Carbon Sequestration Technology - Current Status and Future Outlook[1]

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Foreword

Japan and the countries of the European Union ratified the Kyoto Protocol in 2002, and the prospects for its effectuation now depend on whether or not it is ratified by the Russian Federation. Under these circumstances, the countries which ratified the Protocol are making steady preparations for specific measures to reduce their emission levels through the Kyoto mechanisms, i.e., Clean Development Mechanism (CDM)/Joint Implementation (JI) projects and emissions trading. The Protocol's second pledge period is also becoming a subject of advance discussion. Japan consequently must consider the matter and take account of the possible countermeasures for global warming over the medium and long terms in the process.

Meanwhile, the cost of reduction of greenhouse gas (GHG) emissions in Japan are projected to be higher than in other countries. Consideration of this area therefore demands studies of reduction means resting on perspectives differing from the conventional ones and technological innovation. One type of technology which is coming to the fore in this context is carbon sequestration. With both technical and economical feasibility, sequestration would have great potential for emission reduction in Japan, and be of vital value to Japanese strategy for mitigating global warming. This paper focused on carbon sequestration technology in light of the following three factors: 1) the necessity of measures anticipating technical innovation, formulated from the medium- and long-term perspectives (e.g., the next round of discussion on the Kyoto Protocol); 2) examination of measures with premises differing from those of emission-suppressing technology; and 3) the costs of emission reduction in Japan, which are higher than those in other countries, and the potential for cost decreases and emission reductions in implementation as a domestic measure. This paper presents the results of an assessment of its current status and future outlook, based on its

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technical application possibilities and cost comparison with other countermeasures for global warming.

1. International scheme of carbon sequestration

Internationally, carbon sequestration is being promoted by various entities, including the Carbon Sequestration Leader Forum (CSLF)[2] and the Council for Science and Technology Policy[3] in the Cabinet Office of the Japanese Government. Although there is mention of carbon sequestration as a promising technology in the Kyoto Protocol, Marrakech Agreement, and third report of the Intergovernmental Panel on Climate Change (IPCC), the detailed operating rules have not yet been established, and the technology is not in actual application for emission reduction as a result.

To take a step forward in this situation, the 20th meeting of the IPCC (held on February 2003) produced an agreement on completion of a special report on carbon sequestration in 2005. This report is expected to advance international discussion on the rules to be applied in carbon sequestration. As such, it is important for Japan, too, to deploy an active campaign to pave the way for extensive application of carbon sequestration.

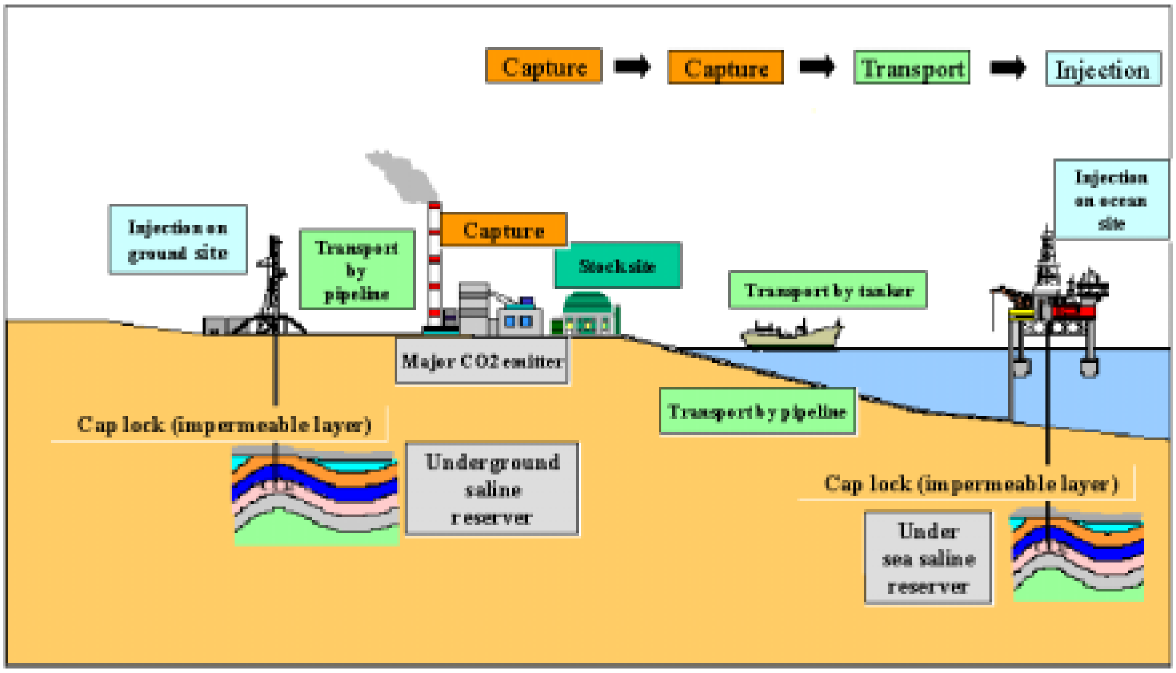
2. Features of carbon sequestration technology

The term "carbon sequestration" refers to the sequence of processes whereby CO_2 emitted from large-scale CO_2 emission sources is separated, recovered, and stored under the ground or at sea (see Figure 2-1). More specifically, the exhaust gas (mainly from combustion) from large-scale CO_2 emission sources such as power plants and steel mills first undergoes a process of separation and recovery exclusively for CO_2 utilizing chemical reactions or the properties of CO_2. This is followed by transportation to the storage site by pipeline or tanker (the latter requiring liquefaction). The sequestration is completed with the forced injection of the transported CO_2 into the ground or in the sea.

