Optimization-based planning of carbon-neutral strategy: Economic priority between CCU vs CCS

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ABSTRACT

This study aims to develop an optimization-based approach to design the carbon capture, utilization, and storage (CCUS) supply chain and analyze the optimal configuration and investment strategies. To achieve this goal, we develop an optimization model that determines the logistic decision-making to maximize the net present value (NPV) and minimize the net CO_2 emissions (NCE) of the strategies of the CCUS supply chain under logical and practical constraints. We estimate the technical (production scale and energy consumption), economic (capital and operating expenditure), and carbon-related (CO_2 emissions) parameters based on the literature. By adjusting major cost drivers and economic bottlenecks, we determined major decision-making problems in the CCUS framework, such as sequestration vs. utilization. As a real case study, the future CCUS system of South Korea was evaluated, which includes three major CO_2 emitting industries in South Korea (power plants, steel, and chemicals), as well as transportation modes and sequestration sites. As a result, we analyzed different design and operation strategies based on various objectives. We provided a strategic solution for national-level planning of the CCUS supply chain. The major finding of this study can support industry stakeholders and government policymakers by providing a practical guideline for investing in the deployment of CCUS.

Keywords: Carbon capture, utilization, and storage (CCUS), optimization, South Korea, MILP, supply chain

1. INTRODUCTION

Global warming is one of the most important issues for humanity, receiving significant attention from the scientific community. Carbon dioxide (CO_2) is one of the major greenhouse gases that can affect global warming. CO_2 emissions are mainly generated through three key areas: fuel combustion, industrial processes, and natural gas processing [1]. According to recent estimates, global CO_2 emissions from fossil fuel combustion have exceeded 37.1 Gt, marking a notable increase of over 2.7% compared to 2017. [2]. To achieve the 1.5°C target set by the Paris Agreement, substantial reductions in CO_2 emissions are required, amounting to 24 Gt of CO_2 per year by 2030, 14 Gt of CO_2 per year by 2040, and 5 Gt of CO_2 per year by 2050 [2, 3]. Achieving these reductions necessitates implementing advanced technological solutions, among which Carbon capture, utilization, and storage (CCUS) has emerged as a promising solution.

In the CCUS process, CO_2 is captured from air or industrial sources using carbon capture technology. Captured CO_2 is then transported to its destination into two main technological pathways. The first pathway is carbon capture and storage (CCS), where CO_2 is delivered to a designated storage site and permanently sequestered in geological formations, such as depleted oil and gas reservoirs or deep saline aquifers. The second pathway is carbon capture and utilization (CCU), which utilizes CO_2 as a key carbon feedstock for producing value-added products. CCUS technologies can reduce CO_2 effectively. For example, gasoline production can reduce more than 5 kg of CO_2 eq per unit of fuel [4]. However, the implementation of associated technologies within the industrial sector is challenging. The limitations are caused by the lack of a supply chain, including CCU and CCS with existing energy and industrial infrastructures.

Recently, a few studies have focused on addressing the CCUS supply chain design. Huang et al. examined the CCUS supply chain utilizing CO_2-enhanced coal bed methane (CO_2-ECBM) recovery [5]. Leonzio et al.

incorporated methanol (MeOH) production via dry reforming for CCU and developed the CCUS supply chain for Germany [6]. A few studies about the economic optimization of CCS are reported for distinct geographical characteristics: Klokk et al. for Norway, and Zhang et al. for China [7,8]. The preceding studies highlight the necessity of developing region-specific CCUS supply chain optimization models, for unique characteristics and constraints specific to each region. These models emphasize the significance of multi-stage planning in achieving efficient carbon management systems. Nevertheless, the expansion of the scope of research is imperative, integrating approaches that address multi-objective and multi-period scenarios. These approaches are essential for capturing the dynamic nature of CO_2 supply and demand, technological advancements, and fluctuating economic and regulatory landscapes.

In this study, we develop an optimization-based framework for the CCUS supply chain to integrate the overall CCUS infrastructure into the supply chain to maximize net present value (NPV). CO_2 is captured, compressed, and transported from CO_2 emission sources. After transporting captured CO_2, we consider the CO_2 utilization technologies, which involve the production of MeOH, and the CO_2 storage option, which includes the CO_2 intermediate storage terminals and offshore storages to sequester CO_2. Then, two distinct scenarios with different criteria (social cost of CO_2, and CO_2 capture rate) are analyzed over a multi-period framework. The proposed model presents strategies that incorporate economic and environmental considerations while addressing future scenarios.

