A cost-optimal scenario of CO_2 sequestration in a carbon-constrained world through to 2050

Takayuki Takeshita

Transdisciplinary Initiative for Global Sustainability, The University of Tokyo, Tokyo, Japan; takeshita@ir3s.u-tokyo.ac.jp

ABSTRACT

In this paper, a regionally disaggregated global energy system model with a detailed treatment of the whole chain of CO_2 capture and storage (CCS) is used to derive the cost-optimal global pattern of CO_2 sequestration in regional detail over the period 2010-2050 under the target of halving global energy-related CO_2 emissions in 2050 compared to the 2005 level. The major conclusions are the following. First, enhanced coalbed methane recovery will become a key early opportunity for CO_2 sequestration, so coal-rich regions such as the US, China, and India will play a leading role in global CO_2 sequestration. Enhanced oil recovery will also have a participation in global CO_2 sequestration from the initial stage of CCS deployment, which may be applied mainly in China, southeastern Asia, and West Africa in 2030 and mainly in the Middle East in 2050. Second, CO_2 sequestration will be carried out in an increasing number of world regions over time. In particular, CCS will be deployed extensively in today's developing countries. Third, an increasing amount of the captured CO_2 will be stored in aquifers in many parts of the world due to their abundant and widespread availability and their low cost. It is shown that the share of aquifers in global CO_2 sequestration reaches 82.0% in 2050.

Keywords: CO_2 Sequestration; Simulation; Optimization; Global Energy System Model

1. INTRODUCTION

Avoiding dangerous climate change is an increasingly formidable challenge. CO_2 capture and storage (CCS) is now recognized as an important option for mitigating climate change. Research, development, and demonstration for CCS are ongoing not only in developed countries, but also in at least 19 developing countries. Although it

has been indicated that CCS has advantages over other CO_2 mitigation options in terms of CO_2 emissions reduction potential and cost-effectiveness (e.g., [1,2]), there are still major hurdles to widespread deployment of CCS. First of all, it must be proven that CO_2 can be permanently and safely stored underground. Second, public acceptance of storing CO_2 underground must be gained.

Under these circumstances, identifying in advance the future likely CO_2 storage sites is considered to be highly useful in overcoming the above two hurdles. This is because much time and effort can be spent on better understanding the geological properties of potential CO_2 storage sites, on giving potential host communities for CO_2 storage sites a detailed explanation on the necessity, scope, and safety of the CO_2 storage project, and on building a reliable relationship with them. Also, taking into account that an important feature of CCS is that it is capital intensive, this would help all stakeholders (including governments, utilities, and CCS industries) make rational decisions on CCS infrastructure design.

Thus, the purpose of this paper is to derive the cost-optimal global pattern of CO_2 sequestration in regional detail over the period to 2050 under a stringent CO_2 emissions reduction constraint (*i.e.*, a halving of global energy-related CO_2 emissions in 2050 compared to the 2005 level). The cost-optimal global pattern of interregional CO_2 transportation to CO_2 storage sites is also drawn and analyzed under this constraint. These analyses are done by using the global energy system model REDGEM70 (an acronym for a REgionally Disaggregated Global Energy Model with 70 regions) [3,4], which treats the whole chain of CCS in detail.

