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# Economic Evaluation of Carbon Capture and Utilization Applying the Technology of Mineral Carbonation at Coal-Fired Power Plant

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**Abstract:** Based on the operating data of a 40 $tCO_2$/day (2 megawatt (MW)) class carbon capture and utilization (CCU) pilot plant, the scaled-up 400 $tCO_2$/day (20 MW) class CCU plant at 500 MW power plant was economically analyzed by applying the levelized cost of energy analysis (LCOE) and $CO_2$ avoided cost. This study shows that the LCOE and $CO_2$ avoided cost for 400 $tCO_2$/day class CCU plant of mineral carbonation technology were 26 USD/MWh and 64 USD/$tCO_2$, representing low LCOE and $CO_2$ avoided cost, compared to other carbon capture and storage CCS and CCU plants. Based on the results of this study, the LCOE and $CO_2$ avoided cost may become lower by the economy of scale, even if the $CO_2$ treatment capacity of the CCU plant could be extended as much as for similar businesses. Therefore, the CCU technology by mineral carbonation has an economic advantage in energy penalty, power plant construction, and operating cost over other CCS and CCU with other technology.

**Keywords:** carbon capture and utilization; levelized cost of energy; mineral carbonation; economic evaluation; coal-fired power plant

## 1. Introduction

Carbon dioxide ($CO_2$) emissions in the atmosphere from anthropogenic activities continue to grow worldwide [1–3], as $CO_2$ emissions in the period 2010 to 2014 grew about 31.9 to 35.5 $GtCO_2$ per year, an average rate of 2.75% per year [4], escalating global warming. Various studies have been made to mitigate carbon emission to hold average global warming below 2 °C above pre-industrial levels [5,6]. Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are evaluated by the International Energy Agency (IEA) and U.S. Energy Information Administration (EIA) as two of the most cost-effective methods for climate change mitigation among various technologies [7]. CCS permanently captures and stores $CO_2$ to reduce greenhouse gas from coal-fired power plants or cement manufacturing facilities [8]. CCU involves chemical reaction, converting $CO_2$ into valuable chemical compounds [9].

CCU by mineral carbonation technology, also called $CO_2$ mineralization, is a less explored method of sequestering $CO_2$ compared to other CCS methods, such as geological sequestration [10–12], ocean disposal [13–15], and biological fixation [16–18]. Mineral carbonation involves the chemical conversion of $CO_2$ to solid inorganic carbonates permanently fixing carbon with a negligible risk of return to the atmosphere without having a great impact on the surrounding environment and ecosystems [19,20].

As CCS and CCU are relatively recent technologies, their effectiveness still needs to be analyzed. Large-scale CCS projects were mostly based on enhanced oil recovery, whereby $CO_2$ is used to obtain the last remains of an oil field by injection of gaseous, liquid, or supercritical $CO_2$ into subsurface reservoirs inducing the geological storage of $CO_2$ in porous rocks, which was proved to be effective for cutting the $CO_2$ emission but still remains to be studied for their cost-effectiveness compared to others technologies [21–23]. Also, IEA has published a research report, "cost and performance of carbon dioxide capture from power generation, IEA, 2011," comparing the economic feasibility of CCS-applied technologies (post-combustion, pre-combustion, oxy-combustion) between the levelized cost of energy analysis (LCOE) and $CO_2$ avoided cost [24]. The economic evaluation of CCS has been made on the assessment method of the expectation of the energy penalty for applying CCS technology [25], comparing LCOE and $CO_2$ avoided cost for applied CCS technology (supercritical, ultra-supercritical, integrated gasification combined cycle (IGCC), oxy-combustion, natural gas combined cycle (NGCC)) at power generation on economic aspects [26].

On the other hand, the economic evaluation of CCU focused on sales profit from selling $CO_2$ compounds produced from applying CCU technology or on the life cycle assessment (LCA) [27]. One analyzed a manufacturing technology of high-valued compounds, sodium bicarbonate ($NaHCO_3$), through carbon dioxide carbonization, and the result of the internal rate of return for 20 years was 67.2% [28]. Techno-economic assessment of $CO_2$ utilization was studied by applying LCA of the Canadian emerald energy from a waste facility [29]. LCA conducted for a comprehensive analysis of the climate change mitigation potential of CCU, in applying fields such as fertilizer process [30], $CO_2$-based polymers used as raw materials for plastics [31], chemical industry [32], and electrocatalytic conversion of $CO_2$ into commercially-valued products, including carbon monoxide, methane, and methanol [33–35].

Most CCS economic evaluation of power generation uses LCOE and $CO_2$ avoided cost, with the CCS technology by applying the energy penalty when constructing the power generation plant [36,37]. As mentioned previously, CCU economic evaluation focuses on the sales revenue of the resulting $CO_2$ compounds from the technology [29,38,39]. LCOE represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle, $CO_2$ captured cost is calculated by comparing a capture plant to any reference plant, and $CO_2$ avoid cost is derived from the equalization of the net present values of costs of the power plant with and without CCUS technology [40].

Based on the operating data and input cost of a 40 $tCO_2$/day (2 megawatt (MW)) class CCU pilot plant at a coal-fired power plant, the scaled-up 400 $tCO_2$/day (20 MW) class CCU plant at 500 MW coal-fired power plant was economically analyzed by applying the LCOE and $CO_2$ avoided cost, considering the energy penalty. Moreover, the CCU technology in this study, utilizing the resulting compounds as construction ingredients, has insufficient economic evaluation and comparative studies according to applied technology on the economic evaluation results [19,41]. Here, we have calculated the LCOE and $CO_2$ avoided cost for mineral carbonation, resulting in 26 USD/MWh and 64 USD/$tCO_2$ each, and conducted comparative studies with other CCS and CCU technologies, which were higher cost for each factor.