2. METHODOLOGY

2.1. Problem statement

The main objective of this study is to develop an optimization-based approach to design a supply chain incorporating both CCS and CCU. The proposed CCUS supply chain optimization model comprises the following components: CO_2 sources, CO_2 capture processes, transportation infrastructure, CO_2 storage facilities, and CO_2 utilization systems. CO_2 storage facilities include intermediate storage terminals and offshore storage sites, while CO_2 utilization focuses on the MeOH production process via direct hydrogenation. The system boundary of the model is illustrated in Figure 1.

In the proposed model, carbon-related data (CO_2 emission sources, location, and annual emissions), transportation data (loading/unloading times and transportation capacities), and technical data (production scales, and raw material consumption) are utilized as basic elements for decision-making [9]. The model determines the optimal number and location of CO_2 storage terminals and MeOH production facilities.

To simplify the model, the following assumptions are made:

- Each CO_2 emission source is linked to a single CO_2 intermediate storage terminal or MeOH production facility.

- MeOH prices are assumed to increase due to inflationary trends, while hydrogen prices are projected to decrease in a multi-period context, reflecting expected technological advancements and market dynamics [9].

2.2. Optimization model

The objective function of the optimization model is to maximize the NPV of the CCUS supply chain. The optimization is formulated using a mixed integer linear programming (MILP) model. The NPV is calculated as the total revenue minus the total cost and is defined as follows:

$$\max NPV = Revenue + TSC - TPC \tag{1}$$

TPC (total production cost) consists of PCC (production capital cost), SCC (storage capital cost), TCC (transportation capital cost), POC (production operating cost), SOC (storage operating cost), and TOC (transportation operating cost).

$$TPC = PCC + SCC + TCC + POC + SOC + TOC \tag{2}$$

PCC & POC quantify the capital expenditures and operating expenditures of MeOH production facilities. TCC &
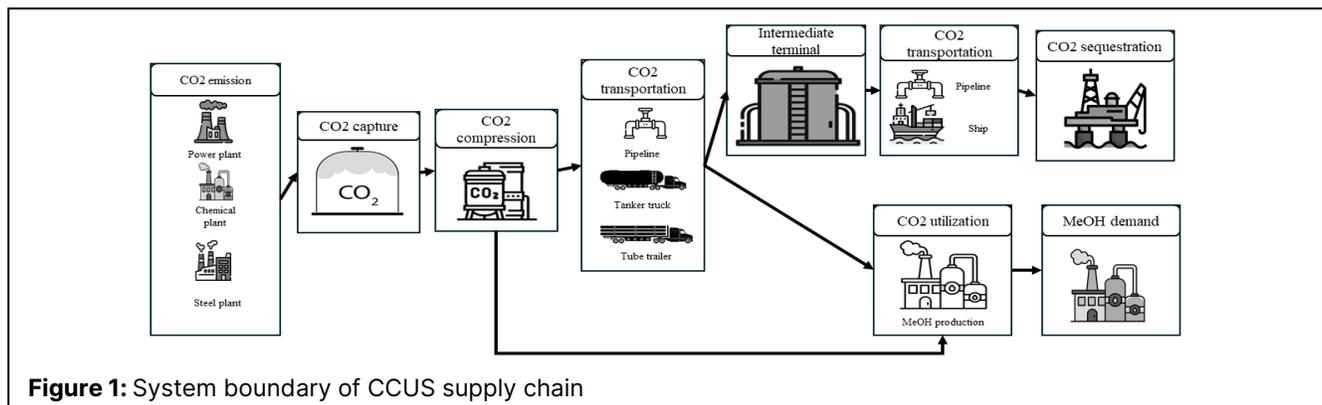
Figure 1: System boundary of CCUS supply chain

TOC quantify the capital expenditures and operating expenditures of transporting CO_2 from its emission sources to MeOH production facilities/CO_2 intermediate storage terminals and from CO_2 intermediate storage terminals to offshore storage facilities. SCC & SOC quantify the capital expenditures and operating expenditures of CO_2 intermediate storage terminals. Revenue quantifies the profit from MeOH sales in CCU. TSC (total salvage cost) quantifies the total salvage cost of MeOH production facilities and CO_2 intermediate storage terminals.

For the mass balance constraints at the CO_2 capture and transportation, Eq (3) indicates that the amount of captured CO_2 is equal to the total amount of CO_2 transported to intermediate terminals of MeOH production facilities.

$$CC_{rt} = \sum_{r'} Q_{trr'}^T + \sum_s Q_{trs}^T + F_{jrt} \qquad (3)$$

Where CC_{rt} and F_{jrt} indicate amount of captured CO_2 and utilized CO_2. $Q_{trr'}^T$ and Q_{trs}^T denote the amount of CO_2 transported to MeOH production facility and CO_2 storage terminals.