2. METHODOLOGY

2.1. Overview of the REDGEM70 Model

REDGEM70 is a technology-rich, bottom-up global energy systems optimization model formulated as an intertemporal linear programming problem. **Figure 1** schematically illustrates the structure of the model. With a 5% discount rate, the model is designed to determine the cost-optimal energy strategy (e.g., the cost-optimal
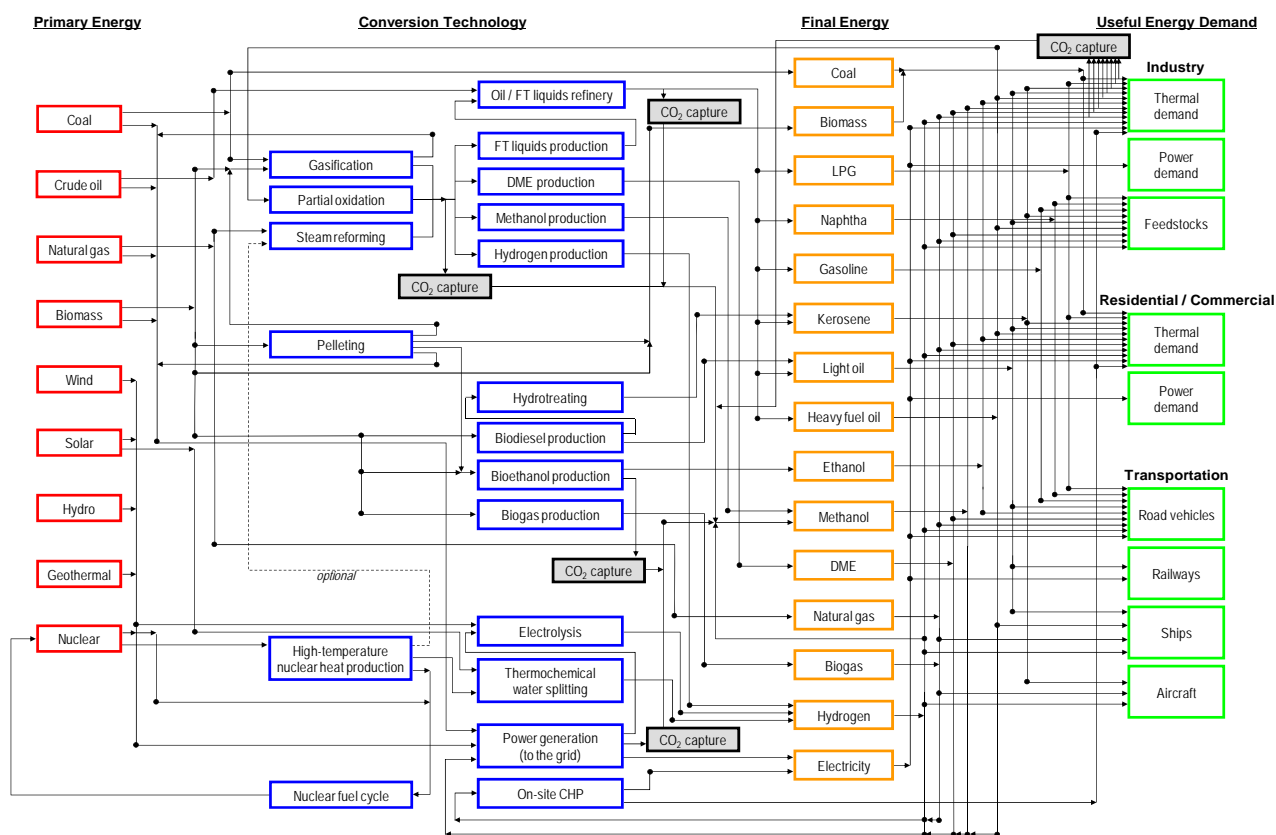
Figure 1. Schematic representation of the structure of REDGEM70[a]. [a]FT: Fischer-Tropsch; DME: dimethyl ether; LPG: liquefied petroleum gas; CHP: combined heat and power.

choice of technology options) from 2010 to 2050 at 10-year intervals for each of 70 world regions so that total discounted energy system costs are minimized under constraints on the satisfaction of exogenously given energy end-use demands, the availability of primary energy resources, material and energy balances, the maximum growth rates of new technologies, etc. In the model, price-induced energy demand reductions and energy efficiency improvements, fuel switching to less carbon-intensive fuels, and CCS in geologic formations are the three options for CO_2 emissions reduction.

Furthermore, in the current version of the model used in this study, there is also a constraint that global energy-related CO_2 emissions in 2050 are to be halved compared to the 2005 level. This constraint is the same as that given in the International Energy Agency's BLUE Map scenario [1,5]. The model has a full flexibility in where CO_2 emissions reduction is achieved to meet this constraint.

Figure 2 shows how the 70 world regions are defined in REDGEM70. These 70 regions are categorized into "energy production and consumption regions" and "energy production regions". The whole world was first divided into the 48 energy production and consumption regions to which future energy end-use demands are al-

located. The 22 energy production regions, which are defined as geographical points, were then distinguished from the energy production and consumption regions to represent the geographical characteristics of the areas endowed with large amounts of fossil energy resources. While the 48 energy production and consumption regions cover the global final energy consumption, all the energy-related activities except final energy consumption are conducted in each of the two region types in the model. Such a detailed regional disaggregation enables the explicit consideration of regional characteristics in terms of energy resource supply, energy demands, CO_2 storage capacity, geography, and climate.

