Techno-Economic Study on Non-Capture CO₂ Utilization Technology

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Abstract

Techno-economic evaluation of Non-Capture CO₂ Utilization (NCCU) technology for the production of high-value-added products using greenhouse gas (CO₂) was performed. The general scheme of NCCU process is composed of CO₂ carbonation and brine electrolysis process. Through a carbonation reaction with sodium hydroxide that is generated from brine electrolysis and CO₂ of the flue gas, it is possible to get high-value-added products such as sodium bicarbonate, sodium hydroxide, hydrogen & chloride and also to reduce the CO₂ emission simultaneously. For the techno-economic study on NCCU technology, continuous operation of bench-scale facility which could treat 2 kgCO₂/day was performed. and based on the key performance data evaluated, the economic evaluation analysis targeted on the commercial chemical plant, which could treat 6 tons CO₂ per day, was performed using the net present value (NPV) metrics. The results showed that the net profit obtained during the whole plant operation was about 7,890 mKRW (million Korean Won) on NPV metrics and annual CO₂ reduction was estimated as about 2,000 tCO₂. Also it was found that the energy consumption of brine electrolysis is one of the key factors which affect the plant operation cost (ex. electricity consumption) and the net profit of the plant. Based on these results, it could be deduced that NCCU technology of this study could be one of the cost-effective CO₂ utilization technology options.

Keywords : CO₂ capture, NCCU, utilization, sodium bicarbonate

.I INTRODUCTION

CO₂ capture and sequestration technology (CCS) enables the reduction of CO₂ emission from large-scale sources such as thermal power plants and steel industries. CCS technology captures a great amount of CO₂ from a large-scale CO₂ generating source and stores it in the ocean or underground, and has a great greenhouse reduction effect. Currently, decades of pilot scale CCS tests are being conducted globally. However, there are limitations when it comes to applying it at a commercial scale power plants when there are no storage sites identified for the captured CO₂, such as in Korea.

Accordingly, the technology that converts the CO₂ generated from coal-fired power plants into high-value-added chemicals has recently been gaining attention. Among them is non-capture CO₂ utilization (NCCU) technology, which fixates the CO₂ among the flue gas by reacting with the metal ions that can form mineralization. Its strength is that it sequestrates the CO₂ of the flue gas in a more stable and permanent manner, no risk of leakage and also there is no need for the additional CO₂ capture or storage process.

NCCU technology is a kind of carbon capture & utilization (CCU) technology that produces high-value-added chemical products using the CO₂ contained in the flue gas. Also, it is a highly economical technology in the sense that it enables the creation of new profits through selling the final products. Thus, related studies are being undertaken actively across the world. Among those are Skyonic and Calera of the USA, and Twence of the Netherlands. Skyonic has been undertaking a study with the project name "SkyMine" since 2009, and is planning to operate a commercial plant that can treat approximately 75,000 tons of CO₂ for the production of sodium bicarbonate from 2015 [1]. Twence

has also embarked on a project in June 2011 with the project name "Sodium Bicarbonate Project". Through this project, Twence is in pursuit of building a chemical plant that could produces sodium bicarbonate from the waste incineration power generation plant. It is expected to be able to capture 6,000 tons of CO₂ and produce 8,000 tons of sodium bicarbonate [2].

In this study, techno-economic evaluation of NCCU process which could capture and convert CO₂ was performed. For this purpose, bench-scale NCCU process was designed which could treat 2 kgCO₂/d. And based on the key performance data, techno-economic evaluation of commercial scale NCCU process was analyzed using the internal rate of return and net present value metrics. And the sensitive analysis as a function of key parameters such as plant operation, electric power consumption of brine electrolysis and price of CO₂ credits was also evaluated.