To remind, this paper is structured as follows: Section 2 introduces the methods and technology of applied examination, with the detailed explanation of the components and the process; Section 3 gives detailed information on the experiment results with the analysis of LCOE and $CO_2$ avoided cost; Section 4 shows the comparison of the economic analysis between the applied technology in this study and other CCU technologies, and also include sensitivity analysis; Section 5 addresses the conclusion on the applied CCU technology.

The following subjects were considered to increase the accuracy of this research, and a comparative analysis was conducted between the resulting economic outcomes and other CCS or CCU references.

1. Considering the energy penalties resulting from the CCU plant at a 500 MW coal-fired power plant.
2. Application of the actual operational data of a 40 $tCO_2$/day (2 MW) class pilot plant installed at a 500 MW coal-fired power plant.

3. Application of the actual operational data of the captured $CO_2$ amount collected through a 40 $tCO_2$/day (2 MW) class continuous-capture-process.
4. For the 400 $tCO_2$/day (20 MW class) CCU plant installed at a 500 MW coal-fired power plant that manages the economic evaluation, apply the estimated price of equipment based on the actual preliminary design.
5. By applying the levelized cost of energy analysis (LCOE), compare the "$CO_2$ avoided cost" and "$CO_2$ captured cost" in similar businesses.

- LCOE = Σ ((Investment cost $_t$ + Operation maintenance cost $_t$ + Fuel cost $_t$ + Power plant abolition cost $_t$)×(1 + r)$^{-t}$)/(Σt(Power generation $_t$ ×(1 + r)$^{-t}$))
- $CO_2$ capture cost [USD/$tCO_2$] = $(LCOE)_{CCS} - (LCOE)_{ref}/(tCO_2/MWh)_{captured}$
- $CO_2$ avoid cost [USD/$tCO_2$] = $(LCOE)_{CCS} - (LCOE)_{ref}/(tCO_2/MWh)_{CCS}$

## 2. Materials and Methods

### 2.1. Applied Technology

Mineral carbonation process can effectively utilize the industrial $CO_2$ emissions to form various products and carbonate precipitates, as it is a thermodynamically favorable reaction. The mineral carbonation using alkaline solid wastes has merits of low feedstock cost and availability near the source of $CO_2$ [27]. The utilization process for this study, CCU of mineral carbonation technology, produces construction ingredients from converting the $CO_2$-captured compounds to $CaCO_3$ through the direct reaction of $CO_2$ in the flue gas at the coal-fired power plant.

This technology operates a 40 $tCO_2$/day (2 MW) class CCU pilot plant at a coal-fired power plant in Korea from November 2017. Inserted partial flue gas, emitted from the power plant duct into the CCU plant, produce $CO_2$-captured compounds ($CaCO_3$), and unreacted $CO_2$ returns to the power plant duct to maintain the $CO_2$ concentration below 1% in the atmosphere. The applied technology and main equipment configuration are as follows (Figure 1, Table 1):

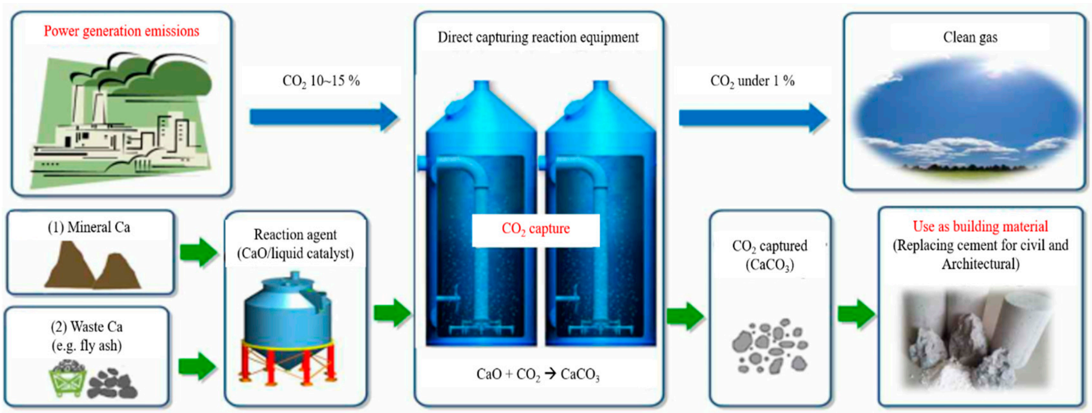


**Figure 1.** Principle of carbon capture and utilization (CCU) technology applied in this study.

**Table 1.** 40 $tCO_2$/day class CCU pilot plant components.

| Classification | Components |
|---|---|
| Facility name | Direct $CO_2$ capture-process pilot plant |
| Facility capacity | 7000 $Nm^3$/h |
| $CO_2$ removal amount | 40 ton/day |
| Monitored $CO_2$ removal amount | 25.94 ton/day |
| $CaCO_3$ production | 61.80 ton/day |

