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Economic Evaluation of Ship-based CCS with Availability

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Abstract

This study developed an economic evaluation model for CCS (Carbon Capture and Storage) chain where pipelines and ships were expected to come into play in transporting CO2 from power plants to offshore storage sites. In case of ship-based transportation, several alternatives with various operating conditions were feasible, demanding optimization of the transportation mode. The economic evaluation model was based on the LCC (Life Cycle Cost) methodology where the operational availability of equipment and systems were taken into consideration in addition to the capital and operating expenditure. The economic evaluation model was applied to the LCC estimation of two cases. The LCC results showed that the governing factor was the OPEX, dominantly affected by the liquefaction system.

Keywords: Ship-based CCS chain; Economic evaluation model; LCC; CAPEX; OPEX; Unavailability cost

1. Introduction

Carbon Capture and Storage (CCS) consists of three parts: capture, transportation and storage. CO2 from power plants is captured and then it is transported to geological storage sites. It is finally injected into the storage site where CO2 is sequestered. When the storage site is offshore, CO2 can be transported by a pipeline or a ship [1,2]. Since several design alternatives with adjustable operating conditions are feasible in ship-based transportation, economic evaluation is required for the optimization. This study focuses on developing the economic evaluation model for ship-based CCS chain.
First of all, the system and design alternatives are described in Section 2. Section 3 shows the methodology of economic evaluation and economic data. Section 4 illustrates the logic of economic evaluation model while the case study is performed in section 5. Finally, conclusions are presented in Section 6.

2. System description and design alternatives

2.1. System description

Fig 1 illustrates the configuration of ship-based CO2 transportation. First, the captured CO2 at a power plant is compressed by a compression system and then it is transported to a barge by a pipeline. After pipeline transportation, the liquefaction system liquefies the transported CO2 because the density of vapor CO2 is too low for economic transportation. It is stored in temporary storage tanks until a CO2 carrier comes to take it. The stored CO2 is transferred into the carrier through a cargo handling system and then the carrier navigates to the storage site. Finally, CO2 is injected to the site.

The assumptions for ship-based CCS chain are as below.
- CO2 emission sources are coal fired power plants which are located near the shore.
- The liquefaction point is near the triple point [3].
- A liquefaction system and temporary storage tanks are installed on the barge instead of onshore site.

2.2. Design alternatives

There are two options for the compression system; the first has only one compressor at the power plant and the second has two compressors installed each at the power plant and the barge. Since CO2 is liquefied just above the triple point, the CO2 should be compressed up to the pressure of the triple point for the liquefaction. When the first option is employed, it is compressed comparatively higher than the second to overcome high pressure drop. The advantage of the first option is that it requires only one compressor and the diameter of pipeline is smaller than the second whereas the disadvantage is to consume more energy. On the other hand, the CO2 is slightly compressed at the power plant and then it is recompressed at the barge in the second option. The merit of this option is stable operation and low pressure drop during the pipeline transportation. Since CO2 is recompressed at the barge, unpredicted pressure drop can be allowed. The demerit is high installation cost as requiring two compressors.
Various refrigeration systems are available for the liquefaction. CO2 near the triple point is liquefied when its temperature is lower than -52 °C. For this reason, the refrigeration system is necessary. The refrigeration system is basically classified into open and closed cycle. The fluid acts the role of the refrigerant in the open cycle while it is cooled down by the refrigerant in the closed cycle. The closed cycle is considered in this study since the open cycle requires lots of energy. The closed cycle is categorized into the single refrigerant cycle and the cascade cycle depending on the number of refrigerants. In the single refrigerant, it could cause air leakage in the evaporator as the pressure at evaporator is below than atmospheric pressure. For this reason, cascade cycle is only considered. The cascade cycle is classified into several cycles through the kinds of refrigerant. Four common refrigerants are investigated: ammonia, propane, R134a and ethane. Ammonia, propane and R134a are used for the refrigerant of top compression in the cascade cycle, whereas ethane is employed for bottom compression.

The optimum size of the CO2 carrier depends on the amount and the distance. When the size of the CO2 carrier is determined, the required number of the CO2 carriers is estimated. The capacity of the barge is assumed to be two times as big as the CO2 carrier to accommodate the unexpected delay of voyage.