Future trajectories for energy end-use demands were estimated as a function of those for socio-economic driving forces such as population and income in the intermediate B2 scenario developed by [6]. Allocation of the energy end-use demand estimates to the 48 energy production and consumption regions was done by using country- and state-level statistics/estimates (and projections if available) on population, income, geography, energy use by type, and transport activity by mode, and by taking into account the underlying storyline of the B2 scenario that regional diversity might be somewhat preserved throughout the 21st century.
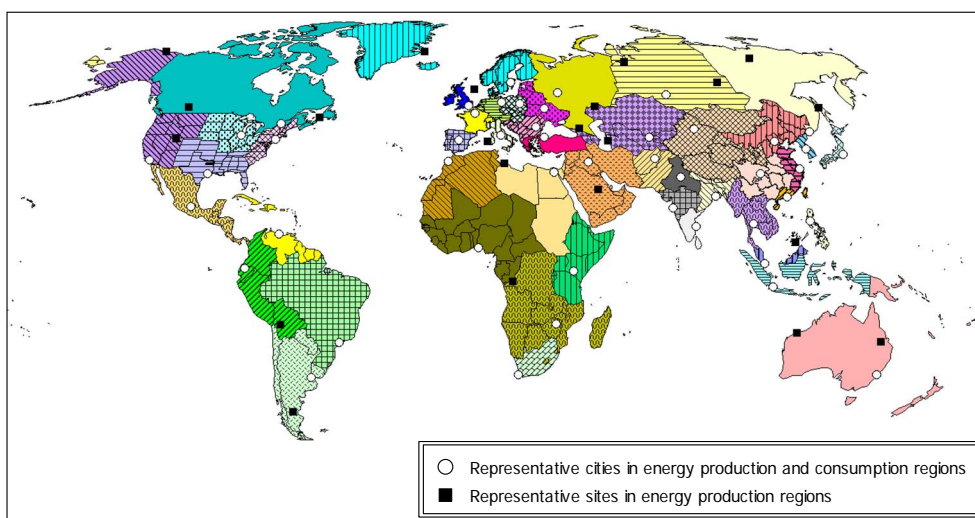
Figure 2. Regional disaggregation of REDGEM70.

Assumptions on the availability and extraction cost of fossil energy resources are taken from [7]. For biomass resources, REDGEM70 considers not only terrestrial biomass (such as energy crops and modern fuelwood), but also waste biomass. The availability of these biomass resources and excess cropland that can be used for energy purposes without conflicting with other biomass uses such as food production was estimated for each region and each time point. They were estimated assuming that biomass is produced in a sustainable way so that biomass-derived energy carriers can be regarded as carbon neutral. Data for these biomass resources (e.g., resource availability, yields per hectare of land, and supply costs) are provided in [8]. These resource availability estimates were then allocated to the 70 model regions by using country-, state-, and site-level statistics/estimates.

2.2. CCS Sector

In REDGEM70 as shown in **Figure 1**, the CO_2 generated from power plants (excluding those used for on-site CHP production and biomass-fired steam-cycle power generation), synthetic fuels production plants (excluding those used for converting stranded gas and decentralized small-scale hydrogen production), ethanol production plants, oil/FT refinery plants, and industrial processes can be captured for subsequent sequestration in geologic formations. It is assumed that the captured CO_2 is transported intraregionally (and interregionally if needed) to a storage site and then stored in geologic formations. Data for CO_2 capture technologies are provided in [8,9]. The costs of all types of CO_2 capture technologies, which represent the bulk of the overall CCS costs, are assumed to be reduced by 15.6% from 2010 to 2050 [10].

The cost of intraregionally transporting the captured CO_2 from fossil-fueled plants to a storage site was estimated to be 24.1 US $\$_{2007}$ per tonne of carbon, assuming that it is transported intraregionally through 250 km of pipeline [8,10]. On the other hand, due to the dispersed nature of biomass feedstocks, the intraregional transportation of the captured CO_2 from biomass-fueled plants to a storage site is assumed to suffer from diseconomies of small scale. Based on [8], the cost of intraregionally transporting the captured CO_2 from biomass-fueled plants to a storage site was estimated to be in the range of 59.0 - 95.4 US $\$_{2007}$ per tonne of carbon depending on secondary energy carriers produced from biomass.

