Techno-economical evaluation and comparison of various CO2 transportation pathways

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Abstract

Carbon Capture and Storage (CCS) is regarded as one of the most promising solutions for reducing emissions of greenhouse gases. Following capture, the CO2 must be transported to the designated storage site. This transportation process can be achieved via various means, such as trucks/trains, or ships. Considerable research has focused on optimizing CO2 transportation, particularly on converting CO2 from a gas to a liquid to reduce volume and transportation costs. After thorough evaluation, it has been determined that acquiring CO2 at 7 bar and -49 ℃, as well as at 15 bar and -28 ℃, represents the most efficient and cost-effective options for truck/train and ship transportation. To transport CO2 in liquid state, liquefaction is a critical step in the pathway. In this paper, three different liquefaction systems including internal refrigeration (open liquefaction), external refrigeration (closed liquefaction) and precooled Linde Hampson process (open liquefaction) were studied. Each process was simulated in Aspen HYSYS, and optimized with a particle swarm optimization (PSO) algorithm in MATLAB to minimize the energy consumption. Afterwards, cost analysis was conducted to compare the liquefaction processes in terms of levelized cost. This study found that precooled Linde Hampson liquefaction process is the most cost-effective for the 7 bar scenario, with a cost of 19.18 $/tCO2 liquified. On the other hand, it was found that the lowest levelized cost is given by external liquefaction with the use of ammonia as refrigerant for 15 bar case, with a levelized cost of 17.54 $/tCO2 liquified.

**Keywords**: Carbon capture and storage, Internal refrigeration, External refrigeration, Precooled Linde Hampson process, Transportation of CO2.

* 1. Introduction

Renewable energy or carbon capture and storage (CCS) technology are playing a pivotal role in reducing the carbon dioxide (CO2)emissions. CCS can be defined as a technology which aims to prevent or reduce the effects of climate change by capturing CO2 from source points or the atmosphere and then storing it at safe conditions. The main goal of CCS is to reduce carbon emissions from energy production, industrial processes and other sources. CCS comprised three critical stages: capture, transport and storage. There are different carbon capture technologies including but not limited to post-combustion, pre-combustion, and oxyfuel combustion carbon capture. Later, transportation takes place and the captured CO2 is transported to designated sites for storage or utilization. Transportation is usually provided by truck/tanker, ship or pipeline (Metz et al., 2005). However, conditioning of CO2 is very important for the transportation because CO2 is captured in the gas form, but it is usually more efficient and cost-effective to transport in the liquid form (Seo et al., 2015). Therefore, liquefaction becomes a vital procedure to facilitate the transportation. The final phase of CCS involves storage, where the transported CO2 is injected into the geological formations such as underground and ocean floor (Metz et al., 2005). While CCS is a prominent technology to reduce carbon emissions in the energy industry, its techno-economic viability and environmental impacts are still being actively researched.

There are various liquefaction methods available for CO2 liquefaction, which can be categorized into open and closed liquefaction processes. The primary difference lies in the use of a refrigerant is required in the closed system (Seo et al., 2015). In the open liquefaction, there is no need for the refrigerant as the CO2 is compressed before it is sent to a valve where Joule-Thomson effect applies and CO2 is converted from gas to liquid-gas mixture. Moreover, the liquefaction process which uses refrigerant can be named as external refrigeration whereas the process without a refrigerant is known as internal refrigeration (Øi et al., 2016). There are different studies for liquefaction of CO2 at different conditions. When the pressure varied between 7 and 70 bar, it was found that the highest cost belongs to the liquefaction at 7 bar whereas the lowest cost was obtained for 40-50 bar (Deng et al., 2019). Decarre et al. (2010) stated that when the liquefaction of CO2 was compared for 7 and 15 bar options, 15 bar was found as more economically favorable for transportation of CO2 by ship. On the other hand, Roussanaly et al. (2021) conducted a study for 7 and 15 barg shipping, and 7 barg shipping of CO2 was found as cheaper. Rather than varying pressure, studies were also conducted for different processes at chosen pressures. Since the cost of liquefaction was determined as lower at the liquefaction pressure of 15 bar when it is compared with 6 bar for ship transportation (Seo et al., 2016), four different processes were evaluated and it was determined that closed system has lowest life cycle cost compared with Linde Hampson system, Linde dual-pressure and precooled Linde Hampson system. Moreover, precooled Linde Hampson system had the lowest life cycle cost among open liquefaction systems (Seo et al., 2015). When internal and external refrigeration were compared for 7 bar option, external refrigeration with ammonia was deemed more cost effective compared to internal refrigeration (Øi et al., 2016). Furthermore, Seo et al. (2015) mentioned that among the refrigerants that can be used in the external refrigeration, ammonia has the lowest work requirement. In summary, the liquefaction pressure is mostly compared between 7 and 15 bar and there are different processes that can be used, but there is no consistent conclusion. This paper focuses on the internal refrigeration (IR), external refrigeration (ER) and precooled Linde Hampson liquefaction (PLHL) processes for 7 and 15 bar liquefaction pressure conditions.