II. NCCU PROCESS

A. Process Overview

The NCCU technology of this study is mainly composed of CO₂ carbonation and brine electrolysis process. The CO₂ carbonation reaction is as shown in Eq. (1).

$$M + CO_2 \rightarrow MCO_3 \text{ or } MHCO_3 + Heat \qquad (1)$$
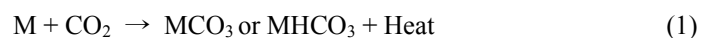
Here, M is the base for carbonation reaction and is mainly a metallic oxide or metal hydroxide such as CaO, CaSiO₃, MgSiO₃, MgO, Mg(OH)₂, Ca(OH)₂ or NaOH. The carbonates or bicarbonates generated may be stored permanently in mineral form, or may be used as raw material for cement, and is also a
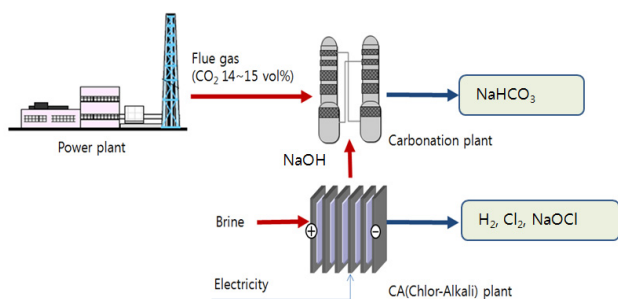
Fig. 1. Process flow of NCCU process

Fig. 2. Process details of NCCU technology

Fig. 3. Key performance data from bench scale NCCU process

high-value-added products used in foods, gas treatment, glass industry, detergent and so on. In the process, the flue gas that is produced from the combustion of fossil fuel initially undergoes pre-treatment for SOx, NOx and dust as well as a cooling process, and then is put into the CO_2 carbonation reaction process. In the carbonation reaction process, sodium hydroxide produced through the electrolysis of brine is fed to produce sodium bicarbonate via carbonation reaction. Also, the chlorine and hydrogen gas are also produced from the brine electrolysis which also could be used in various field of chemical industry. The general scheme of NCCU process is shown in the Fig. 1.

Unlike the existing CO_2 capture process, NCCU process uses CO_2 as the main raw material and additional CO_2 capture and storage processes are not needed. Also, in the case of the existing CO_2 capture process, a great deal of energy is consumed for the regeneration of chemical CO_2 solvent in the stripper which causes lowered power output from power plants. However, for the NCCU technology, since CO_2 from the flue gas could be easily mineralized into sodium bicarbonate without extra heat source, the operating costs are very low. Also, CO_2 reduction is possible simultaneously with the production of sodium bicarbonate which leads to secure carbon credits. Details of NCCU process are as follows.

B. Details of NCCU process

As mentioned above, the NCCU process is composed of the CO_2 carbonation and brine electrolysis process. In the brine electrolysis process, sodium hydroxide, hydrogen and chlorine are produced by the electrolysis of low-cost brine such as seawater. The reliability of the electrolysis process has been proven through several decades of commercial operation. Though, the foregoing processes consume a great deal of electricity for the operation of equipment, and many studies are underway to reduce the operation costs of electrolysis. In this study, considering the energy consumption and electrolysis performance, zero gap brine electrolysis process, which is recently suggested by DOE/NETL of USA, was considered [3].

The general scheme of brine electrolysis process is shown in Fig. 2. In an anode, the chlorine ion (Cl^-) oxidizes into chlorine gas (Cl_2). In a cathode, the water molecule is reduced into hydroxide ions (OH^-) and hydrogen gas (H_2), then forms a sodium hydroxide (NaOH) when it meets sodium ions (Na^+). The sodium hydroxide is then fed to the CO_2 carbonation process for the production of sodium bicarbonate and the other products such as chlorine and hydrogen are subsequently stored for the further usage in various chemical industry.

