions projections of INDCs and strategic response to risk, Media Forum on Climate Change Risk: How to see INDCs of Each Country - From the Point of View of Risk, NIES and IR3S, November 5, 2015

43. K. Akimoto, Climate change response strategy and the role of Japan, The Political Economy of Japan and the EU: challenges and Strategies, Chatham house, UK, November 13, 2015

44. K. Akimoto, Assessment of efforts for INDCs emissions reductions and the global emissions pathways, on the website of International Environment and Economy Institute (IEEI) http://ieei.or.jp/2015/11/special201511004/, November 2015

45. K. Wada, Technology transfer negotiations and mechanism in the context of UNFCCC, COP21 Countdown Seminar, November 18, 2015

46. K. Akimoto, Prospects of energy policy in Japan, National Nuclear Power Plant Municipality Council, November 19, 2015

47. K. Gi, Chapter 10 Industry & living environment (Editor), Chronological Environmental Tables 2015-2016, Maruzen Publishing, December 2015

48. K. Akimoto, RITE's evaluations on emission reduction efforts of the INDCs and the expected global emissions, Japan Pavilion at the COP12, December 9, 2015

49. K. Akimoto, Measuring emission reduction efforts of the INDCs and the expected global emission reductions and economic impacts, Side Event at the COP21, organized by Major Economies Business Forum, Keidanren (BizMEF), December 10, 2015

50. K. Akimoto, Climate change measures & policies and the role of CCS, Committee Relating to Technology Trends Survey on Carbon Dioxide Capture and Storage, December 25, 2015

51. K. Akimoto, Long-term GHG emissions pathways under uncertainty, Review Meeting on How to Study the Future Climate Change Projections, Ministry of Education, Culture, Sports, Science and Technology, December 25, 2015

52. M. Yamaguchi and K. Akimoto, Chapter 8, The view from different parts of the world: A view from Japan, pp. 115-129, Towards a Workable and Effective Climate Regime, CEPR Press, 2015

