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Technology Demonstration, Knowledge Sharing and Non-technical Support for Large Scale Deployment of Geological CO_2 Storage

1. Introduction

The final summary of the CCS Long-term Roadmap Study Group, published by the Ministry of Economy, Trade and Industry in March 2023, clearly states the indispensable role of CCS in achieving a stable energy supply and carbon neutrality in Japan. The business environment must be developed to enable operations by 2030. The government is presenting concrete plans for commercialization in this context. In June 2023, seven "Japanese Advanced CCS projects" were selected as part of the "Japanese Support for CCS projects." In February 2024, the Cabinet approved a draft law on CCS projects which was submitted to the Diet.

In the 213th ordinary session of the Diet, the Bill for the Act on Carbon Dioxide Storage Businesses (CCS Business Act) was passed into law. The CCS business Act establishes a licensing system for storage, exploratory drilling rights, as well as business and security regulations CO_2 transport projects, and other business environment.

In technological development, the law the group will set concrete cost reduction targets and promote technological development and demonstration. RITE, as a member of the Geological Carbon Dioxide Storage Technology Research Association, is promoting technological development with application to domestic CCS projects under a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The group is developing technologies to ensure safety and reduce costs by monitoring geological formations and pipelines with fiber optic sensor technology, supporting the commercialization of CCS and producing technical manuals that will serve as a guide for CCS operators. In developing monitoring technology, we are conducting demonstration tests at domestic and overseas sites, including a commercial

CCS project site in the US. We are conducting a technical demonstration of a method to monitor the integrity of geological storage facilities, such as CO_2 pipelines and wells, and the stability of geological formations by measuring temperature, strain and acoustics using optical fibers.

In addition, we are working on technologies to support the various steps leading to commercialisation of CCS, such as the development of communication methods with local communities, the development of information on the location of emission sources, which is essential for the design of project plans, and the development of cost estimation tools to assess commercial feasibility.

Furthermore, we are also compiling a collection of technical case studies from national and international case studies to share knowledge on each stage of the CCS project, from planning to operation and post-closure. A total of seven editions have been prepared by the end of 2023 and will be made available successively.

2. Main research topics and results

2.1. Development of a fiber optic based formation integrity monitoring system

Subsurface monitoring is one of the essential elemental technologies for CO_2 geological storage projects that are being pursued in earnest in Japan and abroad. To confirm that the injected CO_2 is safely stored in the formation, in addition to monitoring the extent of CO_2 spread, monitoring of formation deformation and the extent of pressure propagation due to increased formation pressure, and monitoring of well integrity to detect any leakage are carried through. As this monitoring is carried out over a long period of time, it is necessary to use economical technology. In addition, real-time monitoring systems are expected to provide information that contributes to immediate decision making, such as changes in injection conditions. Fiber-optic sensing is a promising monitoring technology that meets these requirements.

Fiber optic sensing is a technology that measures environmental changes around an optical fiber by measuring the backscattered light generated when an optical pulse is transmitted through the fiber. Raman scattering is used to measure temperature (DTS: Distributed Temperature Sensing), and Brillouin scattering is used to measure temperature and strain (DSS: Distributed Strain Sensing). Rayleigh scattering light is mainly used for damage detection and acoustic (vibration) measurement (DAS: Distributed Acoustic Sensing) by utilizing the change in scattered light intensity due to bending, etc. Recently, Rayleigh scattering light is also used for high-precision temperature and strain measurement by utilizing its spectral change. Fiber optic sensing technology is characterized by the fact that the entire optical fiber acts as a receiver, making it possible to acquire spatially continuous records. In addition, a single fiber optic cable bundled with multiple fibers can be installed as a multi-sensor to measure temperature, strain and acoustics, significantly reducing the cost of installing a large number of sensors. In particular, the fiber optic cable is thin, with a diameter of only a few millimeters to a few centimeters, and can be easily installed in confined spaces, allowing the cable to be installed in a small gap between the formation and the outside of the steel pipe, known as the casing, that holds the well.