3. Economic evaluation data

LCC (Life Cycle Cost) is employed in order to evaluate the suggested design alternatives in ship-based CCS chain. LCC is the total cost of ownership of a product over its life cycle which includes research and development, construction, operation and maintenance and disposal. The estimated LCC is useful for the decision making in the early design stage. The conventional LCC commonly consists of CAPEX (Capital Expenditure) and OPEX (Operation Expenditure) on the highest level. If the unavailability of system is high, the cost from the deferred production may give considerable impact on the LCC [4]. In consequence, the cost of deferred production is also taken into account to the LCC as unavailability cost in this study. The evaluation data depending on the amount and distance is collected from open literatures.

3.1. Compression system

First, the pressure drop during pipeline transportation should be calculated to estimate the cost of compression system [5]. Several equations are available whether or not it is compressible [6]. The compressible flow equation is applied to this study because its pressure drop is lower than 40 % of the inlet pressure. However, the average pressure of inlet and outlet is used for the calculation of density CO2.

The CAPEX of the compression system is estimated using the way of percentage of delivered equipment cost [7]. Percentage of delivered equipment cost is the methodology to estimate the costs in CAPEX except for equipment cost. This methodology estimates the costs using the equipment cost. Equipment cost is estimated by referring to the website which provides the equipment cost.

The OPEX is valued as referring the energy consumption cost and the CAPEX. The required energy is calculated through the commercial process simulation tool, and then it is converted to the cost by consulting the unit electricity cost in Korea.

3.2. Pipeline

The MIT CO2 pipeline cost model with its correlation is employed for the pipeline cost. This model conveniently provides the cost information depending on length and diameter. This model is selected in
this study to simplify the calculation. The quotation from a pipeline supplier in Korea is used to verify this model.

3.3. Refrigeration system

The energy efficiency is only considered to decide the best refrigeration system. Although various factors affect the decision of refrigeration system, the energy efficiency is considerably dominant than others [8,9]. Fifteen cascade cycles with different refrigerant and condensing temperature are suggested and then these are investigated.

In order to estimate the energy efficiency, the process should be designed first. Fig 2 show the Process flow diagram of ammonia ethane cascade cycle with -30 °C condensing temperature.

The process simulation tool simulates the suggested cycles to predict the energy efficiency. The simulation results indicate that the propane-ethane cascade cycle with -40 °C condensing temperature has the highest efficiency.

The methodology of percentage of delivered equipment cost is employed to estimate the CAPEX of refrigeration system. The costs of equipment such as compressors, coolers and scrubbers are evaluated by the commercial tool. Total equipment cost is proportionally increased depending on the quantity of CO2 as shown in Fig 3(a). The normalized total equipment cost is decreased as the quantity of CO2 is increased as shown in Fig 3(b). This result indicates that refrigeration system has scale up effect.

The OPEX of the refrigeration system is estimated through the process simulation tool and the CAPEX. The process simulation tool predicts the required energy consumption then it is converted to the cost by referring the unit electricity cost. Fig 4(a) indicates the energy consumption with the amount of CO2 and Fig 4(b) demonstrates the normalized energy consumption cost. Although the energy consumption cost is proportionally increased depending on the amount of CO2, the normalized is not. These results show that energy consumption of refrigeration system does not have scale up effect.

Fig. 2. Ammonia-ethane cycle with -30 °C condensing temperature
3.4. Storage tank

The new type of pressure tank is used for temporary CO2 storage instead of conventional cylindrical type. The pressure of CO2 in the storage tanks is above atmospheric pressure hence the pressure tank should be employed. Even though the most frequently used pressure tank is the cylindrical type, it occupies lots of space. In order to solve this problem, the new type of pressure tank is employed.

The cost of new type tank is roughly estimated to be 1.5 times the material cost of cylindrical tank. In order to estimate the amount of material, the optimum radius and length of a cylindrical tank are calculated. This calculation complies with the international standard for the pressure tank and the material cost is estimated. The CAPEX is estimated by the assumption; the material cost is about 55% of CAPEX. OPEX is assumed as 5% of CAPEX.

3.5. Barge

The bulk carrier cost is utilized to estimate the barge cost. Although the bulk carrier has difference with the barge, the main cost factor is material both them and the required material cost for manufacture is similar. The OPEX of the barge for a year is assumed as 5% of CAPEX.
3.6. **CO2 carrier**

The CAPEX is estimated by adding the carrier hull cost to the storage tank cost because carrier can be divided into the carrier hull part and storage tank part. The oil tanker cost from Clarkson is used for the estimation of carrier hull cost.