REDGEM70 treats the interregional transportation of CO_2 between representative cities/sites in the 70 model regions and is able to determine its cost-optimal evolution path. **Figure 3** shows the interregional CO_2 transportation costs as a function of transportation distance for each mode. In advance of model simulations, possible interregional transportation routes were given between representative cities/sites in the 70 model regions and their distances were calculated using geographic information system (GIS) land cover data, GIS land use data, and land elevation data. Thus, the cost of transporting a tonne of carbon between every couple of representative cities/sites in the 70 model regions is an input to the model.

The geologic CO_2 sequestration options included are enhanced oil recovery (EOR), enhanced coalbed methane recovery (ECBMR), depleted gas-field disposal, and aquifer disposal. **Table 1** shows the input data for CO_2 sequestration options. In addition to CO_2 sequestration costs listed in **Table 1**, a monitoring cost of 0.864 US $\$_{2007}$ per tonne of carbon stored is assumed to be required [13].

Figure 4 shows the regional distribution of CO_2 storage capacity. The regional distribution of CO_2 storage capacity in aquifers was derived from data reported in
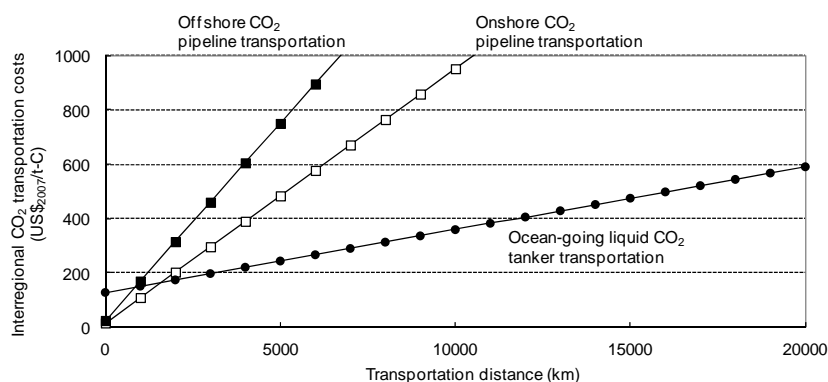
Figure 3. Interregional CO_2 transportation costs as a function of transportation distance.
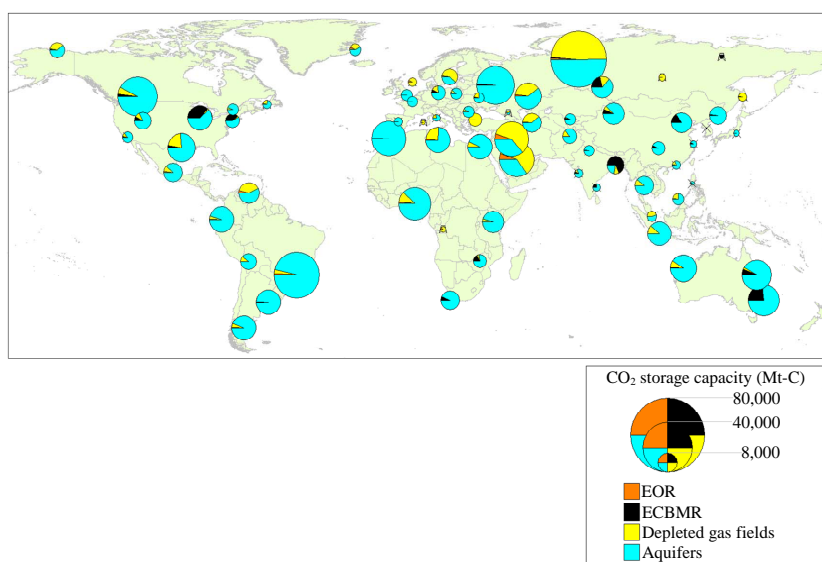

Figure 4. Estimated regional distribution of CO_2 storage capacity[a]. [a]Towers indicate representative sites in energy production regions, while crosses indicate representative cities in energy production and consumption regions.

Table 1. Data for geologic CO_2 sequestration options[a].