Molecular Microbiology and Biotechnology Group

Original Paper

1. T. Jojima, T. Igari, Y. Moteki, M. Suda, H. Yukawa and M. Inui, Promiscuous activity of (*S,S*)-butanediol dehydrogenase is responsible for glycerol production from 1,3-dihydroxyacetone in *Corynebacterium glutamicum* under oxygen-deprived conditions, Appl. Microbiol. Biotechnol., Vol.99, pp.1427-1433, 2015
2. T. Jojima, R. Noburyu, M. Sasaki, T. Tajima, M. Suda, H. Yukawa and M. Inui, Metabolic engineering for improved production of ethanol by *Corynebacterium glutamicum*, Appl. Microbiol. Biotechnol, Vol.99, pp.1165-1172, 2015
3. K. Toyoda, H. Teramoto, H. Yukawa and M. Inui, Expanding the regulatory network governed by the extracytoplasmic function sigma factor σ^H in *Corynebacterium glutamicum*. J. Bacteriol., Vol.197, pp.483-496, 2015
4. T. Kubota, Y. Tanaka, N. Takemoto, K. Hiraga, H. Yukawa and M. Inui, Identification and expression analysis of a gene encoding a shikimate transporter of *Corynebacterium glutamicum*. Microbiology, Vol.161, pp.254-263, 2015
5. N. Takemoto, Y. Tanaka and M. Inui, Rho and RNase play a central role in FMN riboswitch regulation in *Corynebacterium glutamicum*. Nucleic.Acids.Res., Vol.43, pp.520-529, 2015
6. H. Teramoto, H. Yukawa and M. Inui, Copper homeostasis-related genes in three separate transcriptional units regulated by CsoR in *Corynebacterium glutamicum*. Appl. Microbiol. Biotechnol., Vol.99, pp.3505-3517, 2015
7. S. Oide, W. Gunji, Y. Moteki, S. Yamamoto, M. Suda, T. Jojima, H. Yukawa and M. Inui, Thermal and solvent stress cross-tolerance conferred to *Corynebacterium glutamicum* by adaptive laboratory evolution. Appl. Environ. Microbiol., Vol.81, pp.2284-2298, 2015
8. T. Nishimura and M. Inui. Anaerobic bioprocesses to produce hydrogen from biomass. Frontier of Production of Bio-Hydrogen and Development of Carriers of Hydrogen, pp.43-49, 2015
9. Y. Tsuge, K. Uematsu, S. Yamamoto, M. Suda, H. Yukawa and M. Inui. Glucose consumption rate critically depends on redox state in *Corynebacterium glutamicum* under oxygen deprivation. Appl. Microbiol. Biotechnol., Vol.99, pp.5573-5582, 2015
10. Y. Tsuge, S. Yamamoto, N. Kato, M. Suda, A.A. Vertès, H. Yukawa and M. Inui. Overexpression of the phosphofructokinase encoding gene is crucial for achieving high production of D-lactate in *Corynebacterium glutamicum* under oxygen deprivation. Appl. Microbiol. Biotechnol., Vol.99, pp.4679-4689, 2015
11. A. Watanabe, K. Hiraga, M. Suda, H. Yukawa and M. Inui. Functional characterization of *Corynebacterium alkanolyticum* β-xylosidase and xyloside ABC transporter in *Corynebacterium glutamicum*. Appl. Environ. Microbiol., Vol.81, pp.4173-4183, 2015
12. M. Inui and H. Miyauchi. A challenge towards development of a biomass-derived phenolic plastics production technology. PLASTICS AGE, Vol.61, pp.116-117, 2015
13. Y. Tanaka, H. Teramoto and M. Inui. Regulation of the expression of *de novo* pyrimidine biosynthesis genes in *Corynebacterium glutamicum*. J. Bacteriol., Vol.197, pp.3307-3316, 2015
14. T. Kuge, H. Teramoto and M. Inui. AraR, an L-arabinose-responsive transcriptional regulator in *Corynebacterium glutamicum* ATCC 31831, exerts different degrees of repression depending on the location of its binding sites within the three target promoter regions. J. Bacteriol., Vol.197, pp.3788-3796, 2015
15. T. Jojima and M. Inui. Engineering the glycolytic pathway: a potential approach for improvement of biocatalyst performance. Bioengineered, Vol.6, 328-334, 2015

Magazine article

1. Towards development of a bioprocess for 100 % cellulosic jet fuel production, The New Energy Business News, No.112, Oct. 5, 2015

Oral Presentation

1. A. Watanabe, K. Hiraga, M. Suda, H. Yukawa, M. Inui, Functional characterization of *Corynebacterium alkanolyticum* xylosidase and xyloside transporter, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
2. T. Kubota, Y. Tanaka, N. Takemoto, K. Hiraga, H. Yukawa, M. Inui, Shikimate transporter of *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
3. T. Kogure, M. Suda, K. Hiraga, M. Inui, Production of shikimic acid as a precursor of aromatic compounds by metabolically engineered *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
4. T. Jojima, T. Igari, W. Gunji, Y. Moteki, M. Suda, H. Yukawa, M. Inui, Glycerol biosynthesis via dihydroxyacetone in *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
5. T. Tsujimoto, K. Toyoda, H. Teramoto, M. Inui, The isobutanol-responsive transcriptional regulatory mechanism of sigE encoding the ECF sigma factor SigE in *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
6. T. Kuge, H. Teramoto, M. Inui, L-Arabinose-responsive transcriptional regulatory mechanism in *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
7. T. Maeda, Y. Tanaka, N. Takemoto, M. Inui, Role of the RNase III of *Corynebacterium glutamicum* in cell division, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
8. N. Hamamoto, Y. Tanaka, N. Takemoto, M. Inui, RNase J regulates lysine synthesis genes in *Corynebacterium glutamicum*, The 2015 Annual Meeting of Japan Society for Bioscience, Biotechnology and Agrochemistry, Mar. 27, 2015
9. N. Takemoto, Y. Tanaka, S. Watanabe, T. Miyoshi-Akiyama, M. Inui, Utilization of RNase and Rho in regulation by FMN-riboswitch, 9th meeting of young scientists in Society of Genome Microbiology, Japan, Sep. 29-30, 2015
10. T. Kuge, H. Teramoto and M. Inui, Transcriptional regulation of L-arabinose utilization genes in *Corynebacterium glutamicum*, BioMicroWorld 2015, Oct. 28-30, 2015
11. N. Takemoto, Y. Tanaka, T. Maeda, N. Hamamoto, M. Inui, Bacterial transcription termination factor Rho and RNase E/G cooperatively suppress unwanted antisense RNA production in *Corynebacterium glutamicum*, Biochemistry and Molecular Biology 2015, Dec. 1-4, 2015