[2] Resting on an international charter proposed by the United States of America, the CSLF was founded for the purpose of building a framework for international cooperation and R&D related to carbon separation, recovery, transport, and storage as a means of reducing GHG emissions. As of July 2003, it had a membership of 15 countries and territories, including Japan, the EU, India, and China as well as the USA.

[3] In a determination made on 21 April 2003, the Council positioned carbon sequestration as a subject of research and development with an enormous potential for reducing GHG emissions and high need for priority approaches over the medium and long terms, amid the promotion of technical R&D aimed at mitigating global warming.

Figure 2-1 Conceptual diagram of carbon sequestration



Source: data on the major FY2000 results of industrial technology R&D projects, displayed on the METI website

Below is a profile of two cases of carbon sequestration currently under way.

- Sleipner gas field (Norway): Separation and recovery, by chemical absorption (amine method), of CO_2 from natural gas produced at a natural gas field off the coast beginning in 1996; injection of 1 million tons-CO_2 per year (avoidance of carbon tax at a rate of about 50 dollars per ton-CO_2) into aquifers.
- Weyburn EOR* (USA and Canada): Separation and recovery of CO2 by chemical absorption (amine method) from a synthetic gas plant beginning in 2001; transportation of 5,000 tons-CO2 per day for a distance of 330 km by pipeline for injection into an oil field to enhance oil recovery (however, there is speculation that 50% of the injected CO2 could be reemitted, and the matter is still being researched) * EOR = enhanced oil recovery

These cases are important for their aspect of researching carbon storage while operating on a commercial basis. In both, the research is moving ahead along with efforts to establish monitoring methods for CO_2 behavior underground.

3. Main emission sources in Japan

Table 3-1 shows the main CO_2 emission sources and levels in Japan in fiscal 2001. Taken together, the industrial sector and power sector account for about 50 percent of Japan's total GHG emissions. If application of carbon sequestration measures became feasible in terms of both technology and cost, it would give Japan an enormous potential for future emission reduction.

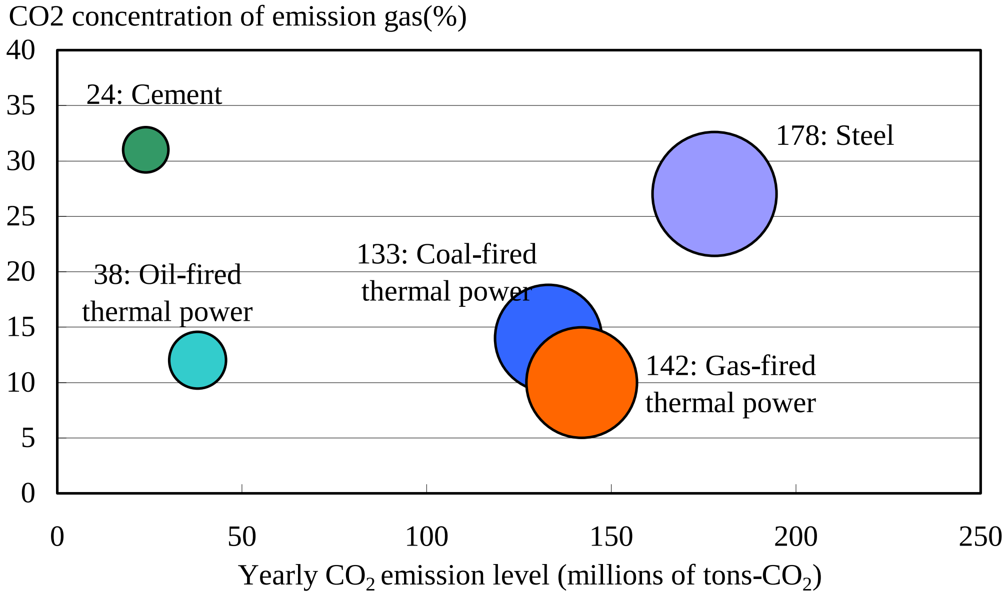
Table 3-1 Main CO_2 emission sources and levels in Japan

		Emission level (tons-CO2)
Power plants	Gas-fired thermal power	142 million
	Coal-fired thermal power	133 million
	Oil-fired thermal power	38 million
General manufacturing facilities	Steel plants	178 million
	Petrochemical complexes	74 million
	Oil refineries	43 million
	Paper/pulp mills	29 million
	Cement plants	24 million

Source: Emission levels for power plants were calculated on the basis of data from "Factors of Change in GHG Emission Levels in FY2001" (prepared by the Ministry of Environment) and the prime units of CO_2 emissions presented in a report by the Central Research Institute of Electric Power Industry (CRIEPI). Those for general manufacturing facilities are from the results of the fifth follow-up study on the Japan Federation of Economic Organizations voluntary action plan (including the power sector).