For CO_2 storage, Eq (4) indicates the amount of CO_2 transported to storage terminals is equal to the amount of CO_2 sequestered.

$$\sum_s CT_{ts}^T = \sum_q S_{tq}^T \qquad (4)$$

CT_{ts}^T and S_{tq}^T present the amount of CO_2 stored in CO_2 intermediate storage terminals and sequestered in offshore storage.

Regarding transportation capacity constraints, Eq (5) the amount of CO_2 does not exceed the capacity of the respective transportations.

$$N_{trr}^T \vartheta_p \leq Q_{trr'}^T \leq N_{trr}^T \theta_p \qquad (5)$$

Where ϑ_p and θ_p indicate minimum capacity and maximum capacity of CO_2 transportation. $N_{trr'}^T$ presents the number of transportation unit. $Q_{trr'}^T$ indicates the amount of CO_2 from CO_2 source to MeOH production facility.

3. CASE STUDY: APPLICATION TO SOUTH KOREA

To demonstrate the effectiveness of the optimization model, we present a case study on the supply chain in South Korea. With annual CO_2 emissions amounting to approximately 600 million tons, representing 1.6% of global emissions, South Korea's major contributors include fossil fuel combustion and industrial activities such as power generation, steel production, and chemical manufacturing. To align with the government's 2050 net-zero target, substantial reductions in industrial sector emissions are projected, aiming to cut up to 80% of current levels through the implementation of CCUS technologies. A comprehensive survey was conducted involving

157 facilities across the country, encompassing 25 power plants, 46 steel facilities, and 86 chemical plants. The annual CO_2 emissions of these facilities were assessed, with the data summarized in Table 1.

Table 1: Category of CO_2 emission sources

| CO_2 source	Number of factories	Total CO_2 emissions
Power plant	25	49.96 Mt
Steel plant	46	123.53 Mt
Chemical plant	86	300.78 Mt
Total	157	474.27 Mt

These facilities were identified as potential MeOH production sites, using captured CO_2 as a feedstock. For CO_2 sequestration, two depleted gas reservoirs located in the East Sea and West Sea were selected as storage sites. Additionally, CO_2 intermediate storage terminals were strategically proposed for each province. Coastal areas favored terminals at ports, while inland areas selected locations in plains over mountainous regions to minimize infrastructure and transport costs. To facilitate offshore sequestration, the transport network links CO_2 intermediate storage terminals to the selected ports. To visualize the CO_2 flow from emission sources to MeOH production facilities or CO_2 intermediate storage terminals, CO_2 emissions were evaluated at the provincial level, as depicted in Figure 2.
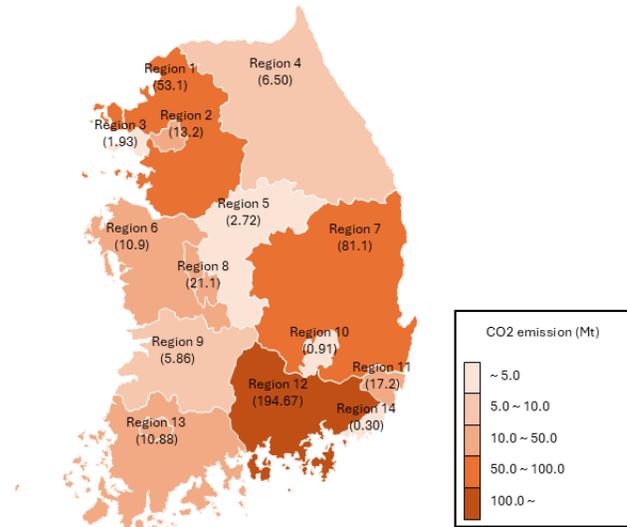
Figure 2. CO_2 emissions map in Korea in 2030