The CO_2 carbonation process proposed is composed of the three packed towers connected in series as also shown in Fig. 2.
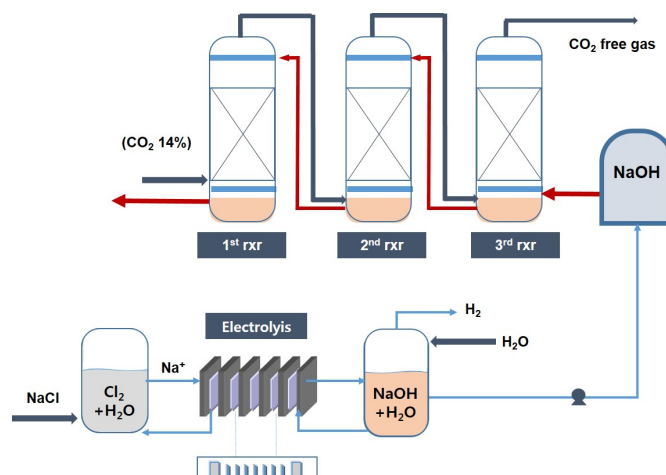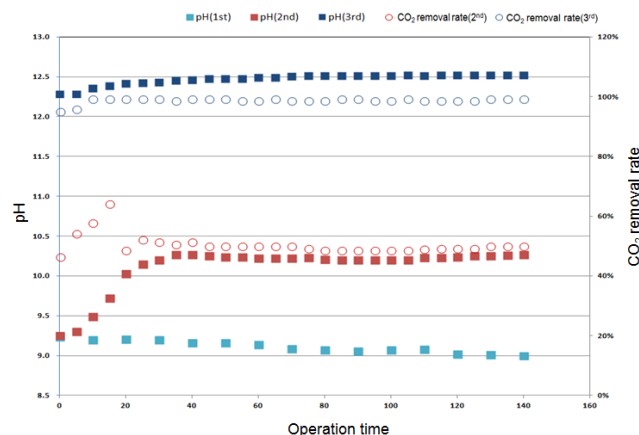
After the flue gas generated from coal-fired power plants through combustion of fossil fuels is cooled off by the gas cooling process, they are fed to the CO_2 carbonation process for the production of sodium bicarbonate. As shown in Fig. 2, The flue gas and the sodium hydroxide is fed counter-currently for the achievement of maximum CO_2 conversion (or CO_2 removal rate). The flue gas is fed to the lower part of the packing tower with the sodium hydroxide solution fed from the top part of the packing tower. The sodium carbonate slurry generated at the packing tower is then transported to the next reactor through a slurry pump. The sodium carbonate initially generated at the packing tower subsequently generates sodium bicarbonate through an additional reaction with CO_2.

Based on above mentioned process scheme, continuous operation of bench scale test which could produce 4 kg sodium bicarbonate per day utilizing 2 kg CO_2/d was performed. The sodium hydroxide for the CO_2 carbonation process is produced from zero-gap membrane type brine electrolysis. The concentration of sodium hydroxide is adjusted to 15% for the CO_2 carbonation reaction with flue gas and the CO_2 concentration in the flue gas is fed as 14%, which is in a range of general operating conditions of the flue gas from coal-fired power plant after de SOx and de-NOx procedure.

The key performance data of test results is shown in Fig. 3. The results showed that various experimental data including reactor temperature, pH & CO_2 removal rate (or CO_2 conversion rate) remained stable during the continuous operation and the

Table 1. Key assumptions for the economic evaluation

List	Figure	Reference
Year	2016	
Discount rate (%)	5.5	KDI [4]
Economic life (year)	20	
Plant operation (%)	70	
Exchange rate (KRW/USD)	1,200	
Construction period (year)	2	
Electricity cost (KRW/kWh)	100	KEPCO [5]

CO_2 conversion rate was kept almost 100%. Also, the purity of final product (sodium bicarbonate) was also checked (>98%) using an X-ray Diffraction analysis. From these results, the feasibility and the reliability of current NCCU process was confirmed.

