A Multi-Criteria Based Approach for Large-Scale Deployment of CO2 Capture, Utilization and Storage

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Abstract

In this study, CCU was coupled with CCS to totally abate the target CO2 emission sources in an economically viable manner. Herein, CO2 was captured from a target source, and separated into two different streams, one of which was prepared for storage. The remaining CO2 stream, together with H2, was utilized for methane production. Rigorous process design was performed to provide necessary data for constructing a multi-criteria based evaluation model, based on which the total system is optimized for maximizing both total economic benefit and CO2 abatement. The results show that coupling CCU with CCS can help reduce the incurred cost and achieve high CO2 reduction when a low carbon tax rate (i.e., $130/ton) is applied and when a low-cost H2 source (i.e., below $1.3/kg) is available. CCU is not necessary to be coupled with CCS if a higher carbon tax rate is applied or when a large supply of low cost green H2 is available.

**Keywords:** Carbon capture and utilization/storage, rigorous process design, multi-criteria based evaluation model, economic benefit, CO2 abatement

1. Introduction

Greenhouse gases (GHG), mainly due to CO2 emissions, have become a worldwide concern. CCS and CCU are key technologies for mitigation of CO2 emissions. In Japan, utilizing CO2 for methane synthesis and storing CO2 at available injection well sites have been considered as important strategies to fulfil the domestic energy demand and to achieve the target GHG emissions reduction. Large-scale implementation of either CCS or CCU is limited due to some technical challenges (Dziejarski et al., 2023) and economic drawbacks (Chen at al., 2022). CCS incurs additional cost for CO2 capture, liquefaction, transport and injection (Storrs et al., 2023). CCU can lead to much lower CO2 emissions than CCS while creating new added value products. Thus, coupling CCU and CCS is expected to be a wise strategy for abating large-scale CO2 emissions economically. However, most of CCU processes need large supplies of heating utilities and raw materials (Hao et al., 2022). In addition, allocating suitable amounts of CO2 for storage and utilization is the key to sustaining economic and environmental viability of an integrated CCUS system. Therefore, optimizing the entire system is strongly needed.

In this study, an integrated CCUS system producing e-fuel as the main product is designed and optimized. Herein, CO2 is captured from a target source, and separated into two different streams, one of which is liquefied, transported to an injection site, and injected while the other CO2 stream, together with H2, is utilized for methane production. A multi-criteria evaluation model is built. It is used to evaluate and optimize the entire system by maximizing total economic benefit and CO2 emission reduction. The impacts of external factors such as carbon tax rate and H2 cost and sources (i.e., grey and green sources) on total process performances are also investigated.

2. Method of study

Figure 1 shows the boundary of the coupling CCUS system considered in this study. The flue gas containing CO2 is led to the capture process, in which CO2 is captured by monoethanolamine solvent and purified. A fraction amount of the CO2 product stream is led to the liquefaction process, producing liquid CO2 which is then transported to the injection site and stored underground. The rest amount of CO2 is mixed with hydrogen and it is used as input for the methane production process, in which methane is synthesized following reaction (1) and purified. The product methane can be sold and used as a replacement to the conventional natural gas fuel.

CO2 + 4 H2 ⇌ CH4 + 2 H2O ΔH298K = -165 kJ/mol (1)

In this study, the following assumptions are made for process design and optimization:

* CO2 is captured from a target emission source at a rate of 208.4 t/h
* Amine-based capture process, CO2 liquefaction and methane production processes are located nearby the CO2 emission source.
* The liquid CO2 is transported by ship for 1,000 km.
* Different sources of H2, both grey and green sources, are available and their amounts are unlimited.
* The produced methane can be used for many purposes; thus, its demand is unlimited.

The methane production and CO2 liquefaction processes are designed using process simulator Pro/II (developed by AVEVA, 2022). The structure and operating conditions (i.e., temperature and pressure) of each process are also optimized to reduce its energy consumption and material loss. However, separately optimizing each process is not necessary a guarantee of an optimal coupling CCUS system which would yield high economic benefit and low CO2 emissions. Therefore, to optimize the target of the integrated CCUS system, a multi-criteria based evaluation model is constructed. It consists of two evaluation indicators, the net present value (NPV) and the potential CO2 reduction (PCR), which are used for maximizing economic benefit and CO2 abatement amount. The model is operated using some fundamental data such as mass and energy balance data obtained from the above process design and simulations, life cycle assessment database, and market price data.

Figure 1. Boundary of process design and evaluation

Here, NPV ($) accounts for all kinds of investment and operating costs (i.e., process plant construction, injection well, CO2 transport, energy and raw material consumption costs, etc.) and benefits gained from selling the product produced by the system (Biegler et al.,1997). Basic parameters used for evaluating NPV are shown in Table 1. PCR (t CO2/year) is the sum of all direct and indirect CO2 emissions due to energy and raw material consumptions minus the amount of CO2 avoided due to substitution of conventional natural gas. The scales of CO2 utilization and storage, which depend on the fractions of CO2 utilized and stored, respectively, directly impact the amounts of salable product (i.e., methane), the size of process equipment, and the amounts of raw material and energy consumed. As a result, they directly impact the evaluation indicators NPV and PCR. Therefore, the optimization problem is defined as following:

max NPV = *f (w1, w2)* (2)

max PCR = *g (w1, w2)* (3)

subject to: *w1 + w2 = 1* (4)

Here, *w1* and *w2* are fractions of CO2 utilized for methane production and stored, respectively.