RITE has been conducting research and development of optical fiber sensing technology through laboratory and field tests, and is currently conducting verification tests at several domestic and overseas sites. At domestic sites, in addition to evaluating the performance of the developed fiber-optic cable and improving the installation method, the effectiveness of the technology is being verified in a CO_2 injection environment, such as injection in multiple wells, assuming a real project. Furthermore, at the CCS site in North Dakota, USA, simultaneous temperature, strain, and acoustic measurements using a single optical fiber cable are being conducted as a technical demonstration of a multi-sensing CO_2 geological storage monitoring system. In Australia, field tests are progressing at the Otway site in Victoria and the South Perth site in Western Australia to monitor leakage from shallow faults and the stability of deep faults.

The following is an overview of the field testing underway at each site.

2.1.1 Domestic test sites

At a test site in the Mobara area of Chiba Prefecture, Japan, we are conducting field tests to verify the technology of the CO_2 geological storage monitoring system using fiber-optic sensors. Various optical fibers have been installed in shallow wells at depths of around 300m, water injection and pumping tests have been carried out using wells to measure and evaluate the optical fibers. Various optical fibers were installed in shallow wells at depths of around 300m, water injection and pumping tests were carried out in the wells to evaluate the measurement ability of the optical fibers. In FY2022, a new well was drilled to a depth of over 900m, and optical fiber cables were installed to measure temperature, strain, and sound simultaneously. Through these tests, we were able to develop the technology for installing optical fiber cables, equipment, also installation method (Figure 1). In parallel, we are in the process of developing fiber optic technology for the evaluation of the cement integrity of the wellbore. The technology is expected to be a real-time monitoring technology that can be used during construction to assess cementing integrity which affects the potential leakage from an injection well at underground CO_2 storage sites.

Long-term continuous monitoring using DSS (strain measurement) has been ongoing at the site since the fiber was installed in FY2022. Strain changes caused by water injection and pumping around the site are measured and used as a technology to evaluate hydraulic properties around the site through geomechanical analysis based on optical fiber strain measurement data. This technology should lead to the efficient placement of multi-well sites, essential for future underground CO_2 storage in Japan.

Figure 1 Fiber optic installation work at a site in Japan

2.1.2 North Dakota CCS Site, USA

The North Dakota CCS project is a commercial project stores approximately 180,000 tons per year of CO_2 collected from the ethanol refining process in a saline aquifer approximately 2,000m deep underground. Injection began in mid-June 2022, and as of March 31, 2024, approximately 250,000 t of CO_2 had been stored.

In this project, fiber optic cables have been installed in four wells (one injection well, one observation well and two shallow groundwater observation wells) and along the CO_2 pipeline (Figure 2), with simultaneous measurements of DAS, DTS and DSS This project is a technical demonstration of multi-sensor technology in a single fiber-optic cable in a commercial project, and we will continue measurements until the injection of 1Mt , which is one of the guidelines for the scale of commercialization in Japan, in order to accumulate knowledge of problems and countermeasures in the operation of monitoring systems for domestic CCS projects.

Imaging techniques using repeated seismic surveys are used to map the CO_2 plume. Vertical seismic profiling (VSP), in which the receivers are placed downhole, is one of the techniques used for seismic profiling because it brings the receivers closer to the target and thus enables high-quality data acquisition. In furthermore, the use of a fiber optic cable equipped with numerous receivers as a downhole receiver reduces the noise caused by the misalignment of the receiver points and also speeds up the data acquisition.

Repeated 3D seismic surveys aimed at understanding how the CO_2 plume spreads are typically conducted every one to several years. To fill this time gap, a fixed Surface Orbital Vibrator (SOV) was introduced to allow frequent data collection.

