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Analysis of GHG Emission Reduction in South Korea Using a CO_2 Transportation Network Optimization Model

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Abstract: Korea's national carbon capture and storage (CCS) master plan aims to commercialize CCS projects by 2030. Furthermore, the Korean government is forced to reduce emissions from various sectors, including industries and power generation, by 219 million tons by 2030. This study analyzes a few scenarios of Korean CCS projects with a CO_2 pipeline transportation network optimization model for minimizing the total facility cost and pipeline cost. Our scenarios are based on the "2030 basic roadmap for reducing greenhouse gases" established by the government. The results for each scenario demonstrate that the effective design and implementation of CO_2 pipeline network enables the lowering of CO_2 units cost. These suggest that CO_2 transportation networks, which connect the capture and sequestration parts, will be more important in the future and can be used to substitute and supplement the emission reduction target in case the execution of other reduction options faces uncertainty. Our mathematical model and scenario designs will be helpful for various countries which plan to introduce CCS technology.

Keywords: carbon capture and storage; pipeline transport; climate change; greenhouse gas

1. Introduction

Carbon capture and storage (CCS) has attracted considerable attention as an effective technology for reducing greenhouse gas (GHG) emissions in response to climate change concerns. The International Energy Agency (IEA) has estimated that CCS has the potential to reduce CO_2 emissions by up to 19% by 2050. Since 1996, CCS technology has been actively applied and developed for oil and natural gas development projects in the United States, Canada, and the European Union (EU). CO_2 underground storage is the most scientifically or technologically effective method for eliminating CO_2 from the atmosphere. Moreover, it is regarded as the best approach in economic or industrial terms. Hence, developed countries, such as the United States, Australia, Japan, and several EU countries, have focused on promoting the commercialization of CCS as a next-generation technology to boost growth. The total annual global investment in CCS technology is around $1 billion, and it is expected to increase significantly by 2020. Thus, governments and private companies in technically advanced countries are jointly promoting CCS technology [1].

South Korea is attempting to develop several types of effective methods for reducing GHG emissions in response to climate change concerns. In December 2016, a detailed plan was presented for reducing the forecasted emissions by 37% (851 million tons) by 2030, following the announcement of the basic plan for climate change response. The main reduction policies include supplying renewable energy, expanding clean fuel generation, improving energy efficiency, implementing emissions trading, and evaluating international carbon market mechanisms [2]. To minimize the industrial burden, the GHG reduction rate (including industrial processes) should not exceed 12% of the "business-as-usual" (BAU) emissions. However, this target presents great difficulties for many companies that produce large amounts of GHGs. To overcome this problem, South Korea is pursuing CO_2 reduction through a large-scale CCS project in order to boost growth through new energy industries.

This study focuses on analyzing the empirical effects of the CCS project being pursued in accordance with the climate change response plan of South Korea. A mathematical model is proposed to construct an optimal CCS network based on the given GHG emission sources, representative candidate sequestration sites, and facility construction–operation costs. In addition, according to the Ministry of Strategy and Finance [2], this study attempts to monitor the impact of the CCS project on the effectiveness of GHG reduction.

Carbon capture and storage, sometimes referred to as carbon capture and sequestration, is an emerging technology that can efficiently reduce CO_2 emissions. According to Zhou et al. [3], CCS is widely regarded as a major means for reducing CO_2 emissions from large point sources, such as fossil fuel power plants and energy intensive industries, such as the steel, petrochemical, and refining industries. The introduction of CCS is expected to not only reduce the industrial burden but also lower voluntary reduction targets.

An integrated CCS project involves three major steps: (1) capturing CO_2 produced by large emission sources; (2) compressing the captured CO_2 and then transporting it to an appropriate geographical site or deep saline aquifer via various modes (truck, pipeline, ship, or marine); and (3) injecting CO_2 for long-term storage. CCS technology is expected to reduce CO_2 emissions by up to 19% by 2050. Moreover, without CCS, the overall cost of halving CO_2 emissions could increase by 70% by 2050 [4]. However, CCS represents a significant financial investment. According to a survey, Europe will invest $4–6 billion for developing 6–12 CCS projects, followed by the United States (approximately $4 billion for 5–10 projects), by 2020. Both developed and developing countries are attempting to identify appropriate ways to reduce investment for CCS projects by considering the associated high capital and operating costs.

As stated above, the key impediment to the introduction of CCS is the enormous budgetary investment. Various studies have focused more on the capture and sequestration aspects rather than on the transport aspect of CCS. Establishing an optimal transportation network is an important requirement considering the large investment required for CCS projects. Nevertheless, important issues related to CO_2 pipelines remain to be addressed, including pipeline cost, pipeline installation sites, and relevant policies. Therefore, to maximize the GHG reduction effect of CCS projects, it is necessary to consider not only the national GHG reduction targets but also the economic aspects.

Over the last 15 years, many studies have been proposed to reduce CO_2 emissions on the basis of CCS technologies [5–7]. Recently, a few studies have assessed the economics of large-scale CO_2 transportation models by focusing on CO_2 sources and geological storage reservoirs. For instance, Li et al. [8] focused on the data, methodology, and results of basin-scale CO_2 storage capacity and CO_2 point emission estimation in China. In Zhou et al. [3], Middleton and Bielicki [9], and Han et al. [10], the authors attempted to develop an optimal model for minimizing the overall cost of large-scale CCS projects. Specifically, Middleton and Bielicki [9] introduced a scalable infrastructure model for CCS (simCCS), considering all the components of CCS infrastructure using a single CO_2 pipeline that directly connects a single source to a single sequestration site. Further, a mixed integer linear programing (MILP) model was applied to construct the proposed approach. Only one pipeline (of any size) is to be constructed on any potential arc. The author demonstrated simCCS by considering the 37 largest CO_2 sources (21 natural gas power plants, one coal power plant, ten oil refineries, and five cement manufacturers) and 14 reservoirs (depleted oil fields). In Zhou et al. [3], a decomposition algorithm was proposed to solve the pipeline network problem by adding intermediate sites (such as pump stations). Further, a mixed integer programming (MIP) model was developed. A real-world case study in North China, involving 45 emissions sources and four storage sinks, was conducted to demonstrate the proposed model. In Han et al. [10], a multi-period model was proposed for maximizing the average annual profit of CCS infrastructure (including utilization, capture, storage, and sequestration facilities) over a long-term planning interval considering the disposal and utilization of CO_2. In addition, the author referred to the concept of intermediate storage technologies that exist only to collect CO_2 captured from emission sources within a particular region and load the collected CO_2 for delivery by different transport modes.

Other existing studies on CCS transport networks in different regions around the world have assumed that CO_2 flowing through a network is static throughout the life of the network. For example, steady-state optimization of CCS networks has been investigated in Australia [11,12] and the United States [13–15]. A major drawback of using a static network model is that it assumes that all CO_2-emission sources are matched to sequestration sites with the same infrastructures (fixed capture capacity, storage capacity, and transport mode within unchanged transport networks) and that CO_2 flow rates remain constant for the entire lifecycle. The CO_2 infrastructures, including capture facilities, storage facilities, transport modes, and injection facilities, proposed in these studies would require significant upfront financial investment to achieve the predicted economies of scale in CO_2 transport and avoidance costs [16].

According to the IEA, to achieve the 2 °C target, no more than one-third of the global proven reserves of fossil fuels can be consumed before 2050, unless CCS is widely deployed. In Europe, four large-scale integrated CCS projects have been implemented in different countries and industries, such as power generation and natural gas [17]. In the roadmap for moving to a competitive low-carbon economy in 2050, the European Commission (EC) suggests that costs will rise if investments in low-carbon technology are postponed, highlighting that CCS needs to be demonstrated and implemented without delay. The United States has indicated its strong interest in CCS technologies over the last two decades, such as the reduction of CO_2 emissions from coal-fired power plants. Given the uncertainties in terms of the technical, economic, and environmental aspects, policies for developing CCS are key factors that could determine the future of this technology [18]. The growing portfolio of operating projects and a number of notable project milestones achieved in 2016 have shown that CCS is capable of not only preventing large quantities of CO_2 from entering the atmosphere but also of storing CO_2 securely and effectively [19].