4. RESULTS AND DISCUSSION

This section presents the results of the optimized CCUS supply chain applied to South Korea, demonstrating the efficacy of the developed model. The optimization problem formulated as a MILP model and solved using
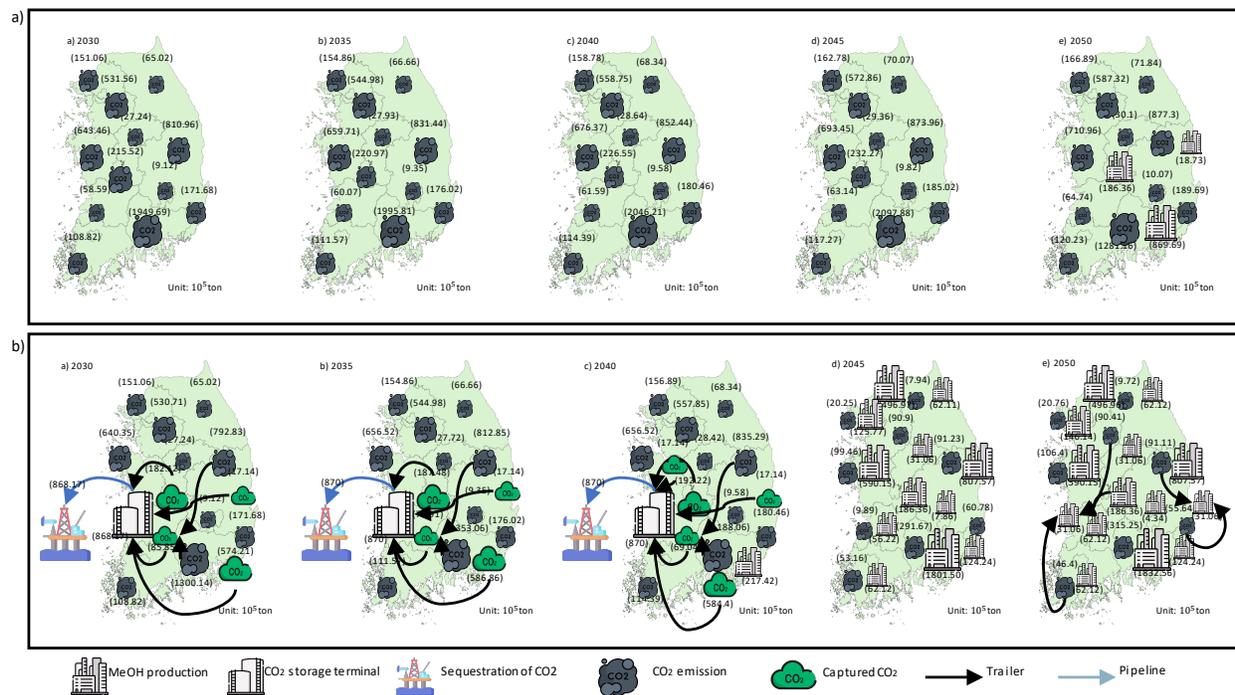
Figure 3: Topology of the optimized CCUS supply chain with (a) $40 and (b) $170 of social cost in South Korea from 2030 to 2050

CPLEX, aimed to maximize the NPV of the system. The analysis was conducted under two scenarios: (1) incorporating social costs of CO_2 emissions which is the monetary value of the environmental damage of each additional ton of CO_2 emitted, and 2) varying CO_2 capture rates for emission sources [10]. The social cost of CO_2 is evaluated from a baseline of $0 per ton of CO_2, representing no economic impact, up to a maximum of $185 per ton of CO_2 reflecting the potential role of the social cost of CO_2 emissions as a financial penalty [11]. Additionally, the CO2 capture rates for emission sources are assessed up to maximum efficiency of CO_2 capture technology.

4.1 Results for CCUS supply chain with social costs

In scenarios with low social costs for CO_2 emissions, the optimization results reveal that deploying CCUS facilities is not economically viable. Instead, the atmospheric emission of CO_2 continues to be economically favorable. However, as the social cost increased to $40 per ton, the CCUS supply chain model suggests the deployment of CCU technologies to produce MeOH as a viable strategy by 2050. The graphical topology of this supply chain at $40 and $170 of social cost is shown in Figure 3. At this price point, the model suggested that regional CO_2 emissions from regions 7, 8, and 12 are captured and utilized directly at local MeOH production sites, eliminating transportation costs. Regions 7, 8, and 12 are primarily associated with steel production facilities, where the

relatively low cost of carbon capture serves as a key driver for CO_2 capture implementation. When the social cost reaches $170 per ton, the model predicts the construction of CO_2 intermediate storage terminals in selected regions such as region 9, by 2030. This cost level facilitates the sequestration of 86.8 million tons of CO_2, reflecting the increased feasibility of CCS under higher social costs.

A multi-period analysis demonstrates that declining hydrogen prices, from $4.21 per kg in 2030 to $3.21 per kg in 2040, and rising MeOH prices influenced by inflationary trends enhance the attractiveness of CCU technologies. Consequently, CO_2 initially allocated for storage is reallocated for utilization, underscoring the dynamic adaptability of the supply chain to economic fluctuations.

4.2 Results for CCUS supply chain with capture rates

This study systematically evaluates the performance of the CCUS supply chain under varying CO_2 capture rates, focusing on CO_2 allocation, infrastructure development, and the economic and operational performance of the network.