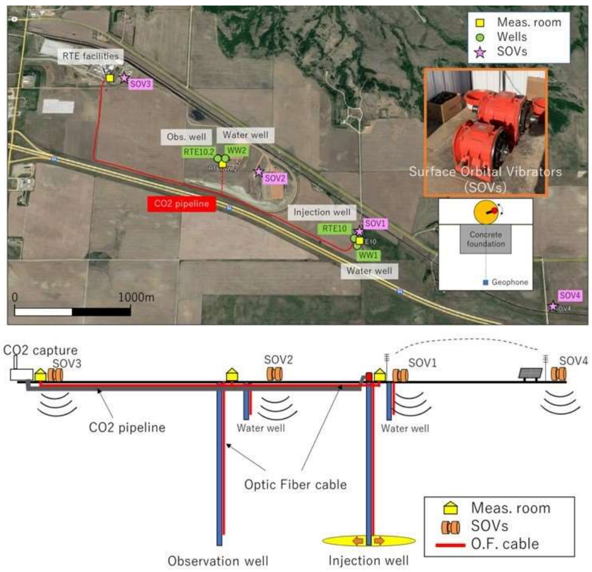


Figure 2 Overview of the fiber optic monitoring system at the North Dakota site

The SOV is a permanent vibration device that transmits vibration into the formation by means of an inclined weight mounted on a concrete block rotating at high speed. They can be remotely and automatically controlled, eliminating the need for an on-site operator to vibrate. At the North Dakota site, SOVs are installed at four locations on the site and vibrate as required. Of the recordings made, the (zero) offset recordings are used to detect the CO_2 plume immediately after injection begins, while the offset VSP recordings are used to determine the spread of the CO_2 plume. Time-lapse analysis of repeated VSP recordings is currently underway to ascertain the CO_2 spread.

In addition, DTS and DSS (temperature and strain measurement) in all sections of CO_2 pipelines and injection wells are conducted to detect any possible leakage. In the past, point measurements were taken by flow meters and temperature/pressure gauges installed at the entrance and exit of the pipeline and at the bottom of the well. Fiber optic sensing technology, on the other hand, continues real-time monitoring of the entire route section, exploiting the fact that the entire fiber is the measuring point.

2.1.3 Australia Site

The risks associated with the deployment of CO_2 geological storage projects in Japan, where there are many faults, include the effects of injection on faults and leakage from faults. To address these risks, fault zone characterization, fault stability monitoring, fault leakage detection and monitoring technology are essential. The fiber optic sensing technology developed by RITE will be an effective tool, but various tests at actual sites are essential to establish these technologies. For this reason, since fiscal 2021, we have been conducting a Japan-Australia joint research project with an Australian research institute that has a test site where known faults are distributed. A CO_2 leak detection field test from a shallow fault using fiber optic sensing technology is underway at the Otway site in southwest Victoria, Australia. The site is a demonstration test site where tens of thousands of t of CO_2 have been injected by the Australian research institute CO2CRC. Two new wells have been drilled at the site, a new fiber-optic cable capable of high performance DSS (strain measurement) has been installed and water injection tests have been conducted. Hydraulic characterization of the site and the fault is now underway using the measured data. We plan to evaluate the performance of small-scale CO_2 injection for leak detection in the future.

Figure 3 Fiber optic installation work at Otway site

At the South Perth site in south-west Western Australia, field tests are underway to assess fault stability, particularly for deep faults. At the test site, a well has been drilled through the deep fault zone and fiber-optic cables have been installed to evaluate the hydraulic and mechanical properties of the fault and fracture zone based on DSS (strain measurement) results and to assess fault reactivity. In FY2023, a new inclined well was drilled. The successful installation of the optical fiber cable in the back of the casing of the inclined well has improved the optical fiber installation technique for CO_2 geological storage monitoring. We plan to conduct fluid injection tests in the future and evaluate the hydraulic and mechanical properties of the fault using the results of the same measurements.

Figure 4 Fiber optic installation at the southern Perth site, Australia

2.2 CCS Commercialization Support

With the start of the Japanese advanced CCS support projects by JOGMEC in FY2023, the large-scale deployment and commercialization of CCS in now started.

RITE is also undertaking research and development to support large-scale deployment of CCS. Specifically, RITE has been conducting research and development on methods to promote understanding of CCS deployment areas, support for setting up appropriate CCS commercialization forms, and economic evaluation of CCS. The progress of the projects are reported below.

2.2.1 Communication with Local Communities in CCS Projects

Once the project candidate sites have been chosen, the project developers need to communicate with stakeholders and local residents to gain their understanding and support for the project. Communication activities should be conducted as early as possible with a wide range of stakeholders. The basic idea is that the communication activity should be a two-way process, with close communication with the local community at an early stage and local ideas and wishes being incorporated into the project plan, rather than a one-way communication from the project proponent to the local community, with the project proponent asking the local community to accept the project after all the project plans have been decided. RITE has conducted research on communication with local communities in the deployment of CCS projects. This paper discusses the importance of raising awareness of CCS in the early stages of communication. There have been cases overseas where local residents and stakeholders were unfamiliar with CCS and the project plan proceeded without their knowledge of CCS, leading to opposition to the project from the local community. Therefore, it is important to have local residents and stakeholders understand CCS.