The CO_2 concentration of the exhaust gas influences the efficiency of separation and recovery; they become more cost-efficient as the concentration rises. As shown in Figure 3-1, in the case of gas-fired thermal power plants, the CO_2 concentration (carbon intensity) of exhaust gas is low because these plants burn natural gas, and this leads to a lower economic efficiency in CO_2 separation and recovery.

Figure 3-1 Yearly emission volume and CO_2 concentration of emission gas



4. Separation and recovery methods and their characteristics

The CO_2 in exhaust gas is separated and recovered from this gas at the emission source. Several methods of separation and recovery for CO_2 in exhaust gas are being researched and developed (see Table 4-1), and some are already at a level permitting practical utilization. Chemical absorption has already been commercialized in a form making use of an amine solution for the absorbent (this is applied in both the Sleipner and Weyburn projects), and is thought to be commercially feasible even at present. However, recovery of CO_2 from the liquid absorbing it requires a lot of thermal energy. As a result, the cost of separation and recovery occupies about 70 percent of the total cost of emission reduction through carbon sequestration, and improvement of the efficiency of this process is a key task.

Polymer membrane separation is being researched and developed as a low-cost method. The membranes per se are costly, but recovery does not require a lot of energy. If it reaches the stage of practical utilization, this method is therefore expected to reduce separation and recovery costs.

Table 4-1 Separation & recovery methods and their features

Separation & recovery methods		Features
Absorption method	Chemical absorption	The chemical reaction of a CO2 absorbent is applied to separate CO2. A large amount of energy (steam) is needed to extract the absorbed CO2. The method yields a CO2 recovery rate of 90 percent and a purity of 99.9 percent.
	Physical absorption	An absorbent is utilized to physically absorb the CO2, which is then recovered through pressure reduction (heating). The recovery rates and purity are on about the same level or slightly below those of chemical absorption (by the amine method).
Adsorption		CO2 is brought into contact with activated charcoal or some other adsorbent, and physicochemically adsorbed by its micropores. The CO2 recovery rate and purity are reportedly 90 and 99 percent, respectively.
Membrane separation	Polymer membrane	CO2 is separated by means of the difference between gas speeds of transmission through the polymer membrane.
	Liquid membrane	CO2 is separated by a membrane holding a carrier substance that selectively transmits CO2. At present, this method is at the stage of basic research.
	Inorganic membrane	Separation is effected by the surface diffusion flow arising in transmission through a porous material.
Oxygen combustion		Fossil fuels are combusted in oxygen to raise the CO2 concentration of the exhaust gas to nearly 100 percent. Testing has confirmed that this method can obtain exhaust gas with a CO2 concentration of 94 or 95 percent.
Sublimation		CO2 in gas is sublimated and recovered in the form of dry ice.
Cryogenic separation		A mixture that is a gas at normal temperature is cooled to a low temperature and separated into its constituent fractions by partial liquefaction for distillation or partial condensation.

5. Transportation methods and their characteristics

Upon its separation and recovery from exhaust gas, the CO_2 is transported to the storage site. Table 5-1 shows the transportation methods and their characteristics. Transportation by pipeline is an efficient method when the source is near the storage site. Conversely, transportation by tanker is more efficient than other methods if the storage site is far from the source. In the case of pipelines, the transportation efficiency is increased by compressing the separated and recovered CO_2 until it is in a supercritical state, and steps must be taken to prevent pipeline corrosion. In the case of transportation by tanker, the separated and recovered CO_2 must be liquefied, and this liquefaction cost cannot be overlooked. There would be no need to build tankers especially for CO_2; judging from its properties, the liquefied CO_2 could be carried in tankers normally used for liquefied petroleum gas (LPG).

Table 5-1 Transportation methods and characteristics

Method	Features
Pipeline	When the storage site is close to the emission source, pipelines can be used to transport the CO_2 resulting from separation and recovery to the storage site in a supercritical state (in which the gas and liquid densities are the same and make it impossible to distinguish the two).
Tanker	When the storage site is far from the emission source (e.g., in another country), tankers can be used to transport the separated and recovered CO_2 in liquefied form to the storage site.

6. Storage sites and their characteristics

Upon transportation to the storage site, the CO_2 is forcibly injected into locations underground or at sea. These storage methods can be classified as shown in Table 6-1 in terms of the location and objective. With the crude oil recovery and coal bed methane recovery methods, the storage of CO_2 has simultaneous by-products (oil and methane gas, respectively). Considering the utilization of these by-products, these methods could reduce the cost of carbon sequestration.