**Table 1.** *Cont.*

| Classification | | Components |
| --- | --- | --- |
| Measured $CO_2$ content in $CaCO_3$ production | | 38.29% (TGA analysis) |
| Measured electric power consumption (Real data) | | 0.8 MW |
| Main equipment | Agent supply system | After storing mineral powder and slag powder, provide a quantitative influx into the reaction agent dissolved tank, and dissolve it for (30–40) min. → Mix (30–40) min for all of the CaO to react → Transport steam and dust generated from the reaction agent reacting process to the desorption liquid storage tank (no wastewater generation). |
| | $CO_2$ removal process system | The first removal of $CO_2$ through reacting agent and gas-liquid contact in the first reaction tower. → Discharge after removing residual $CO_2$ with the reacting agent in the secondary reaction tower. → Supplement from the secondary reaction tower by the $CO_2$-captured transfer pump of the first reaction tower when the chemical agents in the first reaction tower reach below pH 8.5, while reacting with $CO_2$ in the emission gas.<br>Real-time monitoring and analysis of $CO_2$ concentration by $CO_2$ analyzer installed before and after the reaction tower duct.<br>Real-time monitoring and control from the main computer by measuring the temperature, flow rate, flux, and flow pressure. |
| | Captured $CO_2$ treatment system | Some of the generated $CO_2$-captured compounds are used as the ingredient of construction materials (bricks, cements block, and so forth) after the dehydrating process in a dehydrator. The remaining undehydrated $CO_2$-captured compounds are used as reagent, such as a desulfurization agent. → Effluent from the dehydration process is used as the full chemical reagent manufacturing water, and the deficiency is supplemented with water. → The dehydrated cake is placed in a ton bag for a certain time, and then taken out. |

### 2.2. *Applied Scale and Process*

The applicable field scale for this study, a 400 $tCO_2$/day class CCU plant, can be designed by knowing the actual amount of reduced $CO_2$ from the operating 40 $tCO_2$/day class CCU pilot plant, and modifying the operational problems from the pilot plant. Based on this scaled-up field scale plant, the economic evaluation was conducted for a 400 $tCO_2$/day class CCU plant. The scaled-up preliminary design of the 400 $tCO_2$/day class CCU plant is as follows (Table 2, Figure 2):

**Table 2.** Preliminary design outline of the 400 $tCO_2$/day class CCU plant.

| Classification | | Project Outline |
| --- | --- | --- |
| Project name | | Preliminary design of a demonstration plant of the 400 $tCO_2$/day class direct $CO_2$ capture-removal process |
| Location | | Local power plant, cement or steel manufacturing plant |
| Facility capacity | | 60,000 $Nm^3$/h |
| $CO_2$ removal amount | | 400 $tCO_2$/day |
| Task range | Mechanical field | Preliminary design of machinery, such as ingredients and chemical reagent supply facility, $CO_2$ removal reacting facility, $CO_2$-captured treatment facility, and other process facilities. |
| | Electric measurement and control field | Preliminary design of electric measurement and control field, such as motor control center (MCC) module, electric panel, and process measuring instrument. |

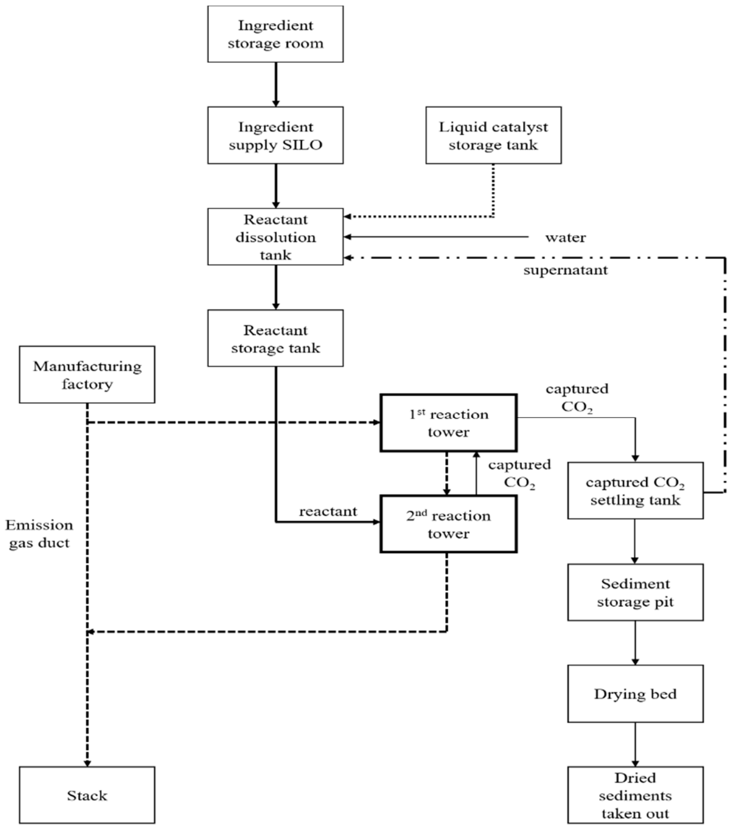


**Figure 2.** Process flow chart of the 400 $tCO_2$/day class direct $CO_2$ capture-process.

Therefore, the applied facility and process of this study are as follows (Table 3):

**Table 3.** Description of the 400 $tCO_2$/day class CCU plant.

| Classification | | Contents |
|---|---|---|
| Facility capacity | | 60,000 $Nm^3$/h (15,000 $Nm^3$/h × 4 series) |
| Operating time | | 24 h/day, 350 days |
| Construction period | | 36 months |
| Treatment process | Chemical reagent supply facility | Ingredient storage room/ingredient input hopper/ingredient transfer conveyor/ingredient supply conveyor/ingredient supply SILO/ingredient input conveyor/reactant dissolution tank/reactant transfer pump/reactant storage tank/reactant supply pump/liquid catalyst storage tank/liquid catalyst supply pump |
| | $CO_2$ removal reacting facility | Emission gas cooling tower/cooling tower circulation pump/emission gas pressurized blower/reaction tower/reaction tower circulation pump/reaction tower transfer pump of $CO_2$-captured |
| | $CO_2$-captured treatment facility | $CO_2$-captured settling tank/sediment collector/sediment outlet/sediment transfer pump/supernatant treating tank/supernatant reuse-pump/sediment storage pit/drying bed |
| | Other facility | Supernatant storage tank/water storage tank/process liquid supply pump/air compressor/pit pump/bottom drain pump |