Chemical Research Group

Original Paper

1. Response Surface Optimization of Impregnation of Blended Amines into Mesoporous Silica for High-Performance CO_2 Capture, Duc Sy Dao, Hidetaka, Yamada, Katsunori Yogo, Energy Fuels, 2015, 29 (2), pp.985-992

2. Enhanced Adsorption of Carbon Dioxide on Surface-Modified Mesoporous Silica-Supported Tetraethylenepentamine: Role of Surface Chemical Structure, Junpei Fujiki, Hidetaka Yamada, Katsunori Yogo, Microporous and Mesoporous Materials, 2015, 215, pp.76-83

3. CO_2 Solubility Measurements and Modeling for Tertiary Diamines: Hiroshi Machida, Hidetaka Yamada, Yuich Fujioka, Shin Yamamoto, Journal of Chemical & Engineering Data, 2015, 60, pp.814-820

4. The increased CO_2 adsorption performance of chitosan-derived activated carbons with nitrogen-doping, Junpei Fujiki, Katsunori Yogo, Chemical Communications, 2016, 52, pp.186-189

5. Development of Hydrogen-Selective Triphenylmethoxysilane-Derived Silica Membranes with Tailored Pore Size by Chemical Vapor Deposition, Xiao-Liang Zhang, Hidetaka Yamada, Takashi Saito, Teruhiko Kai, Kazuya Murakami, Makoto Nakashim, Joji Ohshita, Kazuki Akamatsu, Shin-ichi Nakao, Journal of Membrane Science, 2016, 499, pp.28-35

6. Mesoporous Silica Sorbents Impregnated with Blends of Tetraethylenepentamine and Alkanolamine for CO_2 Separation, Hidetaka Yamada, Duc Sy Dao, Junpei Fujiki, Katsunori Yogo, Separation Science and Technology, 2015, 50, pp 2948-2953

Non Journal Publication

1. CO_2 Capture by Membrane, Teruhiko Kai, Shuhong Duan, Handbook of Climate Change Mitigation and Adaptation, 2015, pp.1-28

Oral Presentation

1. Advanced CO_2 capture technologies at RITE, Takayuki Higashii, 2015 Taiwan-Japan CCT/CCS Information Exchange Program, Taipei, Jan.22, 2015

2. Development of CO_2 molecular gate membrane for CO_2 capture and storage (CCS), Teruhiko Kai, International Workshop on "Recent Progress on Membrane Separation and CO_2 Capture", Japan, Jul.16, 2015

3. Hydrogen Separation in the Hydrogen-Methylcyclohexane-Toluene Gaseous Mixtures through Triphenylmethoxysilane-derived Silica Membrane by Chemical Vapor Deposition, Xiao-Liang Zhang, Hidetaka Yamada, Takashi Saito, Teruhiko Kai, Kazuki Akamatsu, Shin-ichi Nakao, 9th Conference of Aseanian Membrane Society, Taiwan, Jul.19-21, 2015