Option type	Sequestration cost (US $_{2007}$/t-C)	CO_2 storage capacity (Gt-C)
EOR	128 - 184	9
ECBMR	41 - 953	40
Depleted gas field	56 - 80	172
Aquifer	15 - 221	706

[a]Sources: [2,11-13].

[11]. Following the approach taken by [12], the regional distribution of CO_2 storage capacity in EOR sinks, ECBMR sinks, and depleted gas fields was estimated from that of conventional oil resource base, anthracite and bituminous coal resource base, and conventional natural gas resource base, respectively.

3. RESULTS AND DISCUSSION

3.1. Globally Aggregated Results for CO_2 Sequestration

Before examining the cost-optimal pattern of CO_2 sequestration on a regional basis, the focus is placed on the globally aggregated results. **Figure 5** shows the evolution of the global amount of CO_2 sequestration by type of storage option. This result implies that large-scale commercial deployment of CCS is likely to begin around 2030 under the stringent CO_2 emissions reduction constraint. As technological progress in the field of CCS technologies advances over time, they make an increasing contribution to CO_2 emissions reduction. The share of CCS in global energy-related CO_2 emissions reduction compared to the business-as-usual case without any CO_2 constraints increases from 1.5% in 2020 to 17.7% in 2050.
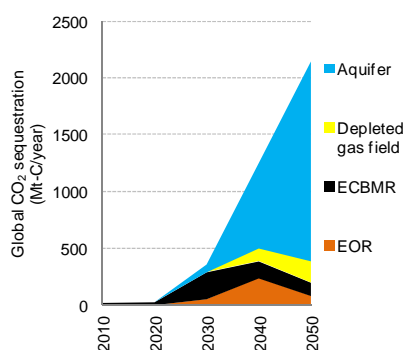

Figure 5. Global CO$_2$ sequestration by type of storage option.

Total cumulative CO$_2$ sequestration over the period 2010-2050 amounts to 38 gigatonnes of carbon, which account for only 4% of global CO$_2$ storage capacity. This means that after meeting the stringent constraint imposed on global energy-related CO$_2$ emissions in 2050 (*i.e.*, in the second half of the century), CCS can play a significant role in reducing CO$_2$ emissions.

As regards geologic CO$_2$ sequestration options, ECBMR is chosen first because very low, or even negative, costs can be achieved through offsetting revenues from the natural gas produced in ECBMR operations. This is also true for EOR: in the initial phase of CCS deployment, EOR operations are one of the pillars of global CO$_2$ sequestration. It can therefore be argued that CO$_2$ sequestration combined with enhanced hydrocarbon recovery creates an early opportunity for CCS.

In contrast, aquifers account for a dominant share of global CO$_2$ sequestration in the second half of the time horizon: their share in global CO$_2$ sequestration increases from 60.2% in 2040 to 82.0% in 2050. This is due to their abundant and widespread availability and their low cost (see **Table 1** and **Figure 4**). It is noteworthy that all the four options have a visible participation in global CO$_2$ sequestration from 2030 onwards, when large-scale CCS deployment begins.

3.2. Cost-Optimal Pattern of CO$_2$ Sequestration and Transportation

Figures 6 and **7** illustrate the global pattern of geologic CO$_2$ sequestration and CO$_2$ transportation for 2030 and 2050, respectively. In 2030, large-scale CO$_2$ sequestration is carried out in a limited number of regions. More specifically, regions rich in coal resource base (e.g., the US, China, India, Australia, and South Africa) take the lead in CO$_2$ sequestration, reflecting the large share of ECBMR operations in global CO$_2$ sequestration at this point in time.

Although not shown here, CO$_2$ capture is implemented predominantly in coal-fueled plants in 2030 because the

incremental cost of CO$_2$ capture is lower for them than for plants fueled by other carbonaceous feedstocks, which is due to economies of scale caused by the high carbon content of coal and the large scale of coal-fueled plants. This also explains why large-scale CCS deployment starts in these coal-rich regions. However, the capture of CO$_2$ from coal-fueled plants loses its share over time under the stringent CO$_2$ emissions reduction constraint. The main reason is that CO$_2$ emissions from coal-fueled plants with CCS are unacceptable under this constraint because coal has the highest carbon emission factor of all fossil fuels and because the efficiency of CO$_2$ capture for those plants is not 100% (about 90% - 95%).