**Table 3.** *Cont.*

| Classification | Contents |
| --- | --- |
| $CO_2$-captured compounds treatment plan | Precipitate the $CO_2$-captured in settling tank, supernatant overflows into the supernatant treating tank, and reuse it as process liquid. The residual sediment is sent to the sediment storage pit, and then stacked on the drying bed by excavator. After the sediments are dried, they are taken out to supply the required site. |
| Rain water and domestic wastewater treatment plan | Connected treatment of rain water through rain water pipeline into the manufacturing plant rainwater pipeline. Connected treatment of domestic wastewater through wastewater pipeline into the manufacturing plant wastewater pipeline. |
| Emission gas capture method | Portion of emission gas is captured from the emission gas transfer duct generated during the carbon fuel combustion process. |

## 3. Results

### 3.1. Cost Calculation of a 500 MW Coal-Fired Power Plant

To conduct the economic evaluation by demonstration plant of the 400 $tCO_2$/day class CCU plant, an economic evaluation of a 500 MW coal-fired power plant was first conducted (Table 4). The applying assumptions are based on the applied data of IEA economic evaluation, and the information provided by the actual domestic power generation companies.

**Table 4.** Estimated cost of the 500 MW coal-fired power plant.

| 500 MW Coal-Fired Thermal Power Plant | Applied Value | Unit | Note |
| --- | --- | --- | --- |
| Discount rate | 7 | % | Assumption (IEA data for reference) |
| Load factor | 85 | % | 3 year average of Domestic power plant |
| Plant lifetime | 25 | Year | Assumption (IEA data for reference) |
| Capacity | 500 | MW | Assumption |
| Annual generated electricity | 3,570,000 | MWh/year | 500 MW × 85% × 350 day × 24 h |
| Thermal efficiency | 40 | % | Assumption (IEA data for reference) |
| Equipment cost | 875 | USD/kW | Assumption (construction cost of domestic power plant) |
| Annual fixed cost | 4 | Construction cost% | Assumption (IEA data for reference) |
| Annual variable cost | 0.5 | Construction cost% | Assumption (IEA data for reference) |
| Fuel cost | 0.83 | USD/GJ | Assumption (IEA data for reference) |
| Capex | 437.5 | M USD | 500 MW × 875 USD/kW |
| Annual operating & maintain cost | 19.7 | M USD/year | 4.5% × 437.5 M USD |
| Annual fuel cost | 26.8 | M USD/year | (3,570,000 MWh/40%) × 3.6 GJ/MWh × 0.83 USD/GJ |
| Capex (present value (PV) | 395.7 | M USD | 3 year (1st year 10%, 2nd year 30%, 3rd year 60%) |
| Opex (PV) | 472.9 | M USD | Opex for 25 year |
| Generated electricity (PV) | 36,337,926 | MWh | Generated electricity for 25 year |

### *3.2. Cost Calculation for the 400 t$CO_2$/day Class CCU Plant*

The additional capex for installing the 400 t$CO_2$/day class CCU plant at the 500 MW coal-fired power plant is based on the 2018 price level, which was also applied for the preliminary design of the 400 t$CO_2$/day class CCU plant. The information on additional construction costs is as follows (Table 5):

**Table 5.** Construction cost for the demonstration plant of the 400 t$CO_2$/day class CCU plant.

| Construction Cost | Applied Value | Unit | Note |
|---|---|---|---|
| Mechanical construction | 6.0 | M USD | Preliminary design report |
| Electric construction | 1.6 | M USD | Preliminary design report |
| Civil/architectural construction | 10.2 | M USD | Preliminary design report |
| Total construction cost | 17.8 | M USD | Preliminary design report |

The additional opex for installing the 400 t$CO_2$/day class CCU plant at the 500 MW coal-fired power plant is based on the 2018 electric and water cost, which was also applied for the preliminary design of the 400 t$CO_2$/day class CCU plant. The information on additional operating costs is as follows (Table 6):

**Table 6.** Annual opex for the 400 t$CO_2$/day class CCU plant.

| Classification | Item | Price Unit | Unit | Usage | Total Amount (USD) |
|---|---|---|---|---|---|
| Labor costs | Operator | 2500 | USD/man month | 32 people, 12 months | 960,000 |
| Electric power cost | Contract power | 8.18 | USD/kw/month | 60,000 | 490,500 |
| | Electric power consumption | 0.075 | USD/kw × h | 22,400,880 | 1,689,361 |
| Sub Total | | | | | 2,179,861 |
| Reagent cost | Calcium hydroxide | 75 | USD/ton | 0 | 0 |
| | Fly ash | 4.17 | USD/ton | 363,672 | 1,515,300 |
| | Liquid catalyst | 416.7 | USD/ton | 763 | 318,000 |
| Sub Total | | | | | 1,833,300 |
| Water cost | Basic fee | 49.2 | USD/ton/month | 12 | 590 |
| | Usage fee | 0.78 | USD/$m^3$ | 385,200 | 301,740 |
| Sub Total | | | | | 302,330 |
| Total annual operating cost | | | | | 5,275,491 |

### *3.3. Economic Evaluation Method and Cost Calculation of the CCU Plant*

#### 3.3.1. Economic Evaluation Method for the 500 MW Coal-Fired Power Plant Including the 400 t$CO_2$/day Class CCU Plant

Based on Sections 3.1 and 3.2, the following considerations are needed to calculate the cost of the 500 MW coal-fired power plant including a demonstration plant with a 400 t$CO_2$/day class CCU plant.