In Japan, awareness of CCS is low, with about half of the general public having never even heard of the term. Therefore, it is necessary to familiarize people with the term "CCS. After all, even if there is a communication event about "CCS" that they have never heard of at all, they are unlikely to want to participate. The government considers CCS as an important option toward carbon neutrality, and advanced CCS projects started last year. We expect to see and hear the term "CCS" more often in the future, and for the time being, CCS providers also need to promote the term "CCS" as a first step in their communication activities.

As more people see and hear the term "CCS," more people are likely to search for and look up CCS. The first information a person decides to look up "CCS" is important. This information may lead them to have positive or negative opinions about CCS. Misinformation about CCS can prevail. For example, information about CCS that was spread by a celebrity social networking site immediately after the Hokkaido Eastern Iburi earth quake was considered "fake news," Initial exposure to misinformation can lead to misconceptions about CCS. It is said that once people believe information and base their ideas on that information, those ideas are not easily changed In addition, people tend to selectively accept only the information that matches their own ideas, and nowadays, through social networking services, people tend to connect only with others who share their ideas, thus reinforcing their ideas. It is therefore important that information based on scientific and academic knowledge about CCS is easy to find in searches.

However, even if it is easy to find in a search, it is meaningless if it is not read. We, RITE, have prepared *FAQs* to answer questions that the general public may have about CCS. This *FAQs* is to help people who are searching or investigating "CCS" to solve their questions. A (Answers) are designed to be readable without prior knowledge for the purpose. We plan to develop the *FAQs* to make it even more approachable and easy to read with inserting diagrams and illustrations.

2.2.2 Analysis of Local Economic impacts by deployment of CCS

When applying CCS projects, it is important to explain not only the technical and scientific aspects of CCS, but also the socio-economic benefits that the project will bring to the local community. RITE has developed methodology for analyzing the local economic impacts of CCS deployment and has applied it to actual areas to appeal the socio-economic benefits. The following outlines how to examine the benefits

① Estimation of CCS Investments

First of all, it is necessary to figure out the CCS scheme and determine the total investment amount. These are specified using the emission source data base (DB) and CCS cost estimation tool described below.

② Analysis of Economic impact by CCS investments

After determining the total amount of the CCS investments, we estimate direct, indirect and induced economic effects and the employment opportunity gains by the CCS investment.

To estimate the CCS investment impacts on the local economy, we could use the input-output table and economic effect analysis tool provided by each local government. However, "CCS" is a new industry and the existing tables and tools do not include such items. Therefore, the components of the CCS industries have examined and arranged by combining existing industry items. Finally, we produce the analysis tool fit on the CCS type and the targeted local economy. As the components of CCS projects are diverse, definition of the details of the CCS industrial structure and its procedures is a future work in progress.

③ Economic impacts of site visits

In addition to the industrial economic impacts of attracting the CCS, the host area will also benefit from the economic impact of the site visits by bringing visitors to understand what is CCS. In fact, many domestic and international visitors came to Tomakomai, Hokkaido, where the large-scale CCS demonstration was tested. It is also important to estimate the number of CCS visitors and analyze the induced impacts of their visits by referring to such previous examples. Some local governments provide tools to assess the economic impact of tourism, which should be applied.

④ Approach to improve economic benefits

The main components of the CCS industry are 'construction' and the procurement of materials and equipment such as 'general-purpose machinery'. Construction can largely be carried out locally, contributing to the expansion of economic impacts. Many materials and equipment, however, cannot be sourced in the CCS deployment area, and this is a factor in the absence of local economic stimulation.

The input-output table shows the self-sufficiency of relevant industries, and improving this value can boost the economic benefits. It provides quantitative guidance on which industries and human resources should be developed locally.

Thus, the consultation of the economic impacts of CCS will also contribute to the design of industrial development policies in the region where it is located.

⑤ CCS/CCU Coordination Effectiveness Analysis

As well as the geological storage of CO_2, the use of CO_2 (CCU) is also attracting attention. In the case of CCU, matching CO_2 supply and demand is critical. In some cases, however, the supply of CO_2 far exceeds demand, forcing the captured CO_2 to be vented. If CCS is used in conjunction with CCU, the excess CO_2 for CCU can be stored underground and create carbon reduction credits.