The remainder of the paper is structured as follows: Section 2 discusses the construction of the CCS network mathematical model. Section 3 describes the application of the proposed model to the Korean first basic plan on climate change. Six scenarios are assumed by considering the uncertainty in the CO_2 reduction methods of various sectors. Finally, Section 4 states the conclusions and briefly explores directions for future research.

2. Mathematical Model

A mathematical approach is proposed for the design of a CO_2 pipeline transportation network for large-scale CCS projects. This study focuses on designing CO_2 pipeline transportation networks by inserting intermediate storage sites that connect CO_2-emission plants and sequestration sites. In addition, emitted CO_2 can be transported from one emission plant to another or from one intermediate storage site to another. Thus, several nodes can share a single pipeline to transport CO_2. The pipeline transportation cost is determined by the pipeline diameter and length, as the maximum transport flow per unit time fluctuates with these parameters. The pipeline transport mode is different from the general transport mode. Basically, the transportation cost is directly proportional to the distance and the vehicle size is directly proportional to the transportation volume. A mixed integer linear programming (MILP) model was formulated to solve the proposed problem.

In general, a network with an existing degree of flow (such as commodities or information) can be designed in the origination-to-destination mode, as shown in Figure 1. Several sub-points should be taken into account: (1) where and when to insert intermediate storage sites; and (2) how, when and where to install how much and what size of pipeline. Pipelines can be built between CO_2-emission sources, intermediate storage sites, and sequestration sites. In addition, they can be built between two different CO_2-emission sources or intermediate storage sites. An intermediate storage site may offer significant economic and operational benefits when designing a pipeline network.

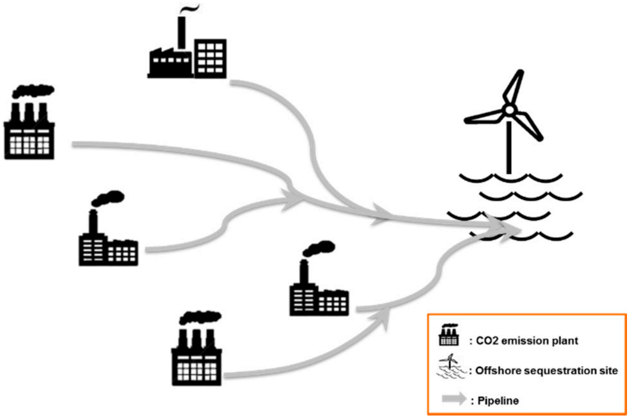

Figure 1. Typical CO_2 pipeline transportation network with direct source-sink connection.

2.1. Assumptions

For the purposes of this study, it was assumed that (1) the sequestration site is located offshore and the injection capacity is unlimited; (2) each CO_2 emission plant has the ability to capture and store CO_2; (3) candidate intermediate storage sites are obtained by a heuristic algorithm in advance [20]; and (4) pipeline transport is the only transport mode.

The problem statement addressed in this study is as follows:

- The entire CCS system is assumed to consist of several fixed CO_2-emission sources, undetermined intermediate storage sites, and candidate offshore sequestration sites for a long time period.
- The objective of the proposed problem is to minimize the total cost of CCS projects over the entire operating time. One of the most critical costs is the pipeline transportation cost, including the pipeline capital cost and pipeline operating cost. The pipeline cost functions are cited from National Energy Technology Laboratory (NETL) studies [21].
- Flow may exist between two different emission plants or intermediate storage sites. In other words, there are four types of pipeline links: (1) emission source–emission source; (2) emission source–intermediate storage site; (3) intermediate storage site–intermediate storage site; and (4) intermediate storage site–sequestration site.
- Standard pipeline diameters are employed and the distance between two different nodes is calculated as the Euclidean distance according to the latitude and longitude.
- Net present value (NPV) calculation of the pipeline cost is used, and its ratio is set at 6% to reflect the case more realistically.

2.2. Model Description

Objective Function

The mathematical model aims to minimize the total relevant costs of the CCS project (Equation (1)), which can be categorized as follows: capital cost of building CO_2 capture facility (Equation (2)) and infrastructure and operating expenses of CO_2 pipeline (Equation (3)). Several types of constraints are involved in this model.

$$Minimize\ Z = \mathrm{TFC} + \mathrm{TPC}, \tag{1}$$

$$\mathrm{TFC} = \sum_{t\in T}\sum_{i\in I}\left(\mathrm{CCF} \times N \times Ccap_i^t \times Y_i^t\right), \tag{2}$$

$$\mathrm{TPC} = \mathrm{PCC} + \mathrm{POC}, \tag{3}$$

Equations (4)–(12) represent the pipeline infrastructure costs, which are determined by the diameter and length of the pipeline installed between two nodes.

$$\mathrm{PCC} = \sum_{t\in T}(\mathrm{TMTC}_t+\mathrm{TLC}_t+\mathrm{TMCC}_t+\mathrm{TRC}_t)\cdot\left[\frac{1}{(1+r)^{T_t}} - \frac{\mathrm{LT}-\mathrm{OT}-1+T_t}{\mathrm{LT}\cdot(1+r)^{\mathrm{OT}+1}}\right], \tag{4}$$

$$\begin{array}{r}\mathrm{TMTC}_t = \sum\limits_{d\in D}\Big(\sum\limits_{i,i'\in I:i\neq i'}\mathrm{MTCPP}^t_{ii'd} + \sum\limits_{i\in I,j\in J}\mathrm{MTCPI}^t_{ijd} + \sum\limits_{j,j'\in J:j\neq j'}\mathrm{MTCII}^t_{jj'd} + \sum\limits_{j\in J,k\in K}\mathrm{MTCIS}^t_{jkd}\Big)\\ \forall t\in T\end{array}, \tag{5}$$

$$\begin{array}{r}\mathrm{TLC}_t = \sum\limits_{d\in D}\Big(\sum\limits_{i,i'\in I:i\neq i'}\mathrm{LCPP}^t_{ii'd} + \sum\limits_{i\in I,j\in J}\mathrm{LCPI}^t_{ijd} + \sum\limits_{j,j'\in J:j\neq j'}\mathrm{LCII}^t_{jj'd} + \sum\limits_{j\in J,k\in K}\mathrm{LCIS}^t_{jkd}\Big)\\ \forall t\in T\end{array}, \tag{6}$$

$$\begin{array}{r}\mathrm{TMCC}_t = \sum\limits_{d\in D}\Big(\sum\limits_{i,i'\in I:i\neq i'}\mathrm{MCCPP}^t_{ii'd} + \sum\limits_{i\in I,j\in J}\mathrm{MCCPI}^t_{ijd} + \sum\limits_{j,j'\in J:j\neq j'}\mathrm{MCCII}^t_{jj'd} + \sum\limits_{j\in J,k\in K}\mathrm{MTCIS}^t_{jkd}\Big)\\ \forall t\in T\end{array}, \tag{7}$$

$$\begin{array}{r}\mathrm{TRC}_t = \sum\limits_{d\in D}\Big(\sum\limits_{i,i'\in I:i\neq i'}\mathrm{RCPP}^t_{ii'd} + \sum\limits_{i\in I,j\in J}\mathrm{RCPI}^t_{ijd} + \sum\limits_{j,j'\in J:j\neq j'}\mathrm{RCII}^t_{jj'd} + \sum\limits_{j\in J,k\in K}\mathrm{RCIS}^t_{jkd}\Big)\\ \forall t\in T\end{array}, \tag{8}$$

