Performance and Cost Analysis of Natural Gas Combined Cycle Plants with Chemical Looping Combustion

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ABSTRACT: The natural gas combined cycle (NGCC) is the most popular and efficient fossil fuel power plant; however, integrating a carbon capture system reduces its performance efficiency. The demand to reduce the carbon capture cost and improve eco-friendliness drives the development of alternatives. In this study, four alternative NGCC-based process schemes were designed: NGCC with amine carbon capture as a base configuration and NGCCs with three different chemical looping combustion (CLC) configurations. Detailed heat and material balances were evaluated for all four cases using the PRO/II simulation package. A comparative analysis of the gross and net power, plant efficiency, and carbon capture efficiency, which are imperative to optimizing the process configuration, was conducted for all of the proposed cases. All NGCC-CLC processes could produce higher net power than NGCC-MEA because the amine regenerator consumes a high amount of power in its operation. In the condition using an equal amount of natural gas supply, NGCC-CLC configurations using excess air could produce a net power of 510.1 MW with a plant efficiency of 44.35%. The excess air fed in both cases enabled the turbine to generate more power. NGCC-CLC using excess air with steam turbine integration has an investment cost of 132.9 $/net MWh, an operating cost of 56.7 $/net MWh year, and a levelized cost of electricity of 90.9 $/MWh. In addition, NGCC-CLC with excess air resulted in a carbon capture efficiency of 99.93% under 59.2 $/ton of CO2, which was higher than that of NGCC-MEA with a carbon efficiency of 95.1%. NGCC-CLC using excess air with steam turbine integration is considered as the most efficient process scheme for generating power from natural gas with regard to efficiency, cost, and environmental impact.

1. INTRODUCTION

Natural gas (NG) is abundant and flexible and continues to serve as a primary source of energy for power generation worldwide. As NG utilization is currently growing at a constant rate of 2.4% annually, the International Energy Agency has predicted that its share of the global energy mix will continue to increase. The Energy Information Administration predicts that NG consumption will increase from 26.9 quadrillion Btu to 30.5 quadrillion Btu over the next 30 years. Natural gas combined cycle (NGCC) power plants are rapidly expanding worldwide to produce electricity due to various advantages compared with other types of gas power plants. The efficiency of NGCC plants ranges from 45 to 57%. Furthermore, carbon dioxide emissions from NGCC power plants are lower than those from coal-fired power plants. The construction period of NGCC plants is shorter than those of other power plants, and they entail lower capital requirements. Since carbon dioxide (CO2) emissions are a global environmental issue, the application of carbon capture technologies to NGCC power plants is essential to reduce CO2 emission. NGCC has been regarded as an efficient fossil fuel plant in recent times; however, its performance efficiency decreases when a carbon capture system is installed. The cost and efficiency penalty associated with integrating carbon capture and storage poses a major challenge.

The amine-based capture process is widely studied as a postcombustion capture process, and various process configurations are feasible to enhance the capture efficiency. The demands to reduce the capture cost and to improve eco-friendliness drive the development of alternatives. One of the strong candidates is the cyclic capture process using chemical dry sorbents. Three different Ca-based sorbents (natural CaCO3, natural dolomite, and synthetic CaO) have been evaluated for carbon capture from NGCC; since the sorbents are operated at a high CO2 recycle temperature, the capacity and stability of sorbents and heat recovery have been investigated. Chemical absorption/adsorption for postcombustion carbon capture was evaluated with respect to the techno-economic

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Figure 1. NGCC with MEA carbon capture (Base case and Case-1).

Figure 2. NGCC-CLC with an air reactor cooler (Case-2).
performance of NGCCs.\textsuperscript{13} It was concluded that the environmental performance of NGCC power plants with carbon capture could be improved.

Among carbon capture technologies, chemical looping combustion (CLC) is widely considered as a highly promising technology for carbon capture. CLC was originally proposed to improve thermal efficiency in power plants and later identified as having inherent advantages for carbon capture.\textsuperscript{14} CLC can prevent the mixing of nitrogen in the air and carbon dioxide generated by combustion and does not require a separate facility to separate oxygen. It exhibits high power generation efficiency without generating thermal NO\textsubscript{x} and captures higher-purity CO\textsubscript{2} from flue.\textsuperscript{15,16} In addition to no direct contact with air in CLC, the transport of oxygen between air and fuel creates a very high-purity CO\textsubscript{2} stream with the help of an oxygen carrier (OC) material.\textsuperscript{17} Nickel-based OCs are highly reactive and mechanically robust and perform well at high temperatures. Despite their high oxygen transport capacity, it was pointed out that Co-based OCs have to overcome their low durability and incomplete fuel conversion. Mn-based OCs have a high mechanical strength and a long service life and can completely or nearly completely burn fuels. The magnetic properties of Mn-based OCs, on the other hand, make it difficult for solids to sinter and contaminate metal parts of reactors. Iron-based OCs are both natural and cost-effective. These characteristics of CLC are vital for carbon capture because no additional energy is required to separate CO\textsubscript{2} from nitrogen (N\textsubscript{2}) as in other postcombustion carbon capture processes.\textsuperscript{20}

A detailed simulation study of the CLC process was typically performed under three conditions: NGCC with precombustion decarburization (PRE), NGCC-PRE with calcium looping, and NGCC with CLC (NGCC-CLC).\textsuperscript{2} The results showed that the highest system efficiencies and lowest exergy destruction are achieved in the NGCC-CLC. A performance model using three different OC materials (Ni-OC, Fe-OC, and Cu-OC) was developed for NGCC-CLC. It was found that the power output and efficiency of the NGCC-CLC were higher than those of conventional NGCC without carbon capture and storage. Among the three OC materials, Ni-OC systems gave the best performance. A new inverse synthesis approach was also developed to evaluate the technology and design of a system based on the system’s requirements.

All three processes utilizing CLC (NGCC-CLC, IGCC-CLC, and in situ gasification-CLC) could provide enormous value by reducing the necessary investment and operating costs of future power systems.\textsuperscript{21} Minimization of capital costs over other factors, such as high efficiency or low OC cost, is a crucial point in favor of the CLC process. A strategy for controlling the temperature in the Ni-based (CLC) process using methane was proposed with the aim of exploiting the inherent advantages of the Ni/NiO redox system.\textsuperscript{22} Technoeconomic analysis is useful to investigate the possibility of deploying present technologies to new markets. Technoeconomic analysis requires investigation of various closely intertwined elements, including technology, project design, project capital costs, operational and maintenance expenses, and operational cash flows.\textsuperscript{23} Different skill sets and tools are required for each stage of the analysis.\textsuperscript{24} Therefore, a simulation study should be executed to examine the energy efficiency and economic effects on carbon capture based on CLC technology. From the analysis of the pressure response and turbine inlet temperature, a high plant efficiency of 54% can
be achieved at a competitive cost through a CLC.\textsuperscript{25} The simulation study was conducted for the heat recovery efficiency, performance factor of the absorption cooling system, and plant efficiency of a solar-assisted NG-fired CLC power plant that utilizes waste heat for absorption cooling