III. TECHNO-ECONOMIC EVALUATION

A. Overall scheme

The investment cost for the economic assessment of NCCU process has been calculated by referring to various literature and actual records from similar plants. For an economic assessment of the cost of operation for plant operation, this study referred to the main guidelines proposed by the International Energy Agency [4]. After establishing cases for various contingencies along with the basic process, yield and profit were analyzed by implementing a sensitivity analysis using net present value (NPV) and internal rate of return (IRR) metrics. NPV is one of the capital budgeting methods which subtract the invested amount from the current value of the net cash flow calculated based on the investment, the net present value is simply the summation of cash flows (C) for each period (n) in the holding period (N), discounted at the investor's required rate of return (r):

$$\text{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n}$$

(1)

While IRR refers to the discount rate when the current value of the expenditure required by the initial investment equals to the current value of the cash income expected from the investment. Mathematically, the IRR can be found by setting the above NPV equation equal to zero and solving for the rate of return. (Eq. 2)

$$0 = \sum_{t=0}^{N} \frac{CF_t}{(1+\text{IRR})^t}$$

(2)

B. Basic assumptions

The major assumptions of an economic assessment for the foregoing analysis are summarized in Table 1. A discount rate for cash flow analysis is used in order to convert the benefits and costs to occur in the future into present value. Whereas the present value of the initial investment cost increases with a higher discount rate, the present value of benefit that occurs after a substantial period of time has elapsed tends to become substantially small. In this study, 5.5 % which was suggested by
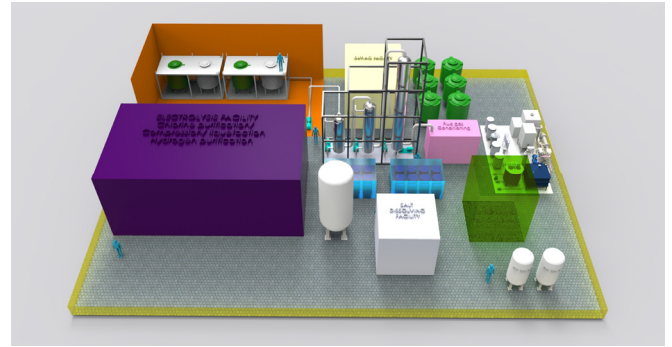

Fig. 4. Process layout NCCU project

KDI was considered as a base figure of discount rate [4]. Also, considering the deployment of First of a kind (FOAK) process, base plant operation rate was assumed as 70%.

C. Cost calculation for economic assessment

1) Overview

For the evaluation of capital expenditure (CAPEX) & operating expenditure (OPEX), the material balance was calculated based on the chemical reaction. As the amount of CO_2 treated in the carbonation process is fixed, the amounts of various feed & product material could also be calculated simultaneously. And based on this material balance data, the CAPEX & OPEX was calculated using literature values to calculate the cash flow of benefits and costs in accordance with annual plant operation. For the unit sales price of chemicals considered for the economic assessment in this study, the most recent price analysis and professional market trend materials were used.

In Fig. 4, the process layout of NCCU project which could produce 12 ton sodium bicarbonate per day was shown based on above mentioned material balance (amount of CO_2 treated : 6 ton CO_2/day). Whole area of current process is estimated about 20 m × 25 m and half of plant area is allocated to the storage for the raw material (ex: salt) and final product (ex: sodium bicarbonate, hydrogen & chlorine).

2) Calculation of capital cost and operating cost

The following are major details regarding investment and operation costs. The investment cost was calculated based on various literature sources and actual records for similar plants. The investment and operation costs used in this study will be verified and supplemented based on the detailed design data through enhanced studies in the future. For the analysis of the effects of plant scale on the net profit, total plant cost of 0.1 MW (or 2 ton CO_2/day) to 0.4 MW (or 8 ton CO_2/day) scale NCCU plant was estimated by domestic contractor.

3) Calculation of prices of raw materials and final products

The prices of raw materials and final products were shown in Table 3. The prices were based on various references sources using 2015 price trends in South Korea as a guideline.