$$\begin{array}{r}\mathrm{MTCPP}^t_{ii'd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{ii'dp}\left[\mathrm{MTC}_1 + \mathrm{MTC}_2\cdot\mathrm{PLPP}_{ii'}\cdot\left(\mathrm{MTC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{MTC}_4\cdot\mathrm{PD}_d + \mathrm{MTC}_5\right)\right]\\ \forall i,i'\in I: i\neq i', d\in D, t\in T\end{array}, \tag{9a}$$

$$\begin{array}{r}\mathrm{MTCPI}^t_{ijd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{ijdp}\left[\mathrm{MTC}_1 + \mathrm{MTC}_2\cdot\mathrm{PLPI}_{ij}\cdot\left(\mathrm{MTC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{MTC}_4\cdot\mathrm{PD}_d + \mathrm{MTC}_5\right)\right]\\ \forall i\in I, j\in J, d\in D, t\in T\end{array}, \tag{9b}$$

$$\begin{array}{r}\mathrm{MTCII}^t_{jj'd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{jj'dp}\left[\mathrm{MTC}_1 + \mathrm{MTC}_2\cdot\mathrm{PLII}_{jj'}\cdot\left(\mathrm{MTC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{MTC}_4\cdot\mathrm{PD}_d + \mathrm{MTC}_5\right)\right]\\ \forall j,j'\in J: j'\neq j, d\in D, t\in T\end{array}, \tag{9c}$$

$$\begin{array}{r}\mathrm{MTCIS}^t_{jkd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{jkdp}\left[\mathrm{MTC}_1 + \mathrm{MTC}_2\cdot\mathrm{PLIS}_{jk}\cdot\left(\mathrm{MTC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{MTC}_4\cdot\mathrm{PD}_d + \mathrm{MTC}_5\right)\right]\\ \forall j\in J, k\in K, d\in D, t\in T\end{array}, \tag{9d}$$

$$\begin{array}{r}\mathrm{LCPP}^t_{ii'd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{ii'dp}\left[\mathrm{LC}_1 + \mathrm{LC}_2\cdot\mathrm{PLPP}_{ii'}\cdot\left(\mathrm{LC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{LC}_4\cdot\mathrm{PD}_d + \mathrm{LC}_5\right)\right]\\ \forall i,i'\in I: i\neq i', d\in D, t\in T\end{array}, \tag{10a}$$

$$\begin{array}{r}\mathrm{LCPI}^t_{ijd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{ijdp}\left[\mathrm{LC}_1 + \mathrm{LC}_2\cdot\mathrm{PLPI}_{ij}\cdot\left(\mathrm{LC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{LC}_4\cdot\mathrm{PD}_d + \mathrm{LC}_5\right)\right]\\ \forall i\in I, j\in J, d\in D, t\in T\end{array}, \tag{10b}$$

$$\begin{array}{r}\mathrm{LCII}^t_{jj'd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{jj'dp}\left[\mathrm{LC}_1 + \mathrm{LC}_2\cdot\mathrm{PLII}_{jj'}\cdot\left(\mathrm{LC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{LC}_4\cdot\mathrm{PD}_d + \mathrm{LC}_5\right)\right]\\ \forall j,j'\in J: j'\neq j, d\in D, t\in T\end{array}, \tag{10c}$$

$$\begin{array}{r}\mathrm{LCIS}^t_{jkd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{jkdp}\left[\mathrm{LC}_1 + \mathrm{LC}_2\cdot\mathrm{PLIS}_{jk}\cdot\left(\mathrm{LC}_3\cdot\mathrm{PD}_d{}^2 + \mathrm{LC}_4\cdot\mathrm{PD}_d + \mathrm{LC}_5\right)\right]\\ \forall j\in J, k\in K, d\in D, t\in T\end{array}, \tag{10d}$$

$$\begin{array}{r}\mathrm{MCCPP}^t_{ii'd} = \sum\limits_{p\in P}\mathrm{ZD}^t_{ii'dp}\left[\mathrm{MCC}_1 + \mathrm{MCC}_2\cdot\mathrm{PLPP}_{ii'}\cdot(\mathrm{MCC}_3\cdot\mathrm{PD}_d + \mathrm{MCC}_4)\right]\\ \forall i,i'\in I: i\neq i', d\in D, t\in T\end{array}, \tag{11a}$$

$$\begin{gathered}\mathrm{MCCPI}_{ijd}^{t} = \sum_{p\in P} \mathrm{ZD}_{ijdp}^{t}\left[\mathrm{MCC}_1 + \mathrm{MCC}_2 \cdot \mathrm{PLPI}_{ij} \cdot (\mathrm{MCC}_3 \cdot \mathrm{PD}_d + \mathrm{MCC}_4)\right] \\ \forall i \in I, j \in J, d \in D, t \in T\end{gathered}, \tag{11b}$$

$$\begin{gathered}\mathrm{MCCII}_{jj'd}^{t} = \sum_{p\in P} \mathrm{ZD}_{jj'dp}^{t}\left[\mathrm{MCC}_1 + \mathrm{MCC}_2 \cdot \mathrm{PLII}_{jj'} \cdot (\mathrm{MCC}_3 \cdot \mathrm{PD}_d + \mathrm{MCC}_4)\right] \\ \forall j, j' \in J : j' \neq j, d \in D, t \in T\end{gathered}, \tag{11c}$$

$$\begin{gathered}\mathrm{MCCIS}_{jkd}^{t} = \sum_{p\in P} \mathrm{ZD}_{jkdp}^{t}\left[\mathrm{MCC}_1 + \mathrm{MCC}_2 \cdot \mathrm{PLIS}_{jk} \cdot (\mathrm{MCC}_3 \cdot \mathrm{PD}_d + \mathrm{MCC}_4)\right] \\ \forall j \in J, k \in K, d \in D, t \in T\end{gathered}, \tag{11d}$$

$$\begin{gathered}\mathrm{RCPP}_{ii'd}^{t} = \sum_{p\in P} \mathrm{ZD}_{ii'dp}^{t}\left[\mathrm{RC}_1 + \mathrm{RC}_2 \cdot \mathrm{PLPP}_{ii'} \cdot (\mathrm{RC}_3 \cdot \mathrm{PD}_d + \mathrm{RC}_4)\right] \\ \forall i, i' \in I : i \neq i', d \in D, t \in T\end{gathered}, \tag{12a}$$

$$\begin{gathered}\mathrm{RCPI}_{ijd}^{t} = \sum_{p\in P} \mathrm{ZD}_{ijdp}^{t}\left[\mathrm{RC}_1 + \mathrm{RC}_2 \cdot \mathrm{PLPI}_{ij} \cdot (\mathrm{RC}_3 \cdot \mathrm{PD}_d + \mathrm{RC}_4)\right] \\ \forall i \in I, j \in J, d \in D, t \in T\end{gathered}, \tag{12b}$$

$$\begin{gathered}\mathrm{RCII}_{jj'd}^{t} = \sum_{p\in P} \mathrm{ZD}_{jj'dp}^{t}\left[\mathrm{RC}_1 + \mathrm{RC}_2 \cdot \mathrm{PLII}_{jj'} \cdot (\mathrm{RC}_3 \cdot \mathrm{PD}_d + \mathrm{RC}_4)\right] \\ \forall j, j' \in J : j' \neq j, d \in D, t \in T\end{gathered}, \tag{12c}$$

$$\begin{gathered}\mathrm{RCIS}_{jkd}^{t} = \sum_{p\in P} \mathrm{ZD}_{jkdp}^{t}\left[\mathrm{RC}_1 + \mathrm{RC}_2 \cdot \mathrm{PLIS}_{jk} \cdot (\mathrm{RC}_3 \cdot \mathrm{PD}_d + \mathrm{RC}_4)\right] \\ \forall j \in J, k \in K, d \in D, t \in T\end{gathered}, \tag{12d}$$