The OPEX is divided into the fuel consumption cost and the general operating cost such as crewing, repair and maintenance, insurance cost. The fuel consumption cost is estimated by the fuel consumption rate of oil tanker. The fuel consumption rate is predicted through the capacity of fuel storage tank and cruising range.

3.7. **Unavailability cost**

Unavailability cost is caused by production loss from the equipment failure and the unpredicted external force like hurricane and strong wind. According to the IEC60050, availability is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over given time interval, assuming that the required external resources are provided. The availability may be estimated by the subtracting the production loss time from the total calendar time of the system operation, and dividing it by total calendar time of the system operation [10].

In this study, the compression system, refrigeration system and CO2 carrier are only investigated for the availability estimation. Since the chemical process has significant effect on the availability, the compression and refrigeration system are considered. Although the CO2 carrier is not the process, the availability is controlled by CO2 carrier’s schedule. Environment conditions like typhoon and strong wind can limit the management of CO2 carrier. Following indicates the assumptions for the availability estimation.

- The Level of the simulation model is the equipment level.
- The reliability data is collected from OREDA (Offshore reliability data) [12].
- Redundancy is not considered.

4. **Logic of economic evaluation model**

This section indicates that how the cost is estimated and how optimal option is selected among the several alternatives. This is the procedure of evaluation model.

- The pressure drop through the pipeline transportation is calculated using the hydrodynamic equations.
- After the pressure drop is taken, the capacity of compressor and the energy consumption are predicted by the commercial process simulation tool.
- The CAPEX and OPEX of compression system are estimated and MIT CO2 pipeline cost model values the expenditure of pipeline.
- Optimum compression system is determined by comparing the LCC of two cases: one or two compressors type.
- The transportation time is estimated through the distance from the barge to the storage site. (The ship speed is assumed as 15 knot. Loading and unloading time are assumed as 20 hours each and entering and leaving port time are assumed as 2 hours each)
- The number of CO2 carriers is estimated depending on the four different size of CO2 carrier: 20K, 40K, 80K, 120K DWT.
- The CAPEX and OPEX for four different size of CO2 carrier are estimated to determine the optimal size.
After the capacity of CO2 carrier is decided, the size of barge is calculated. The CAPEX and OPEX of liquefaction system and storage tank are estimated. The availability analysis is performed and then it is converted to the unavailability cost. Finally, the LCC of ship-based CCS chain is estimated and the optimal alternatives in chain are determined.

5. Case study

The CO2 source is Hadong fossil fuel power plant and Donghae gas field is selected for the CO2 sink. The details about this are indicated below.
- Capacity of power plant (MW): 4000
- Fuel of power plant: coal
- CO2 to be treated (million-ton / year): 1
- Distance from power plant to barge (km): 2.0
- Distance from barge to storage site (km): 270

After performing the evaluation model, the two compressor type is selected and one 20,000 DWT CO2 carrier is determined. The detailed cost information is tabulated in the Table 1.

Table 1. LCC of case study

<table>
<thead>
<tr>
<th>Items</th>
<th>CAPEX (million $)</th>
<th>OPEX (million $)</th>
<th>Unavailability Cost (million $)</th>
<th>LCC (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>13.5</td>
<td>110.3</td>
<td>40.8</td>
<td>630.2</td>
</tr>
<tr>
<td>Pipeline</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrier</td>
<td>28.0</td>
<td>80.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage tank (Carrier)</td>
<td>9.7</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barge</td>
<td>29.1</td>
<td>29.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquefaction</td>
<td>32.7</td>
<td>208.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage tank (Barge)</td>
<td>18.7</td>
<td>18.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>132.2</td>
<td>457.0</td>
<td>40.8</td>
<td>630.2</td>
</tr>
</tbody>
</table>

6. Conclusion

This study developed the economic evaluation model to evaluate several design alternatives in the CCS chain. The CAPEX and OPEX were estimated for the design options with availability. The economic evaluation model was applied the case study. The LCC results showed that the governing factor was OPEX, dominantly affected by the liquefaction system. The production availability gave a significant impact on the estimated LCC so that the wrong conclusion could be drawn on the best method without considering the production availability. The results in the CO2 carrier demonstrated that the size of CO2 carrier should be defined after the economic evaluation because there was no effect of economies of scale. Even though the total cost was decreased with the size of carrier, the total cost of the ship-based CCS chain was not reduced.
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References