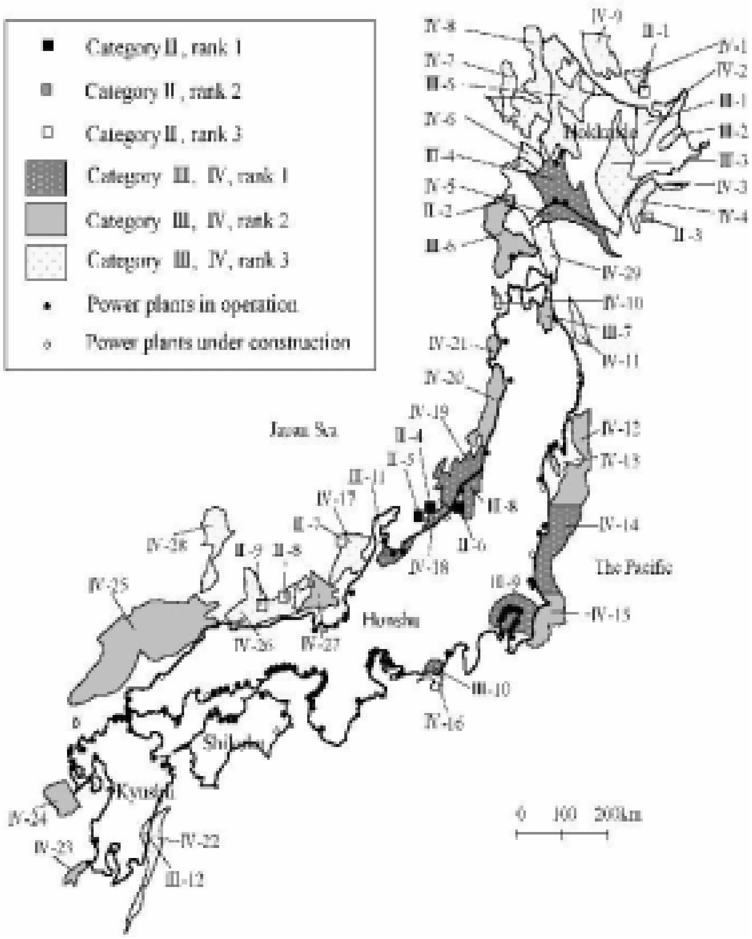
Taking 1990 as the base year, the worldwide capacity for CO_2 storage of the underground type (land) alone is estimated at 280 years, i.e., enough to store 280 years' worth of GHG emissions on the 1990 level. Carbon sequestration therefore is capable of long-term application as a means of mitigating global warming. However, the behavior of CO_2 underground and in the sea has not yet been elucidated, and many technological uncertainties remain to be resolved. For example, there is a need for assessment of the long-term effect of storage on the environment, the influence of earthquakes, and storage potential, as well as the establishment of procedures for detecting leakage and monitoring.

Table 6-1 Storage methods

Sequestration methods		Description	Storage capacity (worldwide)
Underground sequestration	Crude oil recovery	Injection of CO_2 into oil fields on the occasion of tertiary recovery of crude oil, to induce recovery	73.3 - 238.8 billion t-CO_2
	Coal seam methane recovery	Adsorption of CO_2 in unexploitable deep-stratum coal seams, with simultaneous recovery of methane	146.7 billion t-CO_2
	Depleted oil and gas wells	Use of the storage capacity of oil and gas fields that had held reserves of oil and natural gas; proven storage capacity	Oil wells: 366.7 billion t-CO_2 Gas wells: 1,466.7 billion t-CO_2
	Aquifers	Dissolution of CO_2 in underground salt water subject to virtually no fluctuation	At least 3,666.7 billion t-CO_2
Sea-bottom sequestration	Marine dissolution	Injection of CO_2 into the sea to dissolve and diffuse it; termed "gas dissolution" in the case of injection in a gas state and "liquid dissolution" in that of injection in a liquid state	3,666.7 billion t-CO_2
	Deep-sea injection	Formation of CO_2 pools in sea-bottom depressions; expected isolation period of at least 2000 years	
Biological sequestration		Sequestration by flora (plants, sea weed, vegetable plankton, etc.) through photosynthesis	Flora on land: 4.4 billion t-CO_2 per year

Candidate storage sites in Japan are distributed along the coast. Their combined storage capacity, excluding coal bed, is estimated at 75 years in the aforementioned terms, again taking 1990 as the base year (see Figure 6-1). Achievement of storage up to this potential would give Japan a means of global warming mitigation that would be effective into the long term.

Figure 6-1 Sites and possible amounts of storage in Japan



Legend
Category I : depleted oil fields and gas wells
Category II : alluvial basins with a cap lock structure
Category III : inland sites
Category IV : marine sites

Rank 1: capacity of at least 50 million tons-C and location no more than 50 kilometers away from the nearest thermal power plant
Rank 2: capacity of at least 50 million tons-C and location more than 50 kilometers away from the nearest thermal power plant
Rank 3: capacity of less than 50 million tons-C

Source: RITE website

Class	Definition	Possible amount of storage
Category 1	oil and gas seams in large oil and gas fields already discovered, and aquifers	About 2 billion tons
Category 2	confirmed aquifers with anticline structures, found by basic trial boring performed by the authorities in the past	About 1.5 billion tons
Subtotal	possible amount of storage in proven trap structures	About 3.5 billion tons
Category 3	confirmed aquifers without anticline structures in alluvial basins in land areas	About 16 billion tons
Category 4	aquifers without anticline structures in alluvial basins in sea areas	About 72 billion tons
Subtotal	possible amount of storage in ordinary aquifers	About 88 billion tons
Total	possible amount of CO_2 underground storage in Japan and the seas in its vicinity	About 92 billion tons

Source: Engineering Advancement Association of Japan (ENAA)

7. Carbon sequestration technology - current status and future outlook

Carbon sequestration is on a level permitting practical utilization as far as the technology is concerned (see Table 7-1), but there remain numerous issues requiring study.