Equation (13) represents total operating costs of the pipeline and Equation (14) shows the detailed calculation of the operating cost of a pipeline connected between two nodes (CO_2 emission sources, intermediate storage sites, and sequestration sites).

$$\begin{gathered}\mathrm{POC} = \sum_{t\in T}\Big(\sum_{d\in D}\Big(\sum_{i,i'\in I:i\neq i'} \mathrm{POCPP}_{ii'd}^{t} + \sum_{i\in I, j\in J} \mathrm{POCPI}_{ijd}^{t} + \sum_{j,j'\in J:j\neq j',} \mathrm{POCII}_{jj'd}^{t} \\ + \sum_{j\in J, k\in K} \mathrm{POCIS}_{jkd}^{t}\Big)\Big) \cdot \left[\frac{\mathrm{OT}-T_t}{(1+r)^{T_t}}\right]\end{gathered}, \tag{13}$$

$$\mathrm{POCPP}_{ii'd}^{t} = \mathrm{PLPP}_{ii'} \cdot \mathrm{UOCP}_{d}^{t} \cdot \sum_{\tau=1}^{t} \sum_{p\in P} \mathrm{ZD}_{ii'dp}^{\tau} \quad \forall i, i' \in I : i \neq i', d \in D, t \in T, \tag{14a}$$

$$\mathrm{POCPI}_{ijd}^{t} = \mathrm{PLPP}_{ij} \cdot \mathrm{UOCP}_{d}^{t} \cdot \sum_{\tau=1}^{t} \sum_{p\in P} \mathrm{ZD}_{ijdp}^{\tau} \quad \forall i \in I, j \in J, d \in D, t \in T, \tag{14b}$$

$$\mathrm{POCII}_{jj'd}^{t} = \mathrm{PLPP}_{jj'} \cdot \mathrm{UOCP}_{d}^{t} \cdot \sum_{\tau=1}^{t} \sum_{p\in P} \mathrm{ZD}_{jj'dp}^{\tau} \ \forall j, j' \in J : j \neq j', d \in D, t \in T, \tag{14c}$$

$$\mathrm{POCIS}_{jkd}^{t} = \mathrm{PLPP}_{jk} \cdot \mathrm{UOCP}_{d}^{t} \cdot \sum_{\tau=1}^{t} \sum_{p\in P} \mathrm{ZD}_{jkdp}^{\tau} \quad \forall j \in J, k \in K, d \in D, t \in T, \tag{14d}$$

Constraint (15) indicates the maximum amount of transported CO_2 for a certain pipeline diameter per unit time, expressed in tons per hour.

$$\mathrm{Flow}_{\mathrm{d}} = {\mathrm{PD}_d}^2 \cdot \pi \cdot \frac{1}{4} \cdot v \cdot \mathrm{Density}_d \quad \forall d \in D, \tag{15}$$

Constraint (16) indicates the expanded pipeline capacity of each link in time period t, and the actual pipeline capacity of each arc can be obtained by Constraint (17).

$$\mathrm{PaddPP}_{ii'}^{t} = \sum_{d \in D} \left(\mathrm{Flow}_d \cdot \sum_{p \in P} \mathrm{ZD}_{ii'dp}^{t} \right) \cdot \mathrm{PLPP}_{ii'} \ \forall i, i' \in I : i \neq i', t \in T, \tag{16a}$$

$$\mathrm{PaddPI}_{ij}^{t} = \sum_{d \in D} \left(\mathrm{Flow}_d \cdot \sum_{p \in P} \mathrm{ZD}_{ijdp}^{t} \right) \cdot \mathrm{PLPI}_{ij} \quad \forall i \in I, j \in J, t \in T, \tag{16b}$$

$$\mathrm{PaddII}_{jj'}^{t} = \sum_{d \in D} \left(\mathrm{Flow}_d \cdot \sum_{p \in P} \mathrm{ZD}_{jj'dp}^{t} \right) \cdot \mathrm{PLII}_{jj'} \ \forall j, j' \in J : j \neq j', t \in T, \tag{16c}$$

$$\mathrm{PaddIS}_{jk}^{t} = \sum_{d \in D} \left(\mathrm{Flow}_d \cdot \sum_{p \in P} \mathrm{ZD}_{jkdp}^{t} \right) \cdot \mathrm{PLIS}_{jk} \quad \forall j \in J, k \in K, t \in T, \tag{16d}$$

$$\mathrm{PcapPP}_{ii'}^{t} = \mathrm{PcapPP}_{ii'}^{t-1} + \mathrm{PaddPP}_{ii'}^{t} \quad \forall i, i' \in I : i \neq i', t \in T, \tag{17a}$$

$$\mathrm{PcapPI}_{ij}^{t} = \mathrm{PcapPI}_{ij}^{t-1} + \mathrm{PaddPI}_{ij}^{t} \quad \forall i \in I, j \in J, t \in T, \tag{17b}$$

$$\mathrm{PcapII}_{jj'}^{t} = \mathrm{PcapII}_{jj'}^{t-1} + \mathrm{PaddII}_{jj'}^{t} \quad \forall j', j' \in J : j \neq j', t \in T, \tag{17c}$$

$$\mathrm{PcapIS}_{jk}^{t} = \mathrm{PcapIS}_{jk}^{t-1} + \mathrm{PaddIS}_{jk}^{t} \quad \forall j \in J, k \in K, t \in T, \tag{17d}$$

Constraints (18) and (19) ensure that the flow rate of the transported CO_2 does not exceed the maximum tolerance of the existing pipeline capacity.

$$X_{ii'}^{t} \leq \mathrm{PcapPP}_{ii'}^{t} \quad \forall i, i' \in I : i \neq i', t \in T, \tag{18a}$$

$$X_{ij}^{t} \leq \mathrm{PcapPI}_{ij}^{t} \quad \forall i \in I, j \in J, t \in T, \tag{18b}$$

$$X_{jj'}^{t} \leq \mathrm{PcapII}_{jj'}^{t} \quad \forall j, j' \in J : j \neq j', t \in T, \tag{18c}$$

$$X_{jk}^{t} \leq \mathrm{PcapIS}_{jk}^{t} \quad \forall j \in J, k \in K, t \in T, \tag{18d}$$

$$\sum_{i' \in I : i \neq i'} X_{ii'd}^{t} \leq M \cdot Y_i^t \quad \forall\, i \in I, d \in D, t \in T, \tag{19a}$$

$$\sum_{i' \in I : i \neq i'} X_{i'id}^{t} \leq M \cdot Y_i^t \quad \forall\, i \in I, d \in D, t \in T, \tag{19b}$$

$$\sum_{j \in J} X_{ijd}^{t} \leq M \cdot Y_i^t \quad \forall\, i \in I, d \in D, t \in T, \tag{19c}$$

Constraints (20)–(22) represent the mass flow balance equations of the proposed model. The incoming flow should be equal to the outgoing flow at each node as well as in each stage.

$$\sum_{i' \in I : i \neq i'} X_{i'i}^{t} + \mathrm{Ccap}_i^t = \sum_{i' \in I : i \neq i'} X_{ii'}^{t} + \sum_{j} X_{ij}^{t} \quad \forall i \in I, t \in T, \tag{20}$$

$$\sum_{j' \in J : j \neq j'} X_{j'j}^{t} + \sum_{i \in I} X_{ij}^{t} = \sum_{j' \in J : j \neq j'} X_{jj'}^{t} + \sum_{k} X_{jk}^{t} \quad \forall j \in J, t \in T, \tag{21}$$

$$\sum_{i \in I} \mathrm{Ccap}_i^t = \sum_{k \in K} I_k^t \quad \forall t \in T, \tag{22}$$

Constraints (23) and (24) represent the limit of the captured CO_2 volume. The captured volume should be less than the emission volume but greater than the target volume.