4. Modeling of CO_2 Solubility in Tertiary Amine Solvent Using pKa, Hiroshi Machida, Hidetaka Yamada, Shin Yamamoto, 7th International Symposium on Molecular Thermodynamics and Molecular Simulation, Japan, Aug.4-7, 2015

5. Effects of CO_2 Absorption on the Lower Critical Solution Temperature Phase Separation in Amine-H_2O Systems, Hidetaka Yamada, Ryohei Numaguchi, Firoz A. Chowdhury, Kazuya Goto, Tsuguhiro Kato, Yoichi Matsuzaki, Masami Onoda, 34th International Conference on Solution Chemistry, Czech Republic, Aug.30-Sep.3, 2015

6. Development of Novel Single Amine Absorbents and Their Blends for CO_2 Capture , Firoz Alam Chowdhury, Kazuya Goto, Yoichi Matsuzaki, Tsuguhiro Kato, Takayuki Higashii, Masami Onoda, 3rd Post Combustion Capture Conference, Canada, Sep.8-Sep.11, 2015

7. Analysis of the Rate-Limiting Step in Carbon Dioxide Absorption to Amine-Impregnated Solid Sorbent, Ryohei Numaguchi, Hidetaka Yamada, Kazuya Goto, Katsunori Yogo, 3rd Post Combustion Capture Conference, Canada, Sep.8-Sep.11, 2015

8. Carbon dioxide adsorption on chitosan derived N-doped carbon, Junpei Fujiki, Katsunori Yogo, International Conference on Coal Science & Technology 2015, Australia, Sep.27-Oct.1, 2015

9. CO_2 capture technology for CCS, Takayuki Higashii, Taiwan International Green Industry Show 2015- Seminar, Taipei, Oct.1, 2015

10. Advanced CO_2 capture technologies at RITE, Takayuki Higashii, The sixth Korea CCS international Conference, Jan.29, 2016

11. Chemically Tunable Ionic Liquid-Amine Solutions for CO_2 Capture, Firoz A. Chowdhury, Tsuguhiro Kato, Jan.27, 2016

CO_2 Storage Research Group

Original Paper

1. Yi Zhang, Osamu Nishizawa, Tamotsu Kiyama, Ziqiu Xue, Saturation-path dependency of P-wave velocity and attenuation in sandstone saturated with CO_2 and brine revealed by simultaneous measurements of waveforms and X-ray computed tomography images, Geophysics, 80, 4, 2015

2. Yi Zhang, Hyuck Park, Tamotsu Kiyama, Osamu Nishizawa, Yu Liu, Kwang-seok Chae, and Ziqiu Xue, Effect of fluid displacement pattern on complex electrical impedance in Berea sandstone over frequency range 10^4 Hz-10^6 Hz, Geophysical Prospecting, under review

3. Tetsuya Kogure, Yi Zhang, Osamu Nishizawa, Ziqiu Xue, Displacement of brine and supercritical CO_2 during steady-state relative permeability measurements through drainage and imbibition processes under capillary-dominated flow condition, Water Resources Research, submitted

4. Saeko Mito, Kei Okamura, Hideshi Kimoto, Colorimetric pH Measurement of Pressurized Groundwater containing CO_2, Analytical Science, in press

5. Takuma Ito, Takahiro Nakajima, Shun Chiyonobu, Xue Ziqiu, Geostatistical modeling for the spatial mud content: an application to the Nagaoka CO_2 storage site, Japan, Journal of Geological Society of Japan, 121, 311-323, 2015

6. Osamu Nishizawa, Yi Zhang, Takuma Ito, Ziqiu Xue, Tetsuya Kogure, Tamotsu Kiyama,, Rock physics research with application to CO_2 geological storage I: CO_2 flow behavior in capillary-dominated flow region and effects of multi-scale heterogeneity on CO_2 trapping, BUTSURI-TANSA, under review

7. Osamu Nishizawa, Yi Zhang, Ziqiu Xue, Rock physics research with application to CO_2 geological storage II: relationship between CO_2 saturation and P-wave velocity in a porous sandstone., BUTSURI-TANSA, under review