Of the types of CO_2 separation and recovery from exhaust gas, enhanced oil recovery (EOR; separation and recovery by chemical absorption) has already been established on commercial footing. In the area of transportation technology, pipeline transportation is being practiced in EOR, and tanker transportation is thought to be free of problems, seeing that LPG tankers could probably be used. However, injection underground requires elucidation of the impact on the environment (e.g., on organisms and ground water), even though EOR has been commercially established. Storage at the sea raises even more apprehensions about environmental impact than underground storage and demands careful research.

Table 7-1 Applicability of carbon sequestration technology

		Applicability	Reason
Separation and recovery		◎	EOR commercialization (Weyburn), Sleipner gas field
Transport	Pipeline	◎	EOR commercialization (Weyburn)
	Tanker	○	Application of LNG tankers
Storage	Underground	○	EOR commercialization (oil fields), Sleipner gas field (aquifer)
	Sea-bottom	△	At the stage of research

(Note) ◎ : already at the stage of practical utilization
○ : possible
△ : requires further study

8. Cost - current status and future outlook

This section presents trial calculations of the cost of CO_2 emission reduction through the current carbon sequestration technology. The calculations were based on the following specific prospective cases.

1) Storage in a domestic coal mine
- Emissions from a coal-fired thermal power plant (with a generative capacity of 1 million kW), transportation by pipeline (for a straight-line distance of 50 km and with an installation length of 100 km), and storage in an exhausted coal mine in Japan

2) Storage in a depleted oil field overseas
- Emissions from a domestic coal-fired thermal power plant (with a generative capacity of 1 million kW), liquefaction, transportation by LPG tanker (for a distance of about 4,300 km to Malaysia), and storage in a depleted oil field

3) Emissions from natural-gas-fired power plants
- Same as Case 1, but emissions from a natural-gas-fired thermal power plant instead of a coal-fired one

4) Storage in domestic aquifers
- Same as Case 2, but storage in a domestic aquifer

Coal-fired thermal power plants were selected for the prospective cases because of their high level of CO_2 emissions, the commercialization of chemical adsorption for CO_2 separation and recovery from their emissions by the EOR method, and their location in coastal areas facilitating transportation and storage. Table 8-1 shows the premises of Case 1 and Case 2. In Case 2, the separated and recovered CO_2 would be transported by LPG tanker. Considering the current load capacity of such tankers and the level of CO_2 recovery, the transportation would require voyages at the rate of one tanker per week.

Table 8-1 Requirements in prospective cases

(1) Domestic coal mines

Coal-fired thermal power plant	Separation and recovery	-	Pipeline transport	Injection (exhausted coal mine)
- Generated output: 1 million kW - Emission gas flow: 2.004 million Nm^3/h - Emission gas CO_2 concentration: 13.2%	- CO_2 recovery level: 11,224 t-CO_2/day - CO_2 recovery rate: 90% - Recovered CO_2 concentration: 99.9%	-	- Transport distance: 100 km - Input pressure: 10.6 MPa - Output pressure: 8.1 MPa - Interim pressure increase - Pipe diameter: 20"	- Injection pressure: 15.2MPa