$$\mathrm{Ccap}_i^t \leq \mathrm{EV}_i^t \quad \forall i \in I, t \in T, \tag{23}$$

$$\mathrm{TV}^t \leq \sum_{i \in I} \mathrm{Ccap}_i^t \quad \forall t \in T, \tag{24}$$

Constraint (25) indicates that CO_2 transportation should not occur at the same node. Constraint (26) determines whether a pipeline will be constructed. Finally, Constraint (27) is a non-negativity constraint.

$$\mathrm{PaddPP}_{ii'}^t, \mathrm{PcapPP}_{ii'}^t, X_{ii'}^t = 0 \quad \forall i, i' \in I : i = i', t \in T, \tag{25a}$$

$$\mathrm{PaddII}_{jj'}^t, \mathrm{PcapII}_{jj'}^t X_{jj'}^t = 0 \quad \forall j, j' \in J : j = j', t \in T, \tag{25b}$$

$$\begin{array}{r} \mathrm{ZD}_{ii'dp}^t, \mathrm{ZD}_{ijdp}^t, \mathrm{ZD}_{jj'dp}^t, \mathrm{ZD}_{jkdp}^t, Y_i^t \in \{0,1\} \\ \forall d \in D, i, i' \in I : i \neq i', j, j' \in J : j \neq j', k \in K, p \in P, t \in T \end{array}, \tag{26}$$

$$\begin{array}{l} \mathrm{Ccap}_i^t, \mathrm{PaddPP}_{ii'}^t, \mathrm{PaddPI}_{ij}^t, \mathrm{PaddII}_{jj'}^t, \mathrm{PaddIS}_{jk}^t, \mathrm{PcapPP}_{ii'}^t, \mathrm{PcapPI}_{ij}^t, \mathrm{PcapII}_{jj'}^t, \\ \mathrm{PcapIS}_{jk}^t, X_{ii'}^t, X_{ij}^t, X_{jj'}^t, X_{jk}^t \geq 0 \qquad \forall\, i, i' \in I : i \neq i', j, j' \in J : j \neq j', k \in K, t \in T \end{array}, \tag{27}$$

3. Scenario Analysis

3.1. Data

The proposed CCS network optimization model is used to analyze the cost-effectiveness of CCS construction on the basis of South Korean CCS projects.

Since South Korea aims to commercialize CCS projects by 2030, this study selected thermal power plants and large-scale factories that would be operated on the basis of the relevant year when considering the candidate sites for emission sources.

With regard to large-scale factories, only the top seven producers of GHG emissions in South Korea were considered in our study. The geographical information and total amount of emissions for the candidate sites are summarized in Table 1.

Table 1. Candidate power plants and industrial facilities in the CCS network.

No.	Industry Type	Name	Latitude	Longitude	Generation Capacity (MW)	CO_2 Emission (Tons) (2016)
1	Power plant	Donghae	37.486167	129.145755	400	2293
2		Boryeong #1	36.520369	126.491087	4000	22,929
3		Samcheonpo	34.953830	128.103294	3240	18,573
4		Seocheon #1	36.137074	126.496794	400	2293
5		Yeosu #1	34.839776	127.692163	329	1886
6		Yeongdong	37.739142	128.980008	325	1863
7		Yeongheung	37.240886	126.457106	3340	19,146
8		Hadong	34.951411	127.820701	4000	22,929
9		Honam	34.870595	127.732398	500	2866
10		Dangjin	37.055521	126.511184	2000	34,623
11		Samcheok #1	37.253689	129.330733	2000	11,717
12		Bukpyeong	37.479118	129.144303	1000	6972
13		Taean	36.904755	126.232409	2000	34,967
14		Boryeong #2	36.396320	126.506721	2000	5732
15		Yeosu #2	34.853664	127.734543	500	2051
16		Dangjin-Eco	36.889177	126.639142	1000	6796 (scheduled in 2021)
17		Seocheon #2	36.138854	126.497538	1000	5732 (scheduled in 2019)
18		Goseong	34.912132	128.109340	2000	11,923 (scheduled in 2020)
19		Gangneung	37.733047	128.975955	2000	11,923 (scheduled in 2019)
20		Samcheok #2	37.435377	129.186957	2000	12,038 (scheduled in 2021)

Table 1. *Cont.*

No.	Industry Type	Name	Latitude	Longitude	Generation Capacity (MW)	CO_2 Emission (Tons) (2016)
21	Industry	Posco	36.000917	129.388823	-	75,660
22		Hyundai Steel	36.004511	129.377504	-	20,271
23		Ssangyong Cement	37.485633	129.056319	-	12,444
24		Tongyang Cement	37.430384	129.175678	-	7070
25		GS Caltex	35.11251	127.705823	-	5849
26		S-Oil	35.697698	129.342696	-	5369
27		SK energy	35.505224	129.353489	-	4288

The total amount of emissions of each candidate power plant was estimated on the basis of the generation capacity, and the industrial company was estimated through linear regression based on the history of emission volumes. On the other hand, information for the intermediate and sequestration sites is required to run the mathematical model. In Yun et al. [20], a heuristic algorithm was proposed to identify nodes using the central limit theorem. According to this algorithm, the information on the intermediate and sequestration sites is summarized in Table 2. The list of the pipeline costs according to factors [21] and pipeline lifespan is in Table 3.

Table 2. Intermediate storage and sequestration site coordinates.

Site Type	Name	Latitude	Longitude	Storage Capacity
Intermediate storage site	candidate site #1	37.477295	126.69566	undetermined
	candidate site #2	36.626061	126.26392	undetermined
	candidate site #3	34.920193	128.1084	undetermined
	candidate site #4	35.276665	129.23671	undetermined
	candidate site #5	37.479146	129.1329	undetermined
Sequestration site	Samcheok Gate	37.45130	129.18853	unlimited
	Taean Gate	36.77253	126.11306	unlimited
	Busan Gate	35.05965	129.09600	unlimited

Table 3. Pipeline costs and lifespan.

Cost Type	Factor				
	1	2	3	4	5
Materials cost (MTC)	70,350	2.01	330.5	686.7	26,960
Labor cost (LC)	371,850	2.01	343.2	2074	170,013
Miscellaneous cost (MCC)	147,250	1.55	8417	7234	-
Right of way cost (RC)	51,200	1.28	577	29,788	-
Pipeline lifespan (LT)			30		

3.2. *Scenario Configurations*

3.2.1. South Korea's 2030 Basic National Roadmap for Greenhouse Gas Reductions

The Korean government published the "2030 basic roadmap for reducing greenhouse gases" [22] in 2016 and presented the emission reduction targets for each sector (see Table 4). In the conversion sector, it plans to reduce emissions by 35 million tons through a combination of low-carbon power sources, which reduce coal usage, and increased utilization of renewable and clean energy. In addition, it plans to reduce emissions by 12 million tons and 17.5 million tons through demand management and improved power generation and distribution efficiency, respectively.

Table 4. Korea's 2030 target reduction by sector.

Sector		BAU (Million Tons)	Reduction (Million Tons)	Reduction Rate (%)		Detailed Method	Detailed Reduction (Million Tons)
				Compared to Sector BAU	Compared to National BAU		
Conversion		(333) *	64.5	(19.4)	7.6	Power mix	35
						Demand management	12
						Power generation, transmission, and distribution efficiency improvement	17.5
Industry		481	56.4	11.7	6.6	Improve process efficiency	21.3
						Introduction of innovative technologies and application of value-added products	14.8
						Eco-friendly process development	10.6
						Others	9.7
Building		197.2	35.8	18.1	4.2	Cooling and heating energy saving	13.2
						Promoting high-efficiency lighting equipment	19.1
						Optimize energy utilization	3.5
New energy industry		-	28.2	-	3.3	Carbon capture and storage (CCS)	10
						Microgrids	4
						Utilizing unused heat	2.5
						Smart factory	2.4
						Eco-friendly energy town	1.8
						Others	7.5
Transportation		105.2	25.9	24.6	3	Increased use of eco-friendly cars	15.7
						Efficient green logistics	3.9
						Others	6.3
Public others		21	3.6	17.3	0.4	-	
Waste		15.5	3.6	23	0.4	-	
Agriculture		20.7	1	4.8	0.1	-	
Total	Domestic reduction	851 *	219	25.70%	-	-	
	Overseas reduction		96	11.30%	-	-	

* The total emission reduction (domestic reduction and overseas reduction), i.e., 851 million tons, includes process emissions (around 2 million tons) as well as gas production and fugitive emissions (around 8.4 million tons). BAU levels in the conversion sector are indirectly included in each sector's emissions; hence, they are excluded from the total emission estimates.