- Energy penalty caused by the installation of a CCU facility
- Increase in the construction cost according to the increased facility capacity by the energy penalty

First, to calculate the energy penalty by the installation of a CCU plant, the actual measured electric power consumption of the 40 t$CO_2$/day class CCU pilot plant was applied. The electric power consumption per hour of the 40 t$CO_2$/day class CCU pilot plant was 0.8 MW. Accordingly, the power consumption for the 400 t$CO_2$/day class CCU plant was analyzed to consume 4 MW power by applying the "6–10 power rule." Approximate costs can be obtained if the cost of a similar item of different size or capacity is known. The "6-10 power rule," also called 0.6 rule or six tenth rule, is used for scale-up of the capacity-cost when analyzing the plant economics. This rule has its origins in the relationship between the increase in equipment cost (C) and the increase in capacity (V) given by $C_1/C_2 = (V_1/V_2)^{\alpha}$, where $\alpha$ denotes the scale coefficient. The value of $\alpha = 0.6$ refers to equipment such as tanks and pipes which give significant economies of scale [42]. The electric power consumption for the basic design of the 400 $tCO_2$/day class CCU plant was 3.1 MW. The "6–10 power rule" was applied to the relationship between the capacity and the electric power consumption at the 400 $tCO_2$/day class CCU plant and the electric power consumption for the basic design. In this regard, the cost analysis was conducted by applying 4 MW, a conservative energy penalty.

Therefore, to secure the sufficient capacity of 500 MW coal-fired power plants, it should be designed as 504 MW in consideration of the energy penalty, which is calculated to be $(504 - 500)/504 \times 100 = 0.8\%$.

Additional cost is incurred, as the installation of a 504 MW coal-fired power plant increases the power generation capacity owing to the energy penalty. The additional cost was recalculated according to the "6–10 power rule," which is used for scale-up of the capacity-cost in economic evaluation.

#### 3.3.2. Cost Calculation of the 500 MW Coal-Fired Power Plant Including 400 $tCO_2$/day Class CCU Plant

The cost of the 500 MW coal-fired power plant including 400 $tCO_2$/day class CCU plant is presented in Table 7 [43]. Further detailed data can be found in Table S1.

**Table 7.** Cost of the 500 MW coal-fired power plant with 400 $tCO_2$/day class CCU plant.

| 500 MW + CCU Coal-Fired Power Plant | Applied Value | Unit | Note |
|---|---|---|---|
| Discount rate | 7 | % | Assumption (see IEA data) |
| Load factor | 85 | % | Application of 3 year averagefor domestic power companies |
| Plant lifetime | 25 | year | Assumption (see IEA data) |
| Energy penalty | 0.8 | % | Calculation form 3.3 |
| Capacity (with CCU) | 504 | MW | Calculation form 3.3 |
| CCU additional capacity | 4 | MW | Calculation form 3.3 |
| Net capacity | 500 | MW | – |
| Annual generated electricity | 3,598,560 | MWh/year | 504 MW × 85% × 350 days × 24 h |
| Thermal efficiency | 40 | % | Assumption (see IEA data) |
| Capital expenditure (CAPEX) | 875 | USD/kw | Assumption [43] |
| Annual fixed operating expenditure (OPEX) | 4 | Construction cost% | Assumption (see IEA data) |
| Annual variable OPEX | 0.5 | Construction cost% | Assumption (see IEA data) |
| Fuel cost | 0.83 | USD/GJ | Assumption (see IEA data) |
| CAPEX | 439.95 | M USD | 437.5 M USD × ((504/500)^0.7) |
| Annual OPEX | 19.80 | M USD/year | 4.5% × 439.95 M USD |
| Annual fuel cost | 27.00 | M USD/year | 3,598,860 MWh/40% × 3.6 GJ/MWh × USD/GJ |
| Annual emitted $CO_2$ | 3,400,000 | $tCO_2$/year | Actual data of 500 MW domestic coal-fired thermal power plant |
| Levelized cost of energy analysis (LCOE) | 23.90 | USD/MWh | Calculation |
| Only CCU CAPEX | 17.75 | M USD | Amount statement of the $CO_2$ direct capture removal process (400 $tCO_2$/day) |
| Only CCU OPEX | 5.25 | M USD/year | Only cost applied among construction design report of the direct $CO_2$ capture removal process (400 $tCO_2$/day) |
| CAPEX including CCU (PV) | 413,916,667 | USD | 3 year (10% for first year, 30% for second year, 60% for third year) |
| OPEX including CCU (PV) | 537,750,000 | USD | Including 25 year of operating and disposal costs |
| Generated electricity(PV) | 36,328,630 | MWh | Generated electricity for 25 years |

## 3.4. Calculation of $CO_2$ Captured and Avoided Cost

### 3.4.1. $CO_2$ Captured Efficiency and Utilization Rate

The captured efficiency was calculated based on the actual data of a currently running 40 $tCO_2$/day class CCU pilot plant. The utilization rate was calculated through this captured efficiency. The following data is measured data at the site of the 40 $tCO_2$/day class CCU pilot plant, and the continuously measured data for more than 20 h in normal operation was applied. The measured data utilized the real-time continuously measured on-site data of flow rate, and $CO_2$ concentration in the inlet and outlet. The following is the monitoring results from the real-time measuring instrument along the time sequence for every hour from 05/29 14:00 to 05/30 12:00 (Figures 3 and 4).