8. Kazuhiko Nakano, Takuma Ito, Hikari Takahara, Takao Moriyama, Ziqiu Xue, Application to rapid quantitative analysis using loose powder X-ray fluorescent analysis for sediment cores from geological CO_2 sequestration site, Advances in X-ray Chemical Analysis Japan, 46, 227-235, 2015

9. Lauren E. Beckingham, Saeko Mito, Ziqiu Xue, Evaluation of mineral reactive surface area estimates for prediction of reactivity of a multi-mineral sediment, Geochimica et Cosmochimica Acta, submitted

10. Takuma Ito, Takahiro Nakajima, Ziqiu Xue, Depositional environments and geological controlling factor of CO_2 injectivity in terms of grain-size and pore-throat size distributions: a case study of Nagaoka site, Japan, Journal of the Sedimentological Society of Japan, submitted

11. Takuma Ito, Yuhei Komatsu, Tetsuya Fujii, Kiyofumi Suzuki, Kosuke Egawa, Yoshihiro Nakatsuka, Yoshihiro Konno, Jun Yoneda, Yusuke Jin, Masato Kida, Jiro Nagao, Hideki Minagawa, Lithological features of hydrate-bearing sediments and their relationship with gas hydrate saturation in the eastern Nankai Trough, Japan, Marine and Petroleum Geology,66,368-378, 2015

Other Paper

1. Ziqiu Xue, Takahiro Nakajima, Long-term stability of CO_2 geological storage - post injection monitoring at Nagaoka site, Japanese Society for Rock Mechanics, January 2015

2. Shinichiro Hirabayashi, Toru Sato, Michimasa Magi, Tatsuo Suzuki, Numerical study on the effect of artificial mound settled in the shallow ocean for CO_2 fixation, Marine Systems & Ocean Technology 10, 1, 18-25, March 2015

3. Shigeo Horikawa, Takeshi Sasaki, Ziqiu Xue, Takahiro Nakajima, A Study on Seismic Hazard Evaluation at the Nagaoka CO_2 Storage Site, Japan, The Japanese Geotechnical Society, in print

4. Ryozo Tanaka, Global Status of CCS from Five Viewpoints, Electrical Review, October 2015

5. Ziqiu Xue, Micro bubble CO_2 technology development for CO_2 geological storage and CO_2-EOR, The Society of Chemical Engineers, Japan, November 2015

Oral Presentation (International conference)

1. Jun Kita, Environmental Impact Assessment on Offshore Geological Storage of CO_2, Japan-Norway Energy Science Week 2015, May 28, 2015

2. Ryozo Tanaka, Example of Japanese Participation to EU Framework Programme:CO_2CARE（CO_2 Site Closure Assessment Research）Project, Japan-Norway Energy Science Week 2015, May 28, 2015

3. Jun Kita, Act on Prevention of Marine Pollution and Maritime Disaster for Offshore CO_2 Storage in Japan, IEAGHG 10th Monitoring Network Meeting, Jun 04, 2015

4. Mitnick, Elizabeth H., Lauren E. Beckingham, Shuo Zhang, Carl I. Steefel, Li Yang, Marco Voltolini, Alexander M. Swift, Jonathan Ajo-Franklin, David R. Cole, Julie M. Sheets, Saeko Mito, Ziqiu Xue, Donald J. Depaolo, Impact of mineral reactive surface area approximations on predictions of mineral dissolution rates in a CO_2 injection experiment, 2015 Carbon Storage RD Project Review Meeting, Aug 18. 2015

5. Takuma Ito, Takahiro Nakajima, Shun Chiyonobu, Ziqiu Xue, Reservoir characterization of a CO_2 sorage aquifer: a case study of the Nagaoka pilot site,Japan, Asia Oceania Geosciences Society, Aug 3. 2015