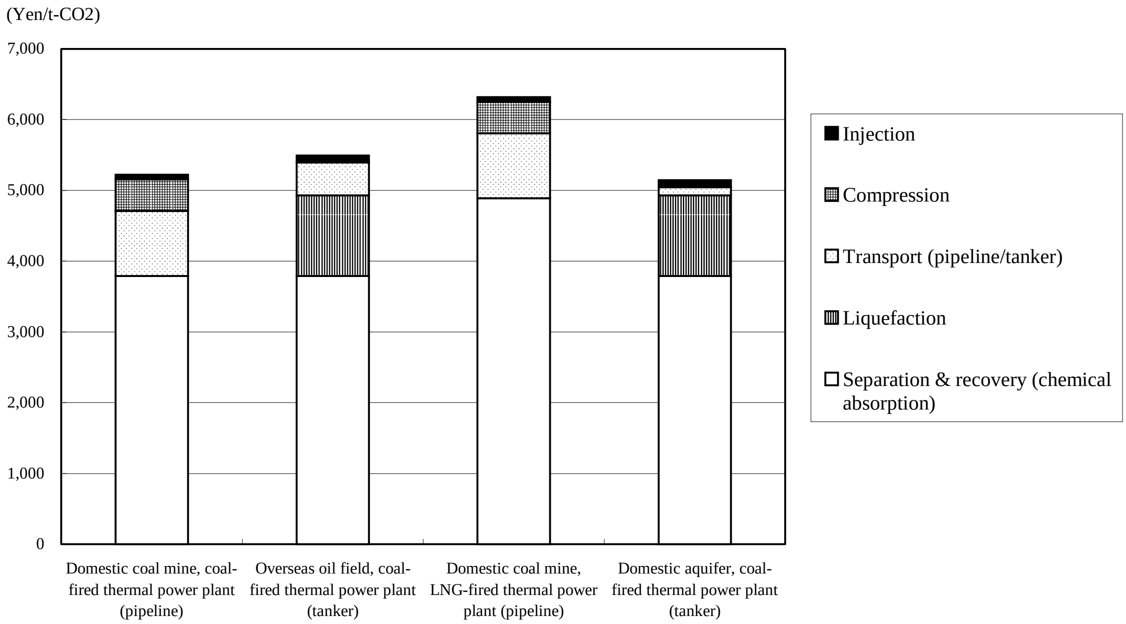
(2) Overseas oil field

Coal-fired thermal power plant	Separation and recovery	Liquefaction	Tanker transport	Injection (depleted oil field)
- Generated output: 1 million kW - Emission gas flow: 2.004 million Nm^3/h - Emission gas CO_2 concentration: 13.2%	- CO_2 recovery level: 11,224 t-CO_2/day - CO_2 recovery rate: 90% - Recovered CO_2 concentration: 99.9%	- Liquefaction pressure: 0.7 MPa - Liquefaction temperature: -50 C	- Transport distance: 4,300 km - Type of tanker: LPG - Load capacity: 78,000 m^3 (1 vessel per week) - Based on a long-term contract	- Injection pressure: 15.2 MPs - No need for overland transport

Source: based on data from the FY2001 NEDO report on investigative research concerning CO_2 separation and recovery technology by RITE/MRI and the FY1992 NEDO report on the second phase of an study concerning systems for CO_2 recovery from thermal power plants

Figure 8-1 shows the cost breakdown in each case. In all cases, the most expensive process would be CO_2 separation and recovery, which would account for about 70 percent of the total cost. The reduction of the cost of this process would consequently be a key priority for promotion of carbon sequestration. Cases 1 and 3 would eliminate the cost of CO_2 liquefaction because they are premised on transportation by pipeline, but would entail a pipeline construction cost and compression cost for transportation. In Case 2, the recovered CO_2 would have to be liquefied for transportation by tanker, and the combined cost of liquefaction and transportation (tanker fees) would be higher than the total cost of Case 1. To bring the transportation cost down, it would be vital to select storage sites close to the emission sources. Comparison of cases 1 and 3 in respect of the source difference reveals that a gas-fired thermal power plant would be marked by a lower recovery efficiency and relatively high separation and recovery cost due to the lower CO_2 concentration of the emission gas.

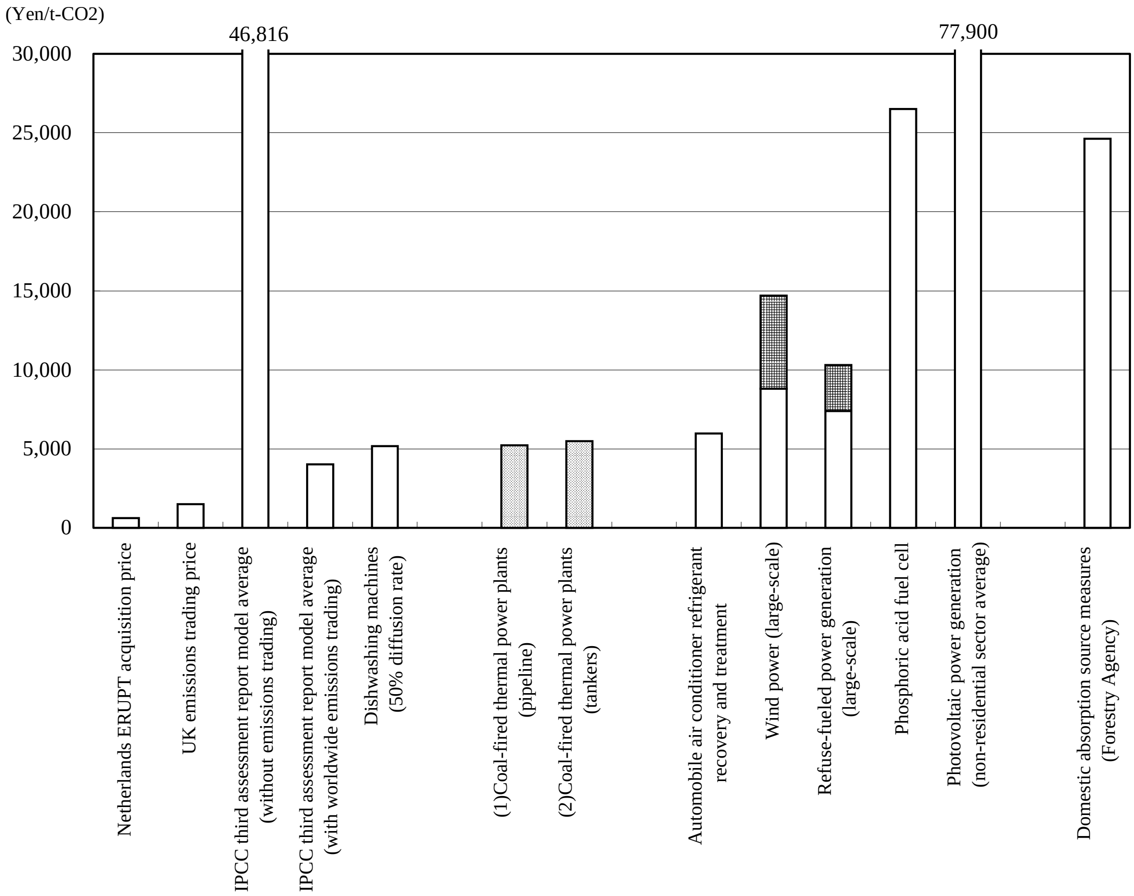
Figure 8-1 Cost breakdown in prospective cases