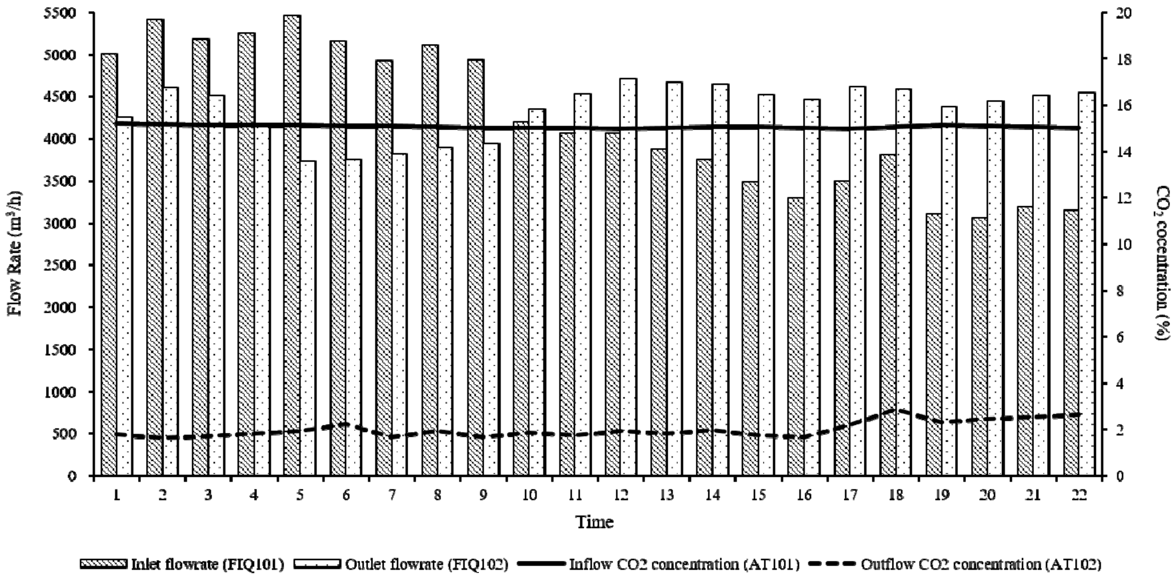


**Figure 3.** Monitoring results from the real-time measuring instrument.

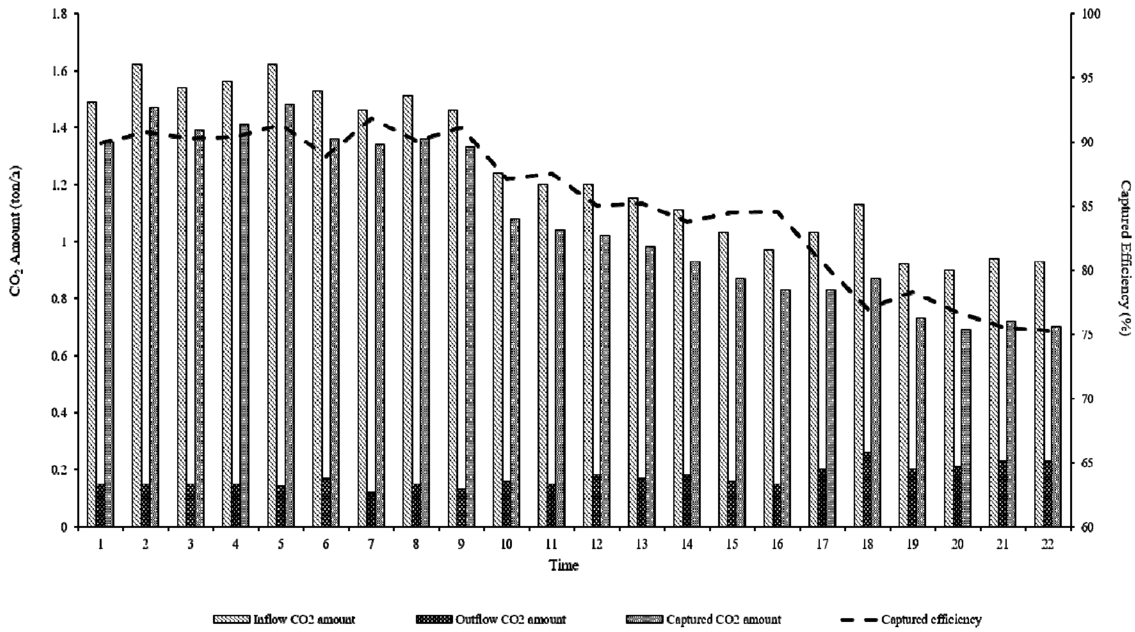


**Figure 4.** Captured $CO_2$ amount and captured efficiency through monitoring results.

To calculate the utilization rate of the CCU plant, it is necessary to convert the power generating capacity of the 400 $tCO_2$/day class CCU plant. Accordingly, by applying the actual data from a domestic coal-fired power plant, the capacity of the CCU plant was converted based on the captured $CO_2$ amount that could be treated based on the amount of greenhouse gas emissions at the 500 MW coal-fired power plant. A domestic coal-fired power plant emits 6800 $tCO_2$ per 1 MW. Moreover, a 400 $tCO_2$/day class CCU plant captures $CO_2$ of 20 MW power generation capacity. The captured efficiency was 85.71% and the utilization rate was 4% for a 400 $tCO_2$/day class CCU plant among the 500 MW coal-fired power plant emitted $CO_2$. As a result, the captured $CO_2$ utilization rate by a CCU plant was calculated to be 3.43%.