In other words, the use of CCS helps to reduce the uncertainty of CCU businesses and increase their predictability; this perspective is also important when discussing the economic benefits of CCS.

⑥ Application and adaptation of the analysis method

The above is an introduction to the methodology for analyzing the local economic impacts of CCS. We have already applied the method in some areas, but we would like to increase the number of practical examples of the analysis and improve its accuracy and usability in the near future. If you are considering the local economic impact of CCS, we would like to hear from you.

2.2.3 Development of CO_2 emission source database

Appropriate matching of CO_2 emission sources and reservoirs is crucial for the commercialization of CCS. Therefore, RITE is working on the development of a CO_2 emission source database (hereinafter referred to as "emission source DB") to support this matching.

Below is an overview of its data structure, functional overview, and future development.

① Data structure of the emission source DB

The Ministry of the Environment's public data based on the "Greenhouse Gas Emissions Calculation, Reporting, and Publication System" (hereafter referred to as "Greenhouse Gas Public Data") contains over 10,000 CO_2 emission source information. The Emission Sources DB is based on this information, and addresses the following a), b), and c) to fit the characteristics of decarbonization through CCS.

a) Estimation of direct CO_2 emissions and DB

The CO_2 emissions of each site in the Greenhouse Gas Public Data include the CO_2 equivalent of electricity and heat supplied by others as a numeric value. CCS collects and stores the direct CO_2 emissions actually emitted by the business site concerned, and it is needs to exclude CO_2 emissions equivalent to electricity and heat. Therefore, a "direct emission factor" is calculated for each business type using a specific statistical method, multiplied by the CO_2 in Greenhouse Gas public Data, and the direct CO_2 emissions from each business site are determined for the database.

b) Inclusion of biomass fuel CO_2 emission source information

The data of the Greenhouse Gas public Data covers CO_2 emissions from fossil fuels, while CO_2 emissions from biomass fuels are not covered because they are carbon neutral. On the other hand, biomass power plants also emit CO_2, which can be captured and stored for BECCS and negative emissions, which are important factors in promoting decarbonization. Therefore, we are also investigating CO_2 emission source information from biomass fuels with reference to information from the Agency for Natural Resources and Energy's Electricity Survey Statistics, etc., to estimate CO_2 emissions and incorporate them into the emission source DB.

c) Reflection of storage potential information

Mapping information on storage potentials from the National Reservoir Availability Survey conducted by RITE is also reflected in the emission source DB.

② Information mapping and screening capabilities

a)Mapping of emission sources with potential reservoirs

In order to properly match emission sources and reservoirs, it is important to visually grasp their location. Therefore, we realized a function to map the data shown in ①. Figure 5 is an example of such a mapping, where emission sources are concentrated on the Pacific Ocean side and reservoirs are mostly located on the Sea of Japan, and their geological characteristics can be easily captured.

Figure 5 Example of integrated display of CO_2 emission source and storage potential

b) Information screening function

The visualized map can be moved freely, and specific areas can be zoomed in on. In addition, information on emission sources can be extracted by circling an area, which can be used to cluster emission sources. It is also possible to display emission sources by type, such as coal-fired power plants and factories. For example, if the display is limited to CO_2 emission sources from biomass fuels, it can contribute to the development of CO_2 offsetting strategies through BECCS.

③ Work towards the Platform to Help Commercialization of CCS

In anticipation of the large-scale and full deployment of CCS, the ability to map existing gas pipelines, the screening of inland emission sources at a certain distance based on the concentration of CO_2 emissions will be added over time to the features already described. The commercialization of CCS requires the cooperation of a wide range of stakeholders, including policy makers, engineers, investors and business managers, to steer the direction of the project.

This database will facilitate quick access to required information and the sharing of information between stakeholders using the visualization function. In addition, we plan to link it with other support functions, such as the CCS cost estimation tool to be introduced next, to create a platform that accurately supports the commercialization of CCS. If you have any comments or requests regarding this DB, please let us know.

2.2.4 Development of CCS cost estimation tool

This tool has been developed to enable industrial companies to compare the costs of several possible project types. In addition to estimating a range of costs from capture to storage for stand-alone CCS, the tool also includes cost estimates for hubs and clusters where multiple emitters are aggregated in coastal areas.