			Separation and recovery (chemical absorption)	Lique-faction	Transport (pipeline/tanker)	Compression	Injection	Total (yen/t-CO_2)
1	Domestic coal mine	Coal-fired thermal power plant (pipeline)	3,791.0		918.3	444.1	67.4	5,220.9
2	Overseas oil field	Coal-fired thermal power plant (tanker)	3,791.0	1,140.8	461.9		99.6	5,493.3
3	Domestic coal mine	LNG-fired thermal power plant (pipeline)	4,889.0		918.3	444.1	67.4	6,318.9
4	Domestic aquifer	Coal-fired thermal power plant (tanker)	3,791.0	1,140.8	112.0		99.6	5,143.4

Figure 8-2 compares the cost of CO_2 emission reduction in cases 1 and 2 with those of other measures to mitigate global warming. The cost of emission reduction by carbon sequestration is currently higher than those of overseas CDM/JI projects and international emissions trading, but on a par with or lower than those of domestic measures for energy conservation and promotion of renewable energy. It is therefore thought that, even under the current cost structure, carbon sequestration would be fully practicable as a means of reducing domestic emissions, once all preparations have been made as regards assessment of environmental impact and establishment of international rules.

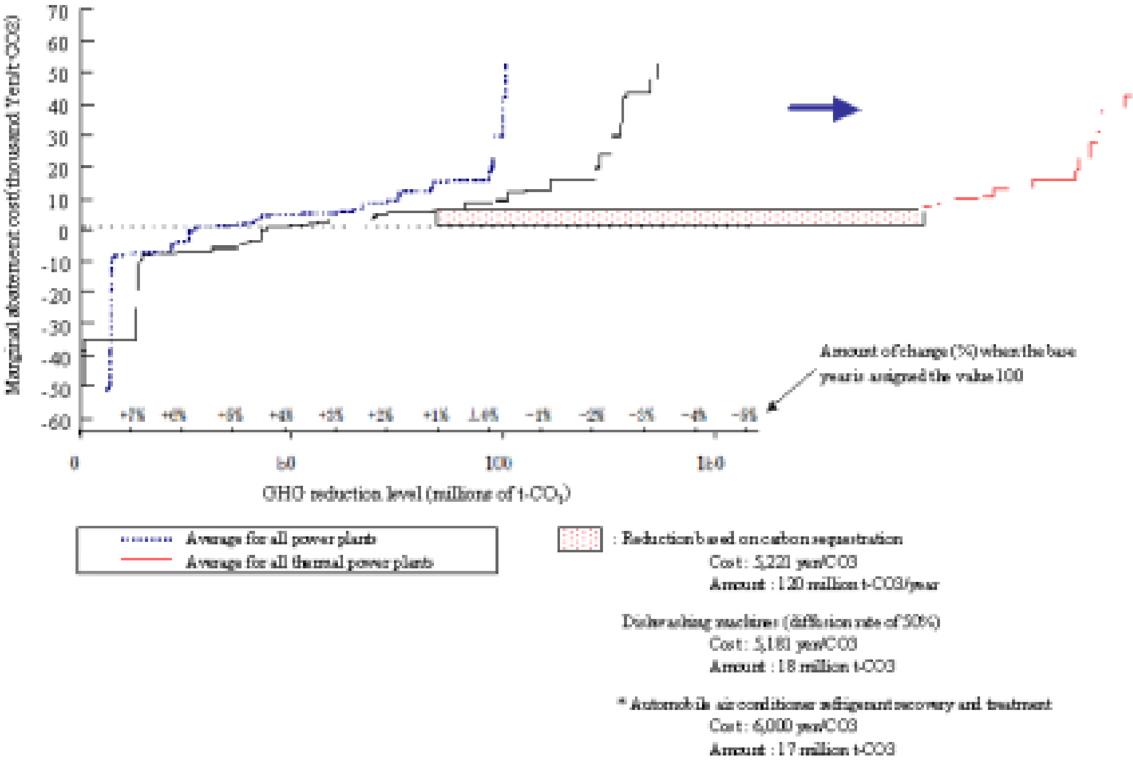
Figure 8-2　Cost comparison of global warming countermeasures



Source: Figures for new energy were calculated on the basis of the June 2001 report of the New Energy Subcommittee of the Advisory Committee on Natural Resources and Energy　The thermal power plant average of 0.68 kg-CO2/kWh was applied for the prime unit of CO_2 emissions.　Figures for energy conservation are based on the interim report of the Target Attainment Scenario Subcommittee within the Ministry of Environment.　Other figures are based on available documentation.