### 3.4.2. Calculation of the $CO_2$ Avoided Cost

The "$CO_2$ avoided" was calculated using the analyzed data from Section 3.4.1. The $CO_2$ avoided is the amount of avoided (reduced) $CO_2$ by operating the CCU plant. The following are the $CO_2$ avoided value (Table 8):

**Table 8.** $CO_2$ avoided of the 400 ton$CO_2$/day class CCU plant.

| Calculation of $CO_2$ Avoided | Applied Value | Unit | Note |
|---|---|---|---|
| **Coal-fired power plant without CCU** | | | |
| Capacity | 500 | MW | |
| Annual generated electricity | 3,570,000 | MWh/year | 500 MW × 85% × 350 day × 24 h |
| Annual emitted $CO_2$ | 3,400,000 | $tCO_2$/year | Actual data of 500 MW domestic coal-fired thermal power plant |
| $CO_2$ emission factor | 0.9524 | $tCO_2$/MWh | $CO_2$ emission/generated electricity |
| **Coal-fired power plant with CCU** | | | |
| Energy penalty | 0.8 | % | Calculated in Section 3.3. |
| Capacity (with CCU) | 504 | MW | |
| Annual emitted $CO_2$ | 3,598,560 | MWh/year | 500 MW × 85% × 350 day × 24 h |
| $CO_2$ emission factor | 0.9524 | $tCO_2$/MWh | |
| $CO_2$ captured and utilization rate | 3.43 | % | $CO_2$ captured efficiency (85.71%) × (20 MW/500 MW) |
| $CO_2$ emission | 3,427,200 | $tCO_2$/year | Generated electricity × $CO_2$ emission factor (Korea) |
| $CO_2$ captured and utilization amount | 117,504 | $tCO_2$/year | $CO_2$ emission × $CO_2$ captured and utilization rate |
| $CO_2$ emission without CCU | 3,400,000 | $tCO_2$/year | Actual data of 500 MW domestic coal-fired power plant |
| Net $CO_2$ emission | 3,309,696 | $tCO_2$/year | $CO_2$ emission–$CO_2$ capture and utilization amount |
| $CO_2$ avoided | 90,304 | $tCO_2$/year | $CO_2$ emission without CCU–net $CO_2$ emission |

As calculated in the above table, the $CO_2$ avoided was calculated to be 90,304 $tCO_2$/year compared to the former coal-fired power plant by the introduction of a 20 MW CCU plant, which can process 400 $tCO_2$/day (Table 9):

**Table 9.** $CO_2$ avoided cost and LCOE.

| Classification | Applied Value | Unit | Note |
|---|---|---|---|
| **Coal-fired plant without CCU** | | | |
| Current construction cost | 395.67 | M USD | |
| Current operation cost | 472.92 | M USD | On a 25 year basis |
| Current electric power generation cost | 36,337,926 | MWh | On a 25 year basis |
| LCOE | 23.90 | USD/MWh | |
| **Coal-fired plant with CCU** | | | |
| Current construction cost | 413.92 | M USD | |
| Current operation cost | 537.75 | M USD | On a 25 year basis |
| Current electric power generation cost | 36,628,630 | MWh | On a 25 year basis |
| LCOE | 25.98 | USD/MWh | |
| $CO_2$ avoided cost | 63.67 | USD/$tCO_2$ | |

## 4. Discussion

### 4.1. Comparative Analysis with Other Studies

To sum up, the economic analysis results show that when $CO_2$ content is 3.43% of captured and utilization, the captured and recovery emission is 117,504 $tCO_2$/year, LCOE as 26 USD/MWh, and $CO_2$ avoided cost as 64 USD/$tCO_2$.

Table 10 compares the economic analysis of this study and other CCS or CCU technology. Different CCS technologies at coal-fired power plants such as IGCC + CCS, NGCC + CCS, PC supercritical, etc., which can capture and utilize 90% of $CO_2$, as compared to have higher LCOE and $CO_2$ avoided cost, considering the cost for the processes like $CO_2$ compression, refinement, transport, and storage. Among CCU technologies in Table 10, the Coal-fired power plant (500 MW, 2010, recovery by dry sorbent), Coal-fired power plant (2010, US), and Aluminum production (2013, Norway) were calculated to have smaller LCOE and $CO_2$ avoided cost than the studied mineral carbonation because they only included the refinement and compression process of $CO_2$ and did not consider the $CO_2$ utilization cost. By comparing with a similar study, Coal powered (UK, 600 MW, mineral carbonation), our study resulted to be more economic.

**Table 10.** Comparison of avoidance cost of $CO_2$ and similar businesses.

| Emitting Source | | Generated Emissions [$tCO_2$/year] | $CO_2$ Captured and Utilization Rate [%] | Captured, Recovery Emissions [$tCO_2$/year] | LCOE [USD/MWh] | $CO_2$ Avoided Cost [USD/$tCO_2$] |
|---|---|---|---|---|---|---|
| Coal-fired thermal power plant, Republic of Korea (mineral carbonation of this study) | | 3,427,200 | 3.43 | 117,504 (Captured efficiency 85.71%) | 26 | 64 |
| CCS | IGCC + CCS, US, 2015, FOAK [11] | 4,245,600 | 90 | 3,819,360 | 141 | 97 |
| | NGCC + CCS, US, 2015, FOAK [11] | 1,971,000 | 90 | 1,769,520 | 78 | 89 |
| | PC supercritical. CCS, US, 2015, FOAK [11] | 4,677,840 | 90 | 4,204,800 | 124–133 | 74–83 |
| CCU | Coal-fired power plant (500 MW, 2010, recovery by dry sorbent) [20] | 4,090,625 | 80 | 3,272,500 | 32.46 | Capture cost 28.15 |
| | Coal-fired power plant (2010, US) [9] | - | 85–100 | - | Included in avoidance cost | Capture cost 43–58 |
| | Aluminum production (2013, Norway) [21] | - | - | Capture rate of 85% | - | Capture cost 80–105 |
| | Coal powered (UK, 600 MW, mineral carbonation) [22] | Approx. 4,000,000 | 85% | 3,400,000 | - | 86–140 |