In the industrial sector, it aims to reduce emissions by 56.4 million tons, i.e., a reduction of 11.7% compared to the BAU levels. Further, it plans to reduce emissions by 21.3 million tons through the early introduction of energy optimization technologies and the efficient operation of factory energy management systems. Moreover, it plans to reduce emissions by 14.8 million tons through the introduction of innovative technologies and the application of value-added products to energy-consuming industries. In addition, developing eco-friendly processes and employing eco-friendly fuels is expected to reduce emissions by 20.3 million tons. In the building sector, reduced energy consumption and increased use of high-efficiency lighting equipment could reduce emissions by 35.8 million tons. Furthermore, emissions can be reduced by 28.2 million tons by fostering new energy technologies, such as CCS technology, microgrids, and smart factories. In the transportation sector, it plans to reduce emissions by 25.9% by increasing the supply to environmentally friendly communities and strengthening the average fuel efficiency system. It also aims to attain a domestic reduction target of 219 million tons by reducing public waste.

In addition, the government has announced that it plans to reduce emissions by 96 million tons overseas, i.e., a reduction of 11.3% compared to the BAU levels, by 2030, through sustainable development mechanisms and direct carbon emission trading.

3.2.2. Scenario Description

Difficulties are anticipated in implementing the reduction targets set out in the national roadmap. To achieve the reduction targets by 2030, the related technologies should be developed and commercialized. However, specific implementation plans remain ambiguous. This study considers various scenarios in which CCS technology is used to substitute and supplement the emission reduction target for each sector, given the uncertainty in the development and commercialization of the related technology for each reduction target in each sector. It is assumed that the uncertainty rate is 30% of the target. In addition, this study tries to estimate the optimal CCS deployment network and costs in order to meet the reduction target level for each scenario.

The first scenario assumes that the development and commercialization of related technologies will proceed as planned in the implementation of the CO_2 reduction targets, and only CCS technology would be used as presented in the national GHG reduction roadmap. As shown in Table 4, in terms of nurturing new energy industries, the Korean government aims to achieve a reduction of 10 million tons by 2030, by developing and commercializing CCS technology to reduce CO_2 emissions from power plants and industries. The Korean government is preparing for a preemptive strategy in response to climate change concerns by intensively fostering new energy industries and intensively investing in it. However, many experts point out that the proliferation of microgrids and smart factories, and the utilization of unused heat, which are regarded as means for reducing emissions in the relevant sectors, will face many difficulties in implementing the target reductions by 2030, if the related technology development and improvement is not supported. Considering the uncertainty in implementing CO_2 reductions by fostering new energy industries, a second scenario is recommended, i.e., the use of CCS technology to achieve 30% of the reduction target of 10.7 million tons, through the proliferation of microgrids and smart factories, and the utilization of unused heat.

A realistic way to reduce GHG emissions in the power generation sector is to reduce the generation of coal-fired power itself by increasing nuclear power generation and liquefied natural gas (LNG) power generation, or to reduce GHG emissions from coal-fired power as much as possible. However, there are many indications that the actual reduction is not sufficient owing to the high cost of LNG generation. In the third scenario, CCS technology replaces uncertainties in the implementation of reductions in the power sector. The Korean government also seeks to achieve its GHG emission reduction targets through increased use of eco-friendly vehicles in the transportation sector. However, problems related to the commercialization of related technologies of hybrid vehicles are often encountered, including mileage limitations due to the battery life of electric cars. Even in the case of hydrogen cars, it will be difficult to optimize their penetration rate by 2030, because global automobile companies are presently in the early stages of launching their initial models. Therefore, this paper formulates a fourth scenario to overcome the uncertainty in the implementation of the reduction target by adopting CCS technology.

The Korean government has presented a national roadmap to divide domestic and overseas reductions, and it has proposed a plan to actively use the global carbon award mechanism reduce emissions by 11.3% of the total BAU levels by adopting an emissions trading scheme. However, to ensure smooth implementation, it is necessary to fulfill certain preconditions, such as international agreements on reduction, the expansion of the global emissions trading market, and preparation of financing schemes. Specific plans for reduction are yet to be finalized. Therefore, significant difficulties are expected for the achievement of such high targets through overseas reduction activities or the international emissions market. A fifth scenario has been proposed, in which CCS technology is adopted to replace the overseas reduction target partially by considering the uncertainty in the implementation of overseas reductions. Finally, this study assumes the worst-case scenario as the sixth scenario and considers the uncertainty in the implementation of mitigation measures at the same time. In this scenario, it aims to establish an optimal CO_2 transportation network under CCS technology to reduce emissions by a total of 57.72 million tons. In Table 5, it describes each scenario's content and reduction targets.

Table 5. Scenario description and reduction targets.

Scenario No.	Scenario Description	Reduction Target
(a)	Only CCS reduced demand	10 million tons
(b)	Including uncertainty in the new energy industry segment, proliferation of microgrids and smart factories, utilization of unused heat, and eco-friendly energy	13.21 million tons
(c)	Including the uncertainty in the conversion segment, low-carbon power mix	20.5 million tons
(d)	Including the uncertainty in the transportation segment, increased use of eco-friendly cars	14.71 million tons
(e)	Including the uncertainty in the offshore sector	38.8 million tons
(f)	Including all the above uncertainties	57.72 million tons

3.3. Scenario Results

Table 6 and Figure 2 show the optimal CO_2 transport network with the CO_2 reduction amount and cost results for each scenario with the CCS network optimization model.

Table 6. The results by cost of each scenario.

Scenario	Total Facility Cost (TFC) (Billion $)	Pipeline Operating Cost (POC) (Billion $)	Pipeline Capital Cost (PCC) (Billion $)	Total Cost (Billion $)	CO_2 Unit Cost ($\$\cdot(\text{t } CO_2)^{-1}$)
(a)	1.3667	0.0692	0.3699	1.8058	43.91
(b)	1.9864	0.0645	0.3458	2.3967	31.06
(c)	3.1966	0.0699	0.3776	3.6441	21.83
(d)	2.1304	0.0627	0.3324	2.5255	26.86
(e)	5.6143	0.2428	1.2751	7.1322	39.12
(f)	9.3387	0.3684	1.9319	11.639	39.85

In scenario (a), to reduce emissions by 10 million tons, i.e., 3.3% of the forecasted CO_2 emission rate in 2030, the best approach is to capture 8.3 million tons and 1.6 million tons of CO_2 from Samcheok power plant (node 20) with 2000 MW generation capacity and Donghae power plant (node 1) with 400 MW generation capacity, then finally transport it to Samcheok Gate (sequestration site 1) through intermediate storage site 5. The total cost is $1.81 billion.

As scenario (b) aims to capture 13.21 million tons of CO_2 and store it deep in the sea, the most efficient approach is to collect 8.7 million and 4.5 million tons of CO_2 from Samcheock power plant (2000 MW generation capacity) and Bukpyeong power plant (1000 MW generation capacity), and to then store it in Samcheock Gate after transporting it through intermediate storage site 5. The estimated cost is around $2.4 billion.