Among others, EOR operations in regions with oil fields that are in decline (e.g., China, southeastern Asia, and West Africa) and aquifer storage in southeastern and western Asia play a role in global CO$_2$ sequestration in 2030. It is important to note that interregional CO$_2$ transportation is not chosen at all in 2030 because of the widespread distribution of geologic formations with large CO$_2$ storage capacity and the high cost of CO$_2$ transportation. In other words, it is cost-effective to sequester the CO$_2$ captured from a model region in geologic formations in that region.

It should be noted, however, that the realization of the CCS potential in today's developing countries actually depends on the effective transfer of technologies and funds from today's industrialized countries and on global efforts to reduce CO$_2$ emissions. Without them, CCS would not be deployed on such a large scale in today's developing countries.

As shown in **Figure 7**, the picture changes dramatically in 2050. At this point in time, geologic CO$_2$ sequestration is carried out all over the world. It should be emphasized that CCS is deployed fairly extensively in today's developing countries. In particular, Latin America, tropical central Africa, and southeastern Asia account for a large share of global CO$_2$ sequestration in 2050. This is because the strategy of negative CO$_2$ emissions provided by combining bioenergy conversion technologies with CCS is adopted in these regions rich in high-quality woody biomass resources to meet the stringent CO$_2$ emissions reduction constraint. On the contrary, the amount of CO$_2$ sequestration is tiny in Japan and Korea due to their very small CO$_2$ storage capacity.

Whereas the large amount of the captured CO$_2$ is stored in aquifers in many parts of the world, the other three options also make a non-negligible contribution to global CO$_2$ sequestration in 2050. Similar to the results for 2030, ECBMR is applied in coal-rich regions such as India, the US, Russia, and Australia. On the other hand, EOR begins to be applied on a large scale in the Middle East, where giant oil fields exist, as oil production from
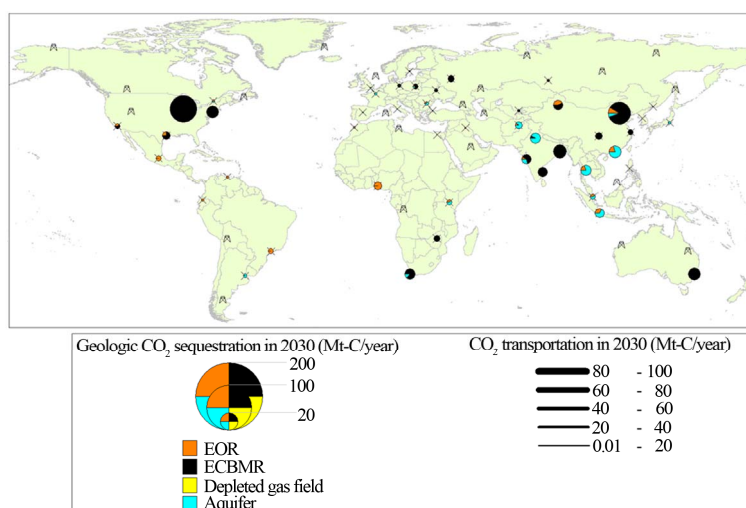
Figure 6. Global pattern of geologic CO_2 sequestration and CO_2 transportation in 2030[a]. [a]Same as footnote a in **Figure 4**.
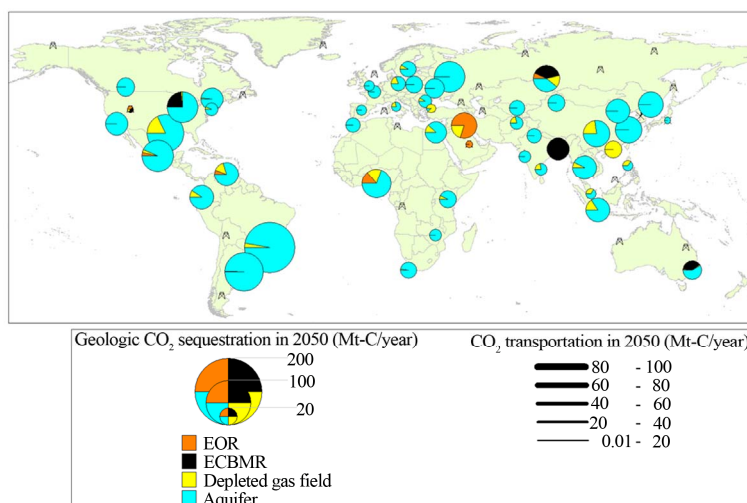

Figure 7. Global pattern of geologic CO_2 sequestration and CO_2 transportation in 2050[a]. [a]Same as footnote a in **Figure 4**.

them becomes increasingly mature. CO_2 sequestration in depleted gas fields is carried out on a large scale in regions where large quantities of conventional natural gas are produced (e.g., the US, the Middle East, and China).