* 1. Methodology

In this section, assumptions that are used to create the process flowsheet are presented as well as the optimization process. Moreover, methods that are used in economic analysis were also presented.

* + 1. Process simulation modelling and optimization

For performing process flow-sheeting and simulation Aspen HYSYS v9 is applied. For the simulations the Peng-Robinson equation of state was chosen as a comprise between calculation speed and accuracy for pure CO2. An automated process of running the defined process simulation flowsheet models was made by combining the process simulator with MATLAB via COM (Microsoft Component Object Model). A black-box wrapper was made in MATLAB, exposing the process simulation as a simple callable object/function taking the independent variables as input, and returning the desired output when the simulation has converged. This approach is similar to the implementation in Olsen et al. (2021). Furthermore, particle swarm optimization (PSO) is used to optimize the built flowsheets in Aspen HYSYS v9 based on the approach by Yu et al. (2019). After defining the variables, lower and upper bounds were set for each variable. Later, constraints and objective function were defined to obtain the lowest duty in each process. In the optimization spreadsheet that was used in Aspen HYSYS, duty was defined as the sum of shaft power of compressors. The inlet conditions were determined as 1.5 bar and 40 ℃. Also, 50 t/h pure CO2 was assumed at the inlet. Ammonia was chosen as a refrigerant due to its low energy requirement.

Table 1. Assumptions used in simulations.

|  |  |  |
| --- | --- | --- |
| Parameters | Value | Unit |
| Adiabatic efficiency of compressors | 80 | % |
| Maximum compression ratio | 4 | - |
| Temperature of hot streams at the outlet of air coolers | 38 | ℃ |
| Pressure drops in the coolers and heat exchangers | 0 | bar |
| Minimum approach temperature in heat exchangers | 5 | ℃ |
| Minimum approach temperature in multi-stream heat exchangers | 3 | ℃ |

Internal refrigeration, external refrigeration and precooled Linde Hampson liquefaction processes were simulated for 7 and 15 bar cases in Aspen HYSYS v9. Figure 1 illustrates the process flow diagram of internal refrigeration. As previously mentioned, compressed CO2 is liquified through valve due to the Joule-Thomson effect. The compression stages of internal refrigeration were determined as 5 and 4 for 7 bar and 15 bar cases, respectively. Moreover, compression stages of external refrigeration were determined as 5 for both 7 and 15 bar cases. While 2 stages were used to compress the CO2, 3 stages were used to compress the ammonia. Lastly, the compression stage number was determined as 5 for 7 and 15 bar cases in precooled Linde Hampson process. Whereas 3 stages were used to compress the CO2, 2 stages were used to compress the ammonia. Process flow diagram of external refrigeration and precooled Linde Hampson processes were not presented in this paper due to space limitation.

Feed

Separator

Joule-Thomson Valve

Heat Exchanger

Air Cooler

Air Cooler

Air Cooler

Figure 1. Internal refrigeration process flow diagram.

Liquified CO2

Mixer

Compressor (Multistage Compression)

Compressor (Multistage Compression)

* + 1. Techno-economic analysis

CAPEX estimation is performed by combining the elaborate equipment cost database published by Woods (2007) with the Enhanced Detailed Factor (EDF) (Aromada et al., 2021) method for total Inside Battery Limit (ISBL) plant cost estimation in a similar fashion as previously applied to CO2 liquefaction (Øi et al., 2016). The methods are programmed in an internal tool (Jensen et al., 2024) and extensive testing and benchmarking against vendor quotes as well as total plant costs have been conducted. The main equipment considered in the present study includes compressors, separators and heat exchangers. For coolers in gas service or condensing service (refrigerant), air cooled heat exchangers (ACHE) have been assumed and heat exchangers for heat recovery or CO2 condensing service have been assumed as Shell and Tube heat exchangers (SHE). As input to the EDF method the material factor is set as stainless steel for all equipment handling CO2 and as carbon steel for all equipment handling refrigerant only. Furthermore, additional construction specific factors have been adjusted to reflect cold insulation, establishment of external power supply, as compressor building.