The latter multiple emitter cost estimation tool is also useful to specifically assess the extent to which the proposed configuration of aggregation groups using the source database (2.2.3) is expected to reduce costs, or whether such a configuration is the best one. Furthermore, because this tool can perform calculations at high speed, results can be checked in real time as parameters are changed. We therefore believe that the tool will be used to support the trial and error process of finding the optimal deployment of a CCS project.

① The cost that the tool can estimate

Assuming CCS in Japan, the tool includes options for each of the capture, transport and storage processes. For example, coal-fired and LNG-fired power plants are among the options for capture while onshore, offshore pipelines and maritime transport are among the options for transport.

In addition to these process-related options, the project period annual CO_2 throughput, discount rate, and exchange rate can be set as options related to the entire CCS project. By selecting and combining these options, users can build the CCS they envision in the tool.

② An example of estimation

Here we present an example of estimation in the storage process. As most storage in Japan is considered subsea, this tool targets subsea storage. The sea area setting is determined by the offshore distance water depth of the storage location, and the system automatically selects one of the following three methods: A. Injection from land (Tomakomai method), B. Injection from a fixed base (jack-up method), or C. Injection from a floating base (semi-submersible method).

Figure 6 shows the three storage methods compared in this study. The left side of the figure shows an image of the storage system, and the right side shows the assumptions used in the estimation.

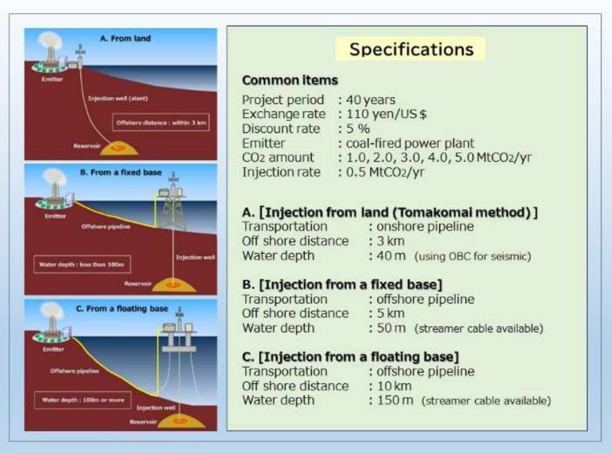


Figure 6 Illustration of storage methods

In addition, the injection of CO_2 into the subsurface requires associated monitoring, so the monitoring costs are also included in the estimation of the storage process.

Figure 7 shows the difference of the costs storage methods.

During the test calculation, we varied the amount of CO_2 (injection volume) in five steps from 1 Mt/yr to 5Mt/yr, and examined how much economies of scale would occur.

The figure shows that the lowest storage cost was achieved by injecting from land, followed by a fixed base type and the floating type. Regarding economies of scale, the floating type was effective up to 3Mt /yr, but not at higher CO_2 throughputs. For the other storage methods, economies of scale were small or almost nonexistent.

In terms of monitoring, on the other hand, economies of scale were found to significant in all three storage methods. In terms of cost, injecting from land was more expensive than the others. This may be because the water depth setting was 45 m, which did not allow for seismic exploration using streamers, therefore seismic exploration using an ocean bottom receiving cable (OBC) was employed.

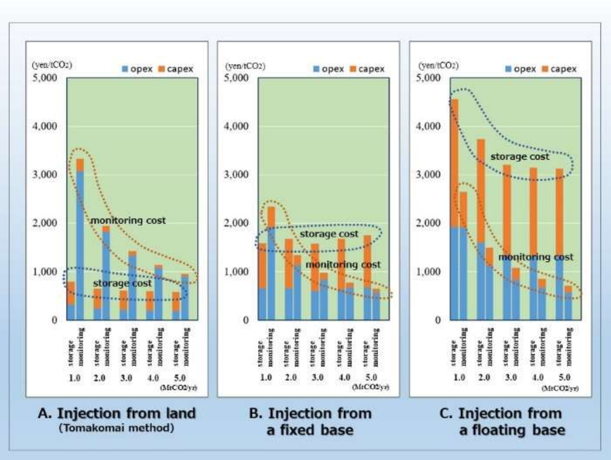


Figure 7 Difference in the cost of storage method

③ Considerations for networking of emitters

In terms of reducing the cost of CCS, the networking of emitters in hubs, clusters and the processing of large quantities of CO_2 can have a significant cost-reducing effect. As networking is a cost-reducing measure that can be implemented with existing technologies, the idea of clustering emitters for joint implementation is a natural concept. In this section, we will explore which of the two networking groups forming in a given coastal area would be more advantageous for intermediate emitters to join.