4) Base case study

Based on the major data mentioned in the foregoing (investment cost, operating cost, etc.), the economics of current NCCU process was evaluated. First, NPV values as a function of scale of NCCU plant was considered from 0.1 to 0.4 MW scale,

Table 2. Key assumptions for the estimation of CAPEX & OPEX

List	Figure	Reference
1. TPC (Total plant cost)	- 0.1 MW scale : 3,000 mKRW - 0.2 MW scale : 4,547 mKRW - 0.3 MW scale : 5,800 mKRW - 0.4 MW scale : 6,892 mKRW	Estimated by domestic contractor
2. Capital cost		
- Owner's costs	7.0 % of TPC	
- Contingencies	5.0 % of TPC	
3. Operating cost		
- Load factor (year 2-20)	70%	
- Load factor, year 1	30%	
- Insurance and local taxes	2.0% of TPC/year	IEA [6]
- Maintenance	1.5% of TPC/year	
- Cost per operator	50,000 USD/year	
- Administrative and support labor	30% of operators cost	
- Administrative and support labor	12% of maintenance cost	

Table 3. Price of final products and inputs

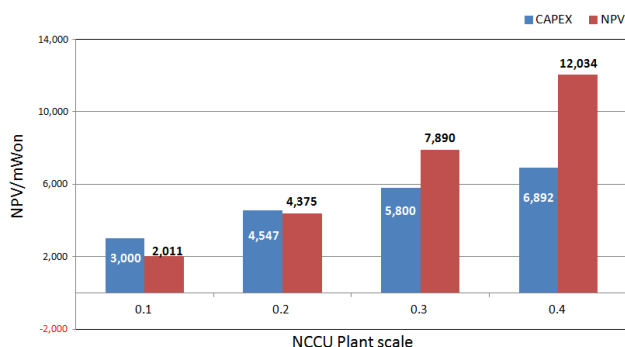| List	Price (KRW/ton)	Reference
1. Input		
- NaCl	60,000	ChemLocus, 2013 [7]
- H_2O	500	
2. Product		
- $NaHCO_3$	370,000	POSCO ICT [8]
- Cl_2	300,000	Hongin Chemical [9]
- H_2	4,430,000	The Korea Price Research Center [10]

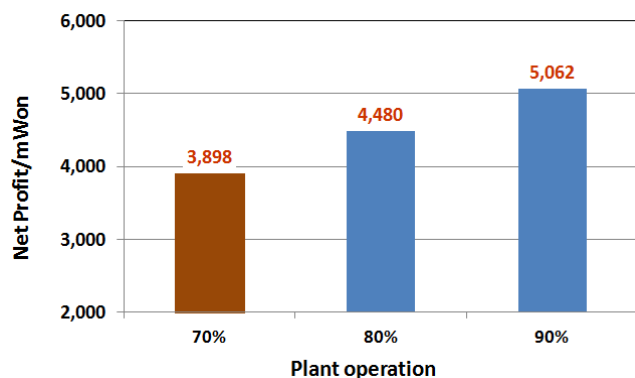Fig. 5. NPV variation as a function of plant scale

Fig. 6. Effects of plant operation on net profit

which corresponds to a 2 tons of CO_2/day (0.1 MW scale) - 8 tons of CO_2/day (0.4 MW scale). The analysis showed that if a plant is fully operated for 20 years, the NPV value would be increased from 2,011 mKRW (0.1 MW scale) to 12,034 mKRW (0.4 MW scale). And in case of plant scale below 0.2 MW, it is hard to get a net profit during the whole operation period (20 years). From

this analysis 0.3 MW scale NCCU plant is considered as a baseline case.

5) Sensitivity analysis

Based on the analysis data for the foregoing basic conditions, a sensitivity analysis was conducted under various conditions as to the major factors that have a substantial effect on plant operating costs, including plant operation, electric power consumption of brine electrolysis and price of CO_2 credits.

a) Effects of plant operation

The plant operation rate, which is an important item in cost evaluation calculation, is a factor that has a great effect on economic assessment. In relation to the basic assumption for the cost assessment in the foregoing, in order to verify the effects of plant operation rate, a sensitivity analysis was conducted. The results were as follows (Fig. 6). The analysis showed that the net profit over 20 years was increased from 3,898 mKRW (plant operation rate: 70%, baseline) to 5,062 mKRW (plant operation rate: 90%).