At a capture rate of 10%, all captured CO_2 amounting to 47.4 million tons by 2030 is directed to offshore storage. The graphical topology of this supply chain at 10% and 30% of the capture rate is shown in Figure 4. Infrastructure development in this scenario required constructing intermediate storage terminals in region 9 and
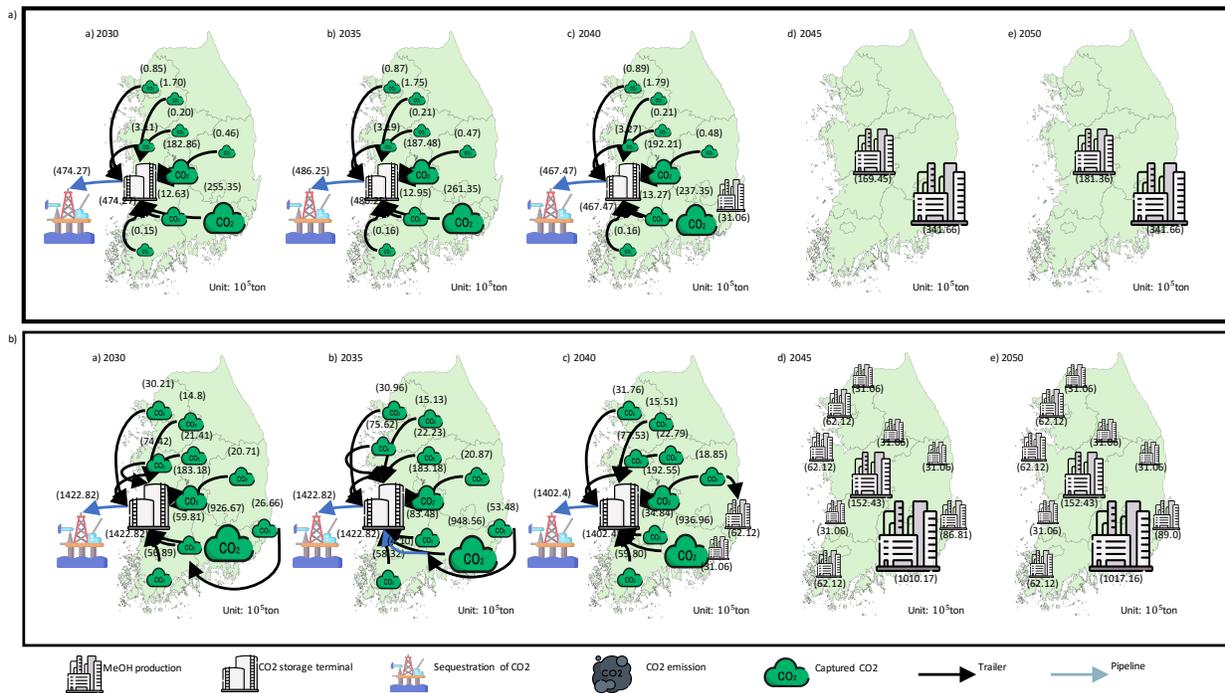
Figure 4: Topology of the optimized CCUS supply chain with (a) 10% and (b) 30% of capture rate in South Korea from 2030 to 2050

deploying pipelines to transport CO_2 to the West Sea. In a multi-period analysis, CCU facilities emerge in regions 8 and 12, enabling MeOH production from captured CO_2 by 2040. Capture rates of 30% or higher facilitate the establishment of additional CO_2 intermediate storage terminals and production facilities.

5. CONCLUSION

The CCUS supply chain plays a critical role in South Korea's efforts to achieve its carbon neutrality target by 2050. This study presents a CCUS supply chain model incorporating two distinct scenario criteria (the social cost of CO_2 and CO_2 capture rate) over a multi-period framework. The result demonstrated that 1) CO_2 utilization holds an economic priority over CO_2 storage due to the significant costs associated with injecting CO_2 into offshore storage sites, and 2) higher social costs and capture rates act as drivers for promoting carbon capture. This study confirms the effectiveness of implementing an optimization strategy for multi-objective, multi-period CCUS supply chains to address the uncertainties in strategic planning. By applying a systematic approach that adapts multi-period and multi-objective scenarios, the proposed model facilitates comprehensive planning that incorporates economic and environmental considerations. The proposed model successfully demonstrates the potential to achieve such integration and optimization, providing valuable insights for future CCUS applications. By utilizing the optimization model from this study, stakeholders and policymakers can develop deployment

strategies that effectively balance economic and environmental objectives.

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