Except for the route from Korea to the Far East in Russia, interregional CO_2 transportation is not chosen in 2050 for the same reason as was described for 2030. The captured CO_2 is interregionally transported only from Korea because it was estimated to have very small CO_2 storage capacity [11], because Korea has access to on-shore geologic formations with sufficient CO_2 storage capacity within a relatively short distance, and because pipelines can make the short-distance transportation of CO_2 over land economical (see **Figure 3**). It can also be seen that the long-distance transportation of CO_2 by sea is unlikely to be done at least until 2050 due to the rela-

tively close geographical proximity between CO_2 sources and sinks and to the high cost of shipping CO_2 by sea over such short distances (see **Figure 3**).

These results do not mean that CO_2 transportation will play a marginal role under the stringent CO_2 emissions reduction constraint. Rather, intraregional CO_2 transportation and CO_2 distribution networks built for this purpose will be a major component of a CCS system because there is to some extent a regional mismatch between CO_2 point sources and CO_2 sinks in most cases [2,13]. Taken together, great emphasis should be put on building infrastructure for short-distance CO_2 transportation over land to establish the cost-optimal CCS system.

Geologic CO_2 sequestration is hardly carried out in the 22 energy production regions of the model throughout the time horizon. This is because the interregional trans-

portation of fossil fuels to the place of their use (*i.e.*, the 48 energy production and consumption regions of the model) followed by their conversion to secondary energy combined with CCS is less costly than their conversion to secondary energy combined with CCS followed by the interregional transportation of secondary energy such as electricity and hydrogen.

4. CONCLUSIONS

Using the regionally disaggregated global energy system model with a detailed treatment of the whole chain of CCS, this paper has derived the cost-optimal global pattern of CO_2 sequestration in regional detail over the period 2010-2050 under the target of halving global energy-related CO_2 emissions in 2050 compared to the 2005 level. Also, prospects for interregional CO_2 transportation have been discussed under this target. Four major findings were obtained.

First, ECBMR will become a key early CO_2 sequestration opportunity because it can generate revenues that offset all or part of the costs of CO_2 capture and transportation. Accordingly, coal-rich regions such as the US, China, India, Australia, and South Africa will take the lead in CO_2 sequestration. For the same reason, EOR will also play a role in global CO_2 sequestration from the initial stage of CCS deployment, which may be applied mainly in China, southeastern Asia, and West Africa in 2030 and mainly in the Middle East in 2050.

Second, over time, CO_2 sequestration activities will become more spatially dispersed and an increasing amount of the captured CO_2 will be stored in aquifers in many parts of the world due to their abundant and widespread availability and their low cost. It is cost-effective to deploy CCS extensively in today's developing countries, implying the importance of the effective transfer of technologies and funds from today's industrialized countries. According to the results for 2050, CO_2 sequestration is carried out in the majority of world regions and the share of aquifers in global CO_2 sequestration reaches 82.0%.

Third, all the four options will make a visible contribution to global CO_2 sequestration. The captured CO_2 may be stored in depleted gas fields mainly in the US, the Middle East, and China.

Fourth, the interregional, long-distance transportation of CO_2 is unlikely to be chosen throughout the time horizon. This is due to the widespread distribution of geologic formations with large CO_2 storage capacity and the high cost of CO_2 transportation.

Readers, however, should be aware of a limitation of this study. As pointed out by many authors, regional differences in CO_2 policy actions and targets, CO_2 policy framework and incentives, and other political issues, which are not fully considered in the model, are likely to

have a large impact on where CCS technologies are deployed in the "real world". Thus, the results of this study must be interpreted with caution. Nevertheless, this study is novel and significant in that the findings obtained from the regionally disaggregated results have important implications for the cost-optimal pattern of CCS deployment and the strategic planning of CCS infrastructure.

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