Furthermore, comparison encompassing both the potential for and the cost of reduction of GHG emissions clearly shows the efficacy of carbon sequestration relative to other domestic emission countermeasures.　When its cost and potential are inserted into the curve for marginal reduction cost in Japan (see Figure 8-3), carbon sequestration can be rated as capable of yielding a substantial amount of reduction if it is accorded expenditures on a par with those of the current countermeasures.

Figure 8-2 Cost comparison of global warming countermeasures



Within Japan, carbon sequestration is therefore cost-competitive with energy conservation and renewable energy measures even under the current circumstances. However, definite rules have not yet been established for it, and its application in other countries is limited to EOR and other projects that involve additional value and are not aimed at carbon sequestration per se; projects exclusively for carbon sequestration have not yet materialized. While the cost of emission reduction through carbon sequestration could come down somewhat in the future with application of technology as an extension of projects already on the commercial basis, there is thought to be little technical margin for much improvement in the cost picture. Even so, the future holds the prospect of an increase in the cost of emission reduction by CDM/JI projects and a price rise in emissions trading. Carbon sequestration therefore may be expected to become more cost-competitive in relative terms (see Table 8-2).

Table 8-2 Cost outlook for emission reduction measures

	Current	Future	Outlook
Overseas projects & transactions	Low	Increase	Because implementation would begin with the low-cost projects, the high-cost ones would be left over.
Carbon sequestration	Medium	Decrease	This is now at the stage of commercialization, and the future should bring a gradual decline.
Domestic energy conservation	Low - high	Increase	Technology will presumably continue to advance, but application would begin with the low-cost measures.
Domestic new energy	Medium - high	Decrease	Costs should come down with technical progress, but there are not good prospects for a substantial improvement.

9. Issues and tasks

The aforementioned issues and tasks related to carbon sequestration may be summarized as follows.

(1) Environmental impact of CO_2 storage

Research must be conducted on the behavior of CO2 in sequestration to determine the impact, if any, on underground and marine organisms and on ground water.

(2) Definition of international rules

Although the technical possibilities of carbon sequestration have been recognized, international rules that would encourage its practical application have not yet been determined. Such rules must be determined upon discussion in forums of international negotiation. A special IPCC report is scheduled to be published in 2005, and this should prompt international discussion on the subject.

(3) Establishment of monitoring methods

Programs must be executed to establish technology for monitoring for leakage and other abnormalities over wide areas, and monitoring methods for long-term microleaks and leakage caused by earthquakes.

(4) Cost reduction

Carbon sequestration is recognized as being cost-competitive with certain other measures of emission reduction, but its cost competitiveness is by no means fully sufficient. Efforts must continue to be made to reduce its cost.

(5) Improvement of the energy efficiency of recovery

Separation and recovery require a large input of energy. The efficiency of this energy use must be improved for more efficient use of resources and reduction of cost.

(6) Selection of sequestration systems adapted to the circumstances

There is a need for research aimed at the construction of optimal total systems with the right combination of technology for the circumstances, including the exhaust gas properties, emission source, and storage site.

It is important for all concerned parties to take action for swift resolution of these issues and tasks in order to enable extensive application of carbon sequestration as one of Japan's key options for global warming mitigation over the medium and long terms, with full consideration of the points raised above.

Conclusions

- ✧ Japan has a large capacity for CO_2 storage by carbon sequestration. This capacity amounts to about 75 years' worth of the country's total GHG emissions in fiscal 1990. Sequestration therefore could be applicable into the long term.
- ✧ Carbon sequestration is on a practical level in technical terms, but the impact of storage on organisms, ground water, and other environmental elements must be elucidated.
- ✧ The cost of emission reduction by carbon sequestration is currently higher than that of overseas projects and international emissions trading, but on a par with or lower than those of domestic energy conservation and renewable energy measures. In the future, its cost competitiveness is expected to rise.
- ✧ To exploit these advantages, Japan ought to work for practical application of carbon sequestration technology, which should be positioned as one of its key measures for mitigation of global warming beginning around 2013.

In addition, Japan could look forward to the following benefits from application of carbon sequestration as a key measure for emission reduction beginning around 2013.

- ✧ Possession of a means of emission reduction that is effective, in terms of both quantity and cost, for domestic application
- ✧ Freedom from position as exclusively a buyer in overseas projects and international emissions trading, and ability to negotiate on equal footing (strengthening of its bargaining position)
- ✧ Availability as a new means in strategy for international negotiations beginning around 2013
- ✧ Applicability as a means of overseas contribution

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