In this study we use the following simplified definition of levelized cost in analogy with NREL’s Levelized Cost of Energy (LCOE) (Short et al., 1995) which assumes overnight capital cost and O&M costs being invariant over the years. The Levelized Cost of CO2 Liquefaction (LCOCL) is given as:

|  |  |
| --- | --- |
|  | (1) |

In Eq. (1), *CRF* is the capital recovery factor, *TPC* is the overnight capital cost as calculated via the EDF method. *O&Mfixed* is the yearly fixed Operations and Maintenance cost invariant of the plant load/capacity and *O&Mvariable* is the yearly Operations and Maintenance cost that scales with plant load. The denominator in the equation is the yearly amount of liquefied CO2, which we set as the nominal mass flow (kg/s) integrated over the year where we assume 8000 hours at the design rate. The variable O&M costs will for simplicity be set at the cost of electricity to power compressor and air cooler fans. The capital recovery factor, which can be seen in Eq. (2), is defined as:

|  |  |
| --- | --- |
|  | (2) |

where *i* is the interest rate and *n* is the number of annuities over project lifetime. In this study, *i* is set to 10 % and the project lifetime is set to 20 years (namely *n* = 20). The fixed O&M cost is set to 5 % of the CAPEX in this study.

* 1. Results and discussion

After simulating the process flowsheets and optimizing them through MATLAB, cost calculations were completed and following results are obtained.

Table 2. Operating Expenses (OPEX) of liquefaction processes.

|  |  |  |  |
| --- | --- | --- | --- |
| Liquefactions Processes | Fixed OPEX (MM $/y) | Power  (MW) | Variable OPEX (MM $/y) |
| IR, 7 bar | 1.46 | 7.20 | 4.03 |
| IR, 15 bar | 1.25 | 6.33 | 3.55 |
| ER, 7 bar | 1.29 | 6.10 | 3.42 |
| ER, 15 bar | 1.24 | 5.12 | 2.87 |
| PLHL, 7 bar | 1.39 | 5.39 | 3.02 |
| PLHL, 15 bar | 1.35 | 4.87 | 2.73 |

In Table 2, fixed operating expenses (OPEX) values are obtained by assuming maintenance cost as 5 % of capital expenses (CAPEX). They were obtained as higher for 7 bar cases in all of these liquefaction processes. Variable OPEX values are directly related to power values, so higher power and variable OPEX values were obtained for 7 bar cases. Power is the sum of electricity consumed by compressors and air coolers. For air coolers, it is assumed that 10 kW of electricity is required to cool 1 MW of hot stream. Upon comparing the results of this study with those presented by Deng et al. (2019), it was observed that the power values are higher than the ones reported in our study. Nonetheless, the consistent pattern prevails, with power values being lower for the 15 bar cases compared to the 7 bar cases, regardless of the chosen liquefaction method. Notably, the primary contributor to power consumption is the electricity utilized by compressors.

Table 3. Levelized Costs of Liquefaction Processes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Liquefactions Processes | CAPEX (MM $) | OPEX (MM $/y) | Annualized CAPEX (MM $/y) | | LCOCL  ($/tCO2 liquified) |
| IR, 7 bar | 29.15 | 5.49 | 3.42 | 22.29 | |
| IR, 15 bar | 25.00 | 4.80 | 2.94 | 19.33 | |
| ER, 7 bar | 25.75 | 4.70 | 3.02 | 19.32 | |
| ER, 15 bar | 24.79 | 4.11 | 2.91 | 17.54 | |
| PLHL, 7 bar | 27.78 | 4.41 | 3.26 | 19.18 | |
| PLHL, 15 bar | 26.97 | 4.08 | 3.17 | 18.11 | |

In Table 3, annualized CAPEX values were calculated by multiplying corresponding values with Capital Recovery Factor (CRF) which was found as 0.12 as a result of using Eq. (2). Later, they were summed up with OPEX values and divided to multiplication of operating hours and tons of CO2 treated in an hour to obtain the levelized costs. It is clear that CAPEX and OPEX values are higher for liquefaction at 7 bar option. Also, levelized cost follows the same trend as it is directly related to them. By comparing levelized costs, 15 bar case seems economically favourable compared to 7 bar. Moreover, external refrigeration with ammonia seems the cheapest liquefaction option for 15 bar case. Deng et al. (2019) presented the LCOCL values as 15.2 and 14.1 €/tCO2 liquified for 7 and 15 bar, respectively. In comparing the LCOCL values obtained in this study with those reported in Deng et al. (2019), it is evident that slight variations exist due to differing assumptions made during flowsheet completion and cost calculations. Despite these discrepancies, the overall trend remains consistent, with the cost for the 15 bar case being lower than that for the 7 bar case, irrespective of the liquefaction method employed.

* 1. Conclusion

This study investigated several liquefaction techniques to facilitate the transportation of CO2. At 7 bar, precooled Linde Hampson is the most cost-effective option in terms of the levelized cost. Although external refrigeration is an economically good option, using it to liquify the CO2 at 7 bar is technically challenging because ammonia has low vapor pressure at the target temperature (-49 ℃). At 15 bar, external refrigeration is the most cost-effective option since it has the lowest levelized cost. In both scenarios, internal refrigeration is the most expensive liquefaction option. Also, the study reveals that 15 bar is more cost-effective option than 7 bar for the liquefaction of CO2 before transportation.

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