b) Effects of brine electrolysis electricity consumption

In the analysis of production costs under the foregoing basic conditions, the factors that had the most substantial impact on production costs are in the order of variable costs for electrolysis (cost of raw materials), electric power consumption charges and investment cost. In this connection, many research teams around the world are carrying out related studies in order to reduce the electric power consumption in the electrolysis process. Thus, this sensitivity analysis sought to analyze the NPV from a reduction of energy consumption in brine electrolysis by taking into account the technology development currently in progress. To this end, a sensitivity analysis was conducted for when the electric power consumption for unit chlorine gas production in the electrolysis process is reduced by 20% from the current 2,500 kWh/tCl₂ (2,000 kWh/tCl₂) and when it is reduced by 30% (1,750 kWh/tCl₂). The analysis showed that the total net profit over a period of 20 years increased by from 3,898 mKRW (basic condition) to 4,074 mKRW (1,750 kWh/tCl₂).

c) Effects of price of CO_2 credits

Following the electric power consumption, an analysis of changes in the price of CO_2 credit was conducted. To this end, the
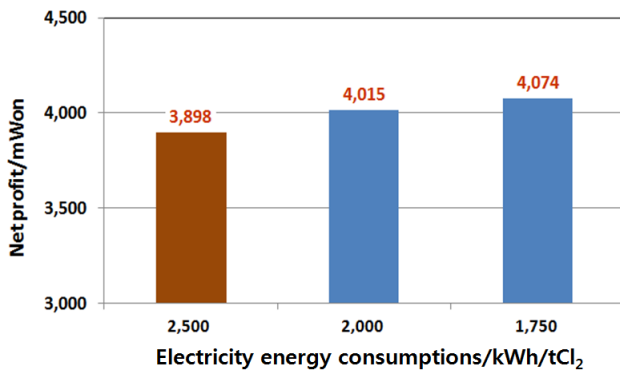
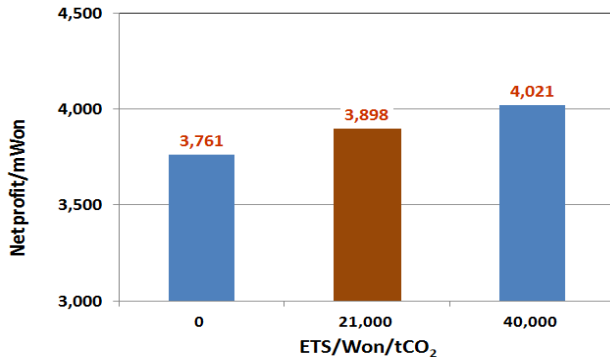Fig. 7. Effects of electrolysis energy consumption on net profit

Fig. 8. Effects of CO_2 credits on net profit

profit change was analyzed in the event when the ETS cost was considered. The analysis showed that, depending on the increase in CO_2 credit price (40,000 KRW), the total net profit over a period of 20 years was increased from 3,898 mUSD (standard conditions) to 4,021 (40,000 KRW/tCO_2)

IV. CONCLUSION

Techno-economic evaluation of NCCU technology for the production of high-value-added products using the greenhouse gas (CO_2) was performed. Through a carbonation reaction with sodium hydroxide that is generated from brine electrolysis and CO_2 of the flue gas, it is possible to get high-value-added products such as sodium bicarbonate, sodium hydroxide, hydrogen & chloride and also to reduce the CO_2 emission simultaneously. Techno-economic evaluation analysis targeted on the chemical plant which could handle 6 tons CO_2 per day was performed using the net present value metrics. The results showed that the profit obtained during the plant operation periods was about 7,890 mKRW on NPV metrics and annual CO_2 reduction was about 2,000 tCO_2. Also it was found that the energy consumption of brine electrolysis is one of the key factors which affect the plant operation cost (ex. electricity consumption) and the net profit. Based on these results, it could be deduced that NCCU technology of this study could be a cost-effective CO_2 utilization technology. And it was shown that the suggested methodolgy of this study could be effectively applied to the related fields.

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