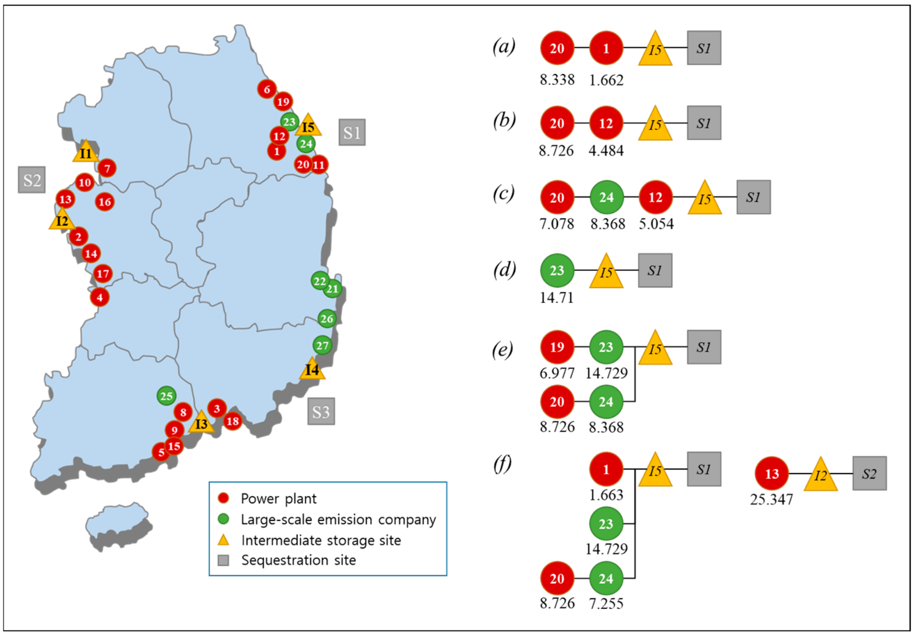

Figure 2. Display of optimal network by scenario.

Scenario (c) replaces some of the GHG emission reductions in the power sector with CCS technology. It is necessary to install a CO_2 capturing facility at Tongyang Cement & Energy Corp., in addition to considering the Samcheock and Bukpyeong power plants considered in scenario (b). The most economical approach for this scenario is to construct a CCS network by capturing 7 million, 5 million, and 8.4 million tons of CO_2 from the three sites, respectively, which is then transport through intermediate storage site 5 and stored at the Samcheok sequestration site, which is located deep in the sea. Toward this end, the total cost of the CCS network is estimated as \$3.6441 million (pipeline construction cost, \$0.38 million; pipeline operation cost, \$0.0699 million; and CO_2 capture and storage installation cost, \$3.1966 million).

In scenario (d), CCS technology is applied as a complementary measure by considering that CO_2-emission reduction through increased use of eco-friendly cars is not implemented smoothly. The required emission reduction target is 14.71 million tons. The optimal CCS operating model collects 14.71 million tons of CO_2 from one site, namely Sangyong Cement Industrial Co., Ltd., and follows the same network as that used in the previous scenario to store the CO_2 at Samcheok gate. The estimated cost is \$2.5255 million.

Scenario (e) aims to reduce emissions by 38.8 million tons by adopting CCS technology, which is expected to partially account for the overseas reduction target of 96 million tons. The optimal network derived from the mathematical model collects the required CO_2 volumes from two thermal power plants with 2000 MW generation capacity and two cement companies (Sangyong Cement Industrial Co., Ltd. (Donghae, Korea), and Tongyang Cement & Energy Corp. (Samcheok, Korea)). The total cost for CCS construction and operation and CO_2 capture and storage is estimated to be around \$7.132 million.

In scenario (f), CCS technology partially replaces the uncertainty in the emission targets for each sector of the national roadmap. A CO_2 capture, transport, and storage network is required to reduce emissions by 57.7 million tons. Two networks need to be created to achieve the target reduction in scenario (f), which is different from the other scenarios. Figure 2 shows that one network should reduce emissions by around 32.4 million tons through one 2000 MW generation capacity plant, two cement factories, and one 400 MW capacity thermal power plant, and the other network should collect 25.3 million tons of CO_2 from only one thermal power plant with a generation capacity of 2000 MW.

The estimated total cost is \$11.639 million, of which around 80% is for building CO_2 capture and storage facilities.

A comparison of the CO_2 unit cost (pipeline operating cost and capital cost) per scenario shows that the basic scenario (a) has the highest cost, and the reduction targets do not increase linearly with the costs. Thus, the reduction target could be met more efficiently if the reduction targets of the CCS project are considered by the Korean government, in addition to other reduction policies and targets, during the planning and decision-making process.

4. Discussion and Conclusions

Global modeling efforts by the Intergovernmental Panel on Climate Change (IPCC) and the IEA highlight the importance of CCS in achieving a climate goal of a 2 °C reduction in global temperatures. In response to climate change concerns, CCS is regarded as a key component of GHG reduction solutions. If the objectives of the Paris Agreement are to be achieved, CCS must be integrated into the mainstream of climate mitigation actions to be undertaken by governments and businesses.

This study attempted to design an optimal pipeline transportation network for large-scale CCS projects. The objective of the proposed model is to minimize the total investment cost of CCS projects, including pipeline capital costs, operation costs, and facility costs, by assuming that the maximum flow in the pipeline changes with its length and diameter. In addition, to implement CCS projects in Korea's master plan to tackle climate change, an optimal CCS network was proposed by considering the CO_2 emission sources, candidate sequestration sites, and facility construction and operation cost data. Various scenarios for CCS projects were experimentally configured to realize different effects on CO_2 reduction by analyzing the total investment.

The results of this research are helpful for the Korean government when deciding to utilize the CCS project as a complement to make up the reduction targets of other sectors, which are uncertain.

They will also serve as an important reference not only for planning CCS projects in South Korea, but also for enabling national and international policy makers to determine investment strategies for developing CCS networks for CO_2 reduction.

In the future, the study plans to extend to CCS networks with different transportation modes besides pipelines. In addition, it plans to present a model that is more realistic and suitable for Korea by considering updated national policies and technologies.

Author Contributions: Suk Ho Jin developed the mathematical model and performed the experiments. Lianxi Bai performed the overall paperwork, Jang Yeop Kim provided secondary data, and Suk Jae Jeong conceived and analyzed the experimental sections of the paper. Kyung Sup Kim developed the overall concept and the basic outline of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Notations

Indices

i	CO_2-emission source number ($i = 1, 2, \ldots, I$)
j	CO_2 intermediate storage site number ($j = 1, 2, \ldots, J$)
k	sequestration site number ($k = 1, 2, \ldots, K$)
d	pipeline diameter ($d = 1, 2, \ldots, D$)
p	pipeline number ($p = 1, 2, \ldots, P$)
t	period number ($t = 1, 2, \ldots, T$)

Parameters

CCF	capital cost of building CO_2 capture facility	t CO_2/h
Density_d	density of CO_2 transported via pipeline with diameter *d*	Kg/L
Flow_d	maximum amount of CO_2 transported per unit time via pipeline with diameter *d*	t CO_2/h
${EV^t}_i$	emission volume from each CO_2-emisson source *i* per unit time in time period *t*	-
LC_1	labor cost factor 1	-
LC_2	labor cost factor 2	-
LC_3	labor cost factor 3	-
LC_4	labor cost factor 4	-
LC_5	labor cost factor 5	-
LT	pipeline lifespan	-
M	a large positive value	-
MCC_1	miscellaneous cost factor 1	-
MCC_2	miscellaneous cost factor 2	-
MCC_3	miscellaneous cost factor 3	-
MCC_4	miscellaneous cost factor 4	-
MCC_5	miscellaneous cost factor 5	-
MTC_1	material cost factor 1	-
MTC_2	material cost factor 2	-
MTC_3	material cost factor 3	-
MTC_4	material cost factor 4	-
MTC_5	material cost factor 5	-
N	number of hours per year	-
OT	total operating time	-
PD_d	pipeline diameter *d*	-
$PLII_{jj'}$	pipeline length between intermediate storage sites *j* and *j′* ($j \neq j'$)	m
$PLIS_{jk}$	pipeline length between intermediate storage site *j* and sequestration site *k*	m
$PLPI_{ij}$	pipeline length between CO_2-emission source *i* and intermediate storage site *j*	m
$PLPP_{ii'}$	pipeline length between CO_2-emission sources *i* and *i′* ($i \neq i'$)	m
r	ratio of NPV	-
RC_1	right-of-way cost factor 1	-
RC_2	right-of-way cost factor 2	-
RC_3	right-of-way cost factor 3	-
RC_4	right-of-way cost factor 4	-
T_t	construction time	-
TV_t	target reduction volume in time period *t*	-
${UOCP^t}_d$	unit operating cost of pipeline with diameter *d* in time period *t*	-
v	speed of flow	m/h