6. Takahiro Nakajima, Takuma Ito,Ziqiu Xue, Effects of heterogeneity on the distribution of CO_2 in a saline reservoir at Nagaoka, Japan, 12TH Annual Meeting AOGS2015, Aug 6. 2015

Oral Presentation (Domestic conference)

1. Takuma Ito, Takahiro Nakajima, Ziqiu Xue, Spatial mud content and its implications for CO_2 geological storage: a case study of the Nagaoka site, Japan, Sedimentological Society of Japan, Apr 26. 2015

2. Saeko Mito, Ziqiu Xue, Geochemical monitoring of CO_2 underground and an evaluation technique of geochemical features, The Japan Geoscience Union Meeting 2015, May 25, 2015

3. Takahiro Nakajima, Takuma Ito, Ziqiu Xue, Shun Chiyonobu,, Effects of heterogeneity on the distribution of CO_2: Numerical

simulation in a CO_2 storage reservoir at Nagaoka, The Japan Geoscience Union Meeting 2015, May 25, 2015

4. Takuma Ito, Takahiro Nakajima, Shun Chiyonobu, Ziqiu Xue, An attempt of geostatistical modeling for spatial mud content: a case study of the Nagaoka pilot site, Japan, The Japan Geoscience Union Meeting 2015, May 25, 2015

5. Ryozo Tanaka, Current Status of CCS in the World, The Japan Geoscience Union Meeting 2015, May 25, 2015

6. Kazuhiko Nakano, Saeko Mito, Ziqiu Xue, Wellbore integrity assessment of CO_2 sequestration site from the geochemical reaction using well composite samples, The Japan Geoscience Union Meeting 2015, May 22—26, 2015

7. Keisuke Uchimoto,Yoshimasa Matsumura, Jun Kita, Yuji Watanabe, A method for assessing the impacts of leaked CO_2 on the marine environment, The Japan Geoscience Union Meeting 2015, May 25, 2015

8. Takamichi Nakamura. Tomoyuki Sato, Taro Kawamura, Trend in the development of microbial technology in carbon capture, utilization and storage(CCUS):a bottleneck in the realization of geo-bioreactors, The Japan Geoscience Union Meeting 2015, May 25, 2015

9. Tsutomu Hashimoto, Ziqiu Xue, Yoshiaki Yamauchi, Geological formation deformation monitoring by optical fiber sensing, Japan Society of Engineering Geology, Sep 24,2015, Sep 25,2015

10. Keisuke Uchimoto, Jun Kita, A method for detecting leaked CO_2 in the sea based on a relationship between DIC and DO, The Oceanographic Society of Japan, Sep 28, 2015

11. Kazuhiko Nakano, Saeko Mito, Ziqiu Xue, Observation of Well Cement after Reaction with Supercritical CO_2 for CO_2 sequestration site - 2nd report, 64th Annual Meeting of the Japan Society for Analytical Chemistry, Sep9-11, 2015

Publication

1. Kazuhiko Nakano, Chapter 7. Reference materials for XRF analysis, Recent advances in X-ray fluorescent analysis, 2nd ed. I. Nakai, Asakura shoten, Tokyo

2. Ryozo Tanaka, Update on the latest Research and Development into CCS in Japan, Coaltrans Japam

3. Ziqiu Xue, Tetsuma Toshioka, Ryozo Tanaka,, Permanent Ocean Bottom Cable System for Offshore CO_2 Storage, 6th CSLF Ministerial Meeting

4. Takamichi Nakamura, Application of microbial technology in CCS sites, Hokkaido Branch, The Mining and Materials Processing Institute of Japan Forum 2015

RITE Today 2016 Vol.11
Annual Report

Research Institute of Innovative Technology for the Earth

Research Institute of Inovative Tecnology for the Earth

URL: www.rite.or.jp/en

9-2, Kizugawadai, Kizugawa-Shi,
Kyoto 619-0292 JAPAN
Telephone: +81 774-75-2300
Facsimile: +81 774-75-2314