Additionally, for precise comparison, they should be compared with the same capacity and $CO_2$ captured efficiency. However, this study shows the economic analysis results of a 20 MW CCU facility, handling 400 $tCO_2$/day based on the operating CCU plant. Therefore, the reliability lowering assumption, such as capacity expansion, and capture amount increase, was not included.

### 4.2. Sensitivity Analysis

The sensitivity of LCOE and $CO_2$ avoided cost, which were results from the economic analysis, was analyzed as the initial conditions changed (Figure 5). The sensitivity of LCOE was analyzed according to the alternation of capital expenditure (CAPEX) and operating expenditure (OPEX) cost and the sensitivity of $CO_2$ avoided cost was analyzed according to the change in $CO_2$ captured and utilization rate, and energy penalty (Figure 5a). Figure 5b illustrates when CAPEX was altered ±10%, LCOE was ±6.55% altered, and the ±10% OPEX alternation resulted in ± 5.65% alternation of LCOE. ±10% change of energy penalty and $CO_2$ captured and utilization rate resulted ±0.71% and −9.09~11.11% alternation of $CO_2$ avoided cost each. LCOE was most affected by the CAPEX and the OPEX also effected the LCOE as it is linked with CAPEX. $CO_2$ captured and utilization rate affected the $CO_2$ avoided cost the most, showing greater sensitivity than by the effect of energy penalty alternation.

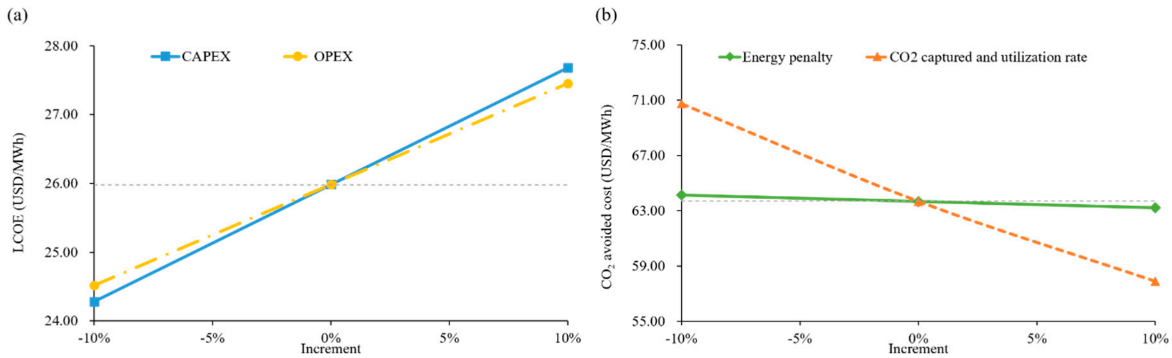


**Figure 5.** Sensitivity analysis according to the increment. (**a**) LCOE (**b**) $CO_2$ avoided cost.

The sensitivity analysis represented that the $CO_2$ avoided cost of the mineral carbonation technology in this study, was greatly affected by the $CO_2$ captured and utilization rate; however, owing to the low energy penalty of this study, the energy penalty had little impact.

## 5. Conclusions

Using LCOE and $CO_2$ avoided cost, the economic assessment was conducted for the mineral carbonation CCU technology at the coal-fired thermal power plant, which produces $CaCO_3$ through direct reaction with CaO without refinement or compression process for $CO_2$ in the flue gas. In order to increase the accuracy and reliability of this analysis, based on the actual operating data of the 40 $tCO_2$/day class CCU pilot plant, the scaled-up 400 $tCO_2$/day CCU plant factors were used. Furthermore, the additionally generated power capacity from the CCU facility energy penalty was also considered for the economic analysis including coal-fired power plant construction and operating cost. The utilization rate for the $CO_2$ capture of the CCU plant in this study is 3.43%, which represents a lower capacity of CCU compared to similar businesses and the $CO_2$ avoided cost for the 400 $tCO_2$/day class CCU plant applying mineral carbonation technology was 64 USD/$tCO_2$, representing low avoided cost, compared to similar scaled CCS and other CCU plant. However, according to the sensitivity analysis, LCOE was greatly affected by CAPEX, showing 6.55% variation, and $CO_2$ captured and utilization rate was the biggest effect to cause variation to the $CO_2$ avoided cost. Based on this study, the $CO_2$ avoided cost may become lower by the economy of scale, even if the $CO_2$ treatment capacity of the CCU plant could be extended as much as similar businesses. This suggests that CCU technology by mineral carbonation has an economic advantage in energy penalty, power plant construction, and operating cost over other CCS and CCU with other technology.

Also, this economic analysis is based on the actual operation data of CCU plant and has a relatively small CCU plant capacity compared to other studies. Therefore, there is a limitation that CO2 captured and utilization rate is low. However, with further research, we plan to conduct economic analysis on actual large scaled CCU plant and plan to contribute to commercialization of CCU technology.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2071-1050/12/15/6175/s1, Table S1: Economic evaluation of the 500 MW coal-fired power plant installed 400 $tCO_2$/day class CCU plant.

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