Figure 8 shows an image of the consolidation group formation process. The figure shows that there are two groups under consideration, Group A and Group B. The setting is that there is a difference in the total amount of CO_2 already contracted between Groups A and B. It is assumed that Group A and Group B have 3Mt/yr and 1.5M t/yr of CO2 secured, respectively. It is also assumed that emitter X bears the cost of the onshore pipeline from emitter X (1 Mt/yr) to the hub of each group, and that the ship transportation distance and storage method are the same for both groups. The distance between Port A and Port B was assumed to be 100 km (with a hub at each port).

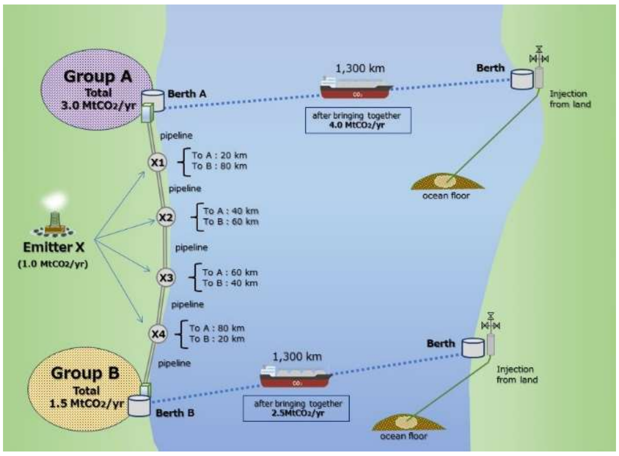


Figure 8 Image of CCS facilities grouping formation

Figure 9 shows the relationship between distance from emitter X to port A and CCS costs. The purple line shows the cost of using Port A and the orange line shows the cost of using Port B. The top figure in Figure 9 is for the case where emitter X implemented CCS alone and was not affected by the networking group, so both costs simply meet at the midpoint between the two ports (50 km).

On the other hand, in the lower panel of Figure 9, emitter X is affected by the networking group, and Group A, which originally had a larger CO_2 processing scale, has a larger cost reduction than Group B. As a result, the purple line has moved more downward, and thus the intersection of the lines has moved to the right. This shows that for emitter X, it is less expensive to participate in group A when the distance from port A is within 80 km, and beyond that, i.e., when the distance from port B is within 20 km, it is less expensive to participate in group B.

Note that in the above discussion, we considered only the CO_2 throughput and distance from source X for Groups A and B. In reality, there are many variations. For example, Groups A and B could have different shipping distances, different storage methods, different injection rates, different project periods, and even one of the groups could bear the cost of laying the pipeline.

④ Working towards the release of the tool

At this point, we have completed the installation of the planned costing engine, which allows us to perform the trial calculations shown above. On the other hand, in order to make the tool publicly available, it is necessary to provide an interface that is easy for anyone to understand, and at the same time, it is important to provide easy-to-understand output in the form of charts and diagrams. Furthermore, since this tool will be released as a web system, measures against cyber-terrorism are also considered essential.

After completing these various tasks, we plan to conduct tests (field tests) before releasing the system to the public on the Internet, and release it to the public once its reliability and stability are confirmed.