Table 1. Basic parameters used for evaluating NPV.

|  |  |
| --- | --- |
| Operating hours per year | 8400 hours |
| Useful plant life | 15 years |
| Depreciation life (straight line method) | 12 years (straight line method) |
| Contingency and fee costs | 20% bare module cost |
| Auxiliary facilities costs | 20% bare module cost |
| Working capital  | 19.4% fixed capital investment cost |
| Labor | 10% operating cost |
| Other cost (maintenance, supplies, etc.) | 11% process capital cost |
| Tax rate | 35% |
| After tax rate of return | 10% |

The optimization of each objective is performed using an optimization solver, namely What’s Best (an add-in to Excel) (Lindo Systems Inc., 2023). To support different stakeholders to make decision based on different targets of CO2 abatement, different target PCR values, calculated based on *ε* (varying in the range of 0 and 1) and optimal PCR result, are assigned as constraints (equation (5)) for optimizing the NPV.

*Target PCR = ε\*PCRmax*(5)

To illustrate evaluation results, varying in wide ranges, the following equations are used to normalize the NPV and PCR results:

$NPV\_{Norm}=exp\left(^{NPV}/\_{NPV\_{max}}\right)$ (6)

$PCR\_{Norm}=exp\left(^{PCR}/\_{PCR\_{max}}\right)$ (7)

Thus, when *NPVNorm* is higher than 1, economic benefit is gained, and vice versa. When *PCRNorm* is higher than 1, CO2 emission can be reduced, and vice versa.

3. Evaluation result

To examine the impact of the external factors on the evaluation objective NPV and PCR, different scenarios of carbon tax rates and H2 sources and prices (S1 – S6) were considered. As Table 2 clearly shows, the optimal results of NPV and PCR markedly change when these external factors change. Figure 2 shows the changing tendencies of these objectives as functions of fraction amount of CO2 utilized for methane production.

Table 2. Different scenarios considered in this study.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Scenario ID | S1 | S2 | S3 | S4 | S5 | S6 |
| Input conditions |  |  |  |  |  |  |
| H2 type | Grey | Grey | Green | Green | Green | Green |
| H2 price a) ($/kg H2) | 1.26 | 1.26 | 2.0 | 2.0 | 1.3 | 1.3 |
| H2’s CO2 factora) (kg CO2/kg H2) | 12.4 | 12.4 | 1.99 | 1.99 | 1.99 | 1.99 |
| CH4 priceb)($/kg CH4) | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| Carbon tax rate ($/ton CO2) | 0 | 130 | 0 | 130 | 0 | 130 |
| Optimization results |  |  |  |  |  |  |
| max NPV (x $100MM) | 5.90 | 4.75 | 8.59 | 1.14 | 5.11 | 14.8 |
|  max PCR (MMt CO2/year) | 0.96 | 0.96 | 1.58 | 1.58 | 1.58 | 1.58 |

a) data are obtained from Parkinson et al., (2019)

b) average value in Japan as of 2022 (New Power Net, 2022)

As the results clearly show, S1 can gain some economic benefit when CO2 in the target source is utilized for methane production. However, because grey H2 has extremely high CO2 emission factor, the total amount of CO2 emitted is much higher than the amount of CO2 utilized and avoided. As a result, *PCRNorm* result is lower than 1 when *w1* increases. Thus, with the conditions of S1, CO2 emissions cannot be reduced. S2, using the H2 source similar to S1, has much worse economic performance, as the carbon tax rate increases from 0 to $130/ton.

Scenarios S3-S6 use green H2 source, thus, their *PCRNorm* results are always higher than 1, indicating high potential of CO2 abatement. However, their economic viability heavily depends on the H2 market price and on the carbon tax rate. When the H2 price increases beyond $1.5/kg, a carbon tax rate of at least $130/ton CO2 is required to compensate for the H2­ cost expense and to make the target system economically viable (scenario 4). A H2 price below $1.3/kg (scenarios S5 and S6) will make the target system economically feasible without need of applying carbon tax.

Figure 2. Changing tendencies of *NPVNorm* and *PCRNorm* towards CO2 utilization fraction

4. Conclusion

In this study, a coupling CCUS system was designed for abating the target fixed CO2 emission source. Here, methane is considered as the main product. Based on a constructed multi-criteria evaluation model, the system was optimized, considering different scenarios of carbon tax rate and H2 sources. The optimization results show that when grey H2 is used and low carbon tax rate is applied, coupling CCU and CCS can help reduce the additional cost incurred by CCS and increase CO2 emission reduction. Nevertheless, when large supply of green H2 is available and high carbon tax rate is considered, it is more economically and environmentally beneficial for the whole amount of CO2 to be utilized for methane production.

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