Variables

${Ccap^t}_i$	amount of CO_2 captured at emission source *i* in per unit time in time period *t*	t CO_2/h
${I^t}_k$	amount of CO_2 injected at sequestration site *k* in time period *t*	t CO_2/h
${LCII^t}_{jj'd}$	labor cost between intermediate storage sites *j* and *j′* ($j' \neq j$) through pipeline with diameter *d* in time period *t*	\$
${LCIS^t}_{jkd}$	labor cost between intermediate storage site *j* and sequestration site *k* through pipeline with diameter *d* in time period *t*	\$
${LCPI^t}_{ijd}$	labor cost between CO_2-emission source *i* and intermediate storage site *j* through pipeline with diameter *d* in time period *t*	\$
${LCPP^t}_{ii'd}$	labor cost between CO_2-emission sources *i* and *i′* ($i' \neq i$) through pipeline with diameter *d* in time period *t*	\$
${MCCII^t}_{jj'd}$	miscellaneous cost between intermediate storage sites *j* and *j′* ($j' \neq j$) through pipeline with diameter *d* in time period *t*	\$

$\mathrm{MCCIS}^{t}{}_{jkd}$	miscellaneous cost between intermediate storage site j and sequestration site k through pipeline with diameter d in time period t	$
$\mathrm{MCCPI}^{t}{}_{ijd}$	miscellaneous cost between CO_2-emission source i and intermediate storage site j through pipeline with diameter d in time period t	$
$\mathrm{MCCPP}^{t}{}_{ii'd}$	miscellaneous cost between CO_2-emission sources i and i' ($i' \neq i$) through pipeline with diameter d in time period t	$
$\mathrm{MTCII}^{t}{}_{jj'd}$	material cost between intermediate storage sites j and j' ($j' \neq j$) through pipeline with diameter d in time period t	$
$\mathrm{MTCIS}^{t}{}_{jkd}$	material cost between intermediate storage site j and sequestration site k through pipeline with diameter d in time period t	$
$\mathrm{MTCPI}^{t}{}_{ijd}$	material cost between CO_2-emission source i and intermediate storage site j through pipeline with diameter d in time period t	$
$\mathrm{MTCPP}^{t}{}_{ii'd}$	material cost between CO_2-emission sources i and i' ($i' \neq i$) through pipeline with diameter d in time period t	$
$\mathrm{PaddII}^{t}{}_{jj'd}$	expanded pipeline capacity from intermediate storage site j to j' ($j' \neq j$) in time period t	-
$\mathrm{PaddIS}^{t}{}_{jkd}$	expanded pipeline capacity from intermediate storage site j to sequestration site k in time period t	-
$\mathrm{PaddPI}^{t}{}_{ijd}$	expanded pipeline capacity from CO_2-emission source i to intermediate storage site j in time period t	-
$\mathrm{PaddPP}^{t}{}_{ii'd}$	expanded pipeline capacity from CO_2-emission source i to i' ($i' \neq i$) in time period t	-
$\mathrm{PcapII}^{t}{}_{\mathrm{jj'd}}$	pipeline capacity from intermediate storage site j to j' ($j' \neq j$) in time period t	-
$\mathrm{PcapIS}^{t}{}_{jkd}$	pipeline capacity from intermediate storage site j to sequestration site k in time period t	-
$\mathrm{PcapPI}^{t}{}_{ijd}$	pipeline capacity from CO_2-emission source i to intermediate storage site j in time period t	-
$\mathrm{PcapPP}^{t}{}_{ii'd}$	pipeline capacity from CO_2-emission source i to i' ($i' \neq i$) in time period t	-
PCC	pipeline capital cost	$
POC	pipeline operating cost	$
$\mathrm{POCII}^{t}{}_{jj'd}$	operating cost between intermediate storage sites j and j' ($j' \neq j$) through pipeline with diameter d in time period t	$
$\mathrm{POCIS}^{t}{}_{jkd}$	operating cost between intermediate storage site j and sequestration site k through pipeline with diameter d in time period t	$
$\mathrm{POCPI}^{t}{}_{ijd}$	operating cost between CO_2-emission source i and intermediate storage site j through pipeline with diameter d in time period t	$
$\mathrm{POCPP}^{t}{}_{ii'd}$	operating cost between CO_2-emission sources i and i' ($i' \neq i$) through pipeline with diameter d in time period t	$
$\mathrm{RCII}^{t}{}_{jj'd}$	right-of-way cost between intermediate storage sites j and j' ($j' \neq j$) through pipeline with diameter d in time period t	$
$\mathrm{RCIS}^{t}{}_{jkd}$	right-of-way cost between intermediate storage site j and sequestration site k through pipeline with diameter d in time period t	$
$\mathrm{RCPI}^{t}{}_{ijd}$	right-of-way cost between CO_2-emission source i and intermediate storage site j through pipeline with diameter d in time period t	$
$\mathrm{RCPP}^{t}{}_{ii'd}$	right-of-way cost between CO_2-emission sources i and i' ($i' \neq i$) through pipeline with diameter d in time period t	$
TFC	total facility cost	$
TLC_{t}	labor cost of pipeline in time period t	$
TMCC_{t}	miscellaneous cost of pipeline in time period t	$
TMTC_{t}	material cost of pipeline in time period t	$
TPC	total pipeline cost	$
TRC_{t}	total right-of-way cost of pipeline in time period t	$

$X^t{}_{ii'}$	amount of CO_2 transported from emission source i to i' ($i' \neq i$) per unit time in time period t	t CO_2/h
$X^t{}_{ij}$	amount of CO_2 transported from emission source i to intermediate storage site j per unit time in time period t	t CO_2/h
$X^t{}_{jj'}$	amount of CO_2 transported from intermediate storage site j to j' ($j' \neq j$) per unit time in time period t	t CO_2/h
$X^t{}_{jk}$	amount of CO_2 transported from intermediate storage site j to sequestration site k per unit time in time period t	t CO_2/h

Binary Variables

$$ZD^t_{ii'dp} = \begin{cases} 1, & \text{if pipeline } p \text{ with diameter } d \text{ is expanded between CO}_2\text{-emission source } i \text{ and } i' \\ & \text{in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$ZD^t_{ijdp} = \begin{cases} 1, & \text{if pipeline } p \text{ with diameter } d \text{ is expanded between CO}_2\text{-emission source } i \text{ and} \\ & \text{intermediate storage site } j \text{ in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$ZD^t_{jj'dp} = \begin{cases} 1, & \text{if pipeline } p \text{ with diameter } d \text{ is expanded between intermediate storage site } j \\ & \text{and } j' \text{ in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$ZD^t_{jkdp} = \begin{cases} 1, & \text{if pipeline } p \text{ with diameter } d \text{ is expanded between intermediate storage site } j \text{ and} \\ & \text{sequestration site } k \text{ in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$Y^t_i = \begin{cases} 1, & \text{if CO}_2 \text{ capture facility is built at site } i \text{ in time period } t \\ 0, & \text{otherwise} \end{cases}$$

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