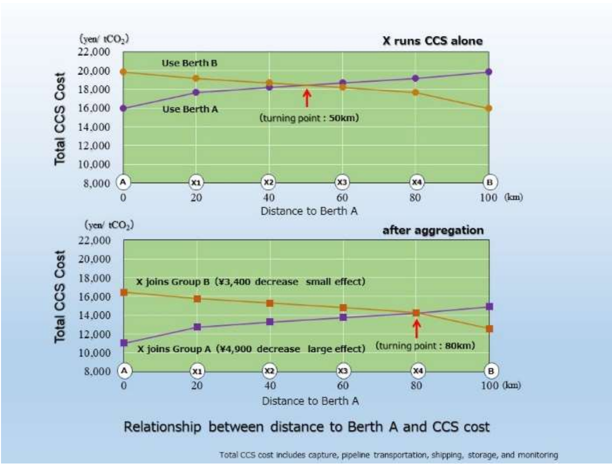
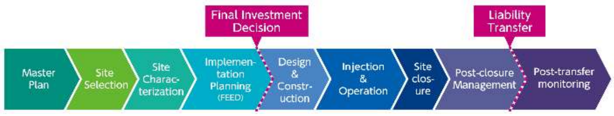


Figure 9 Distance from emission source X to port A and CCS Cost Relationship

2.3. Practical Guidance

RITE has been working on the development of various technologies and methodologies, including monitoring technologies, for the practical application of CO_2 geological storage technology. Based on the results of these efforts, RITE has been is preparing a *Practical Guidance for Geological CO_2 Storage* (hereinafter referred to as this *Practical Guidance*) as part of the development of conditions and standards for the widespread use of CCS.

Designed as a reference for future CCS operators, this collection of case studies summarizes national and international technical information and case studies on geological storage of CO_2. For example, the main findings of "Development of Carbon Dioxide Geological Storage Technology" (FY2000-2007; Nagaoka CO_2 Injection Demonstration Test), "On Safe Implementation of CCS Demonstration Project" (2009, METI), "Large-scale CCS demonstration test project in Tomakomai" (2022, METI, et al.), etc. Manuals and guidelines summarizing the results of large-scale geological CO_2 storage projects by overseas organizations are also referenced. Figure 10 shows the overall CO_2 geological storage project described in this *Practical Guidance*.



- Master Planning ------------- Development of a master plan for a CCS
- Site selection ---------- Extraction of multiple candidate storage sites
- Decision on the site ---- Evaluation of the characteristics of candidate sites, selection of the optimal site, and conceptual designs
- Implementation planning---- Development of implementation plans, basic designs, and economic evaluations
- Design and construction------ Detailed design and construction, such as project equipment and the development of a management plan
- Operation and management -- Operation and management of sequestration and execution of the monitoring plan
- Site closure ------------------------------- Plugging the injection well
- Post-closure care---- Site care until project responsibility is transferred

Figure 10 Overall structure of the CO_2 geological storage project

(1)Master Planning

The overall picture/basic concept of the project (including economic feasibility study), work policy and content in each phase, timetable, etc. are presented.

(2) Site selection (screening)

Based on the overall plan presented in the master plan, candidate site(s) that meet the requirements as CO_2 storage site(s) will be selected using existing geological data.

(3) Decision on the site

CO_2 Geological data will be gathered for candidate storage sites as necessary and evaluated in detail. A geological model will be developed and the CO_2 storage capacity will be evaluated by injection simulation, and an economic and risk assessment will be performed based on the conceptual design of transport and injection facilities. As a result, the injection site will be finalized.

(4) Implementation planning

Based on the results of the site characterization, develop a specific project deployment, work plan for CO_2 injection operations and monitoring. Make a final investment decision including total project cost/economics study, risk assessment, etc., and submit the deployment plan for project application to the regulatory authority.

(5) Design and construction

Once the project is approved by the regulatory authority, the detailed design of the injection and transportation facilities, etc. is carried out on the basis of the conceptual and basic designs made up to that point, as well as the construction and commissioning.

(6) Operation and management

Injection operations will be carried out according to the deployment plan. The spread of the CO_2 plume injected underground and pressure changes in the reservoir will be monitored, and if there are deviations from the CO_2 behavior simulation, the geological model will be improved to develop the accuracy of the long-term behavior prediction. Monitoring of CO_2 leakage will also be conducted.

(7) Site closure

Upon completion of CO_2 injection, the injection well will be closed, all facilities will be removed except those required for post-closure monitoring. Following site closure, confirmation of CO_2 behavior and leak monitoring will continue. After some time, when the regulatory authority determines that the site is safe, the site management and other operations will be transferred to a public organization.

Figure 11 *Practical Guidance for Geological CO_2 Storage, Series 1-7*

Series 1-7 of *Practical Guidance*, has been written and will be uploaded successively on websites of METI and NEDO to share the knowledge with the Southeast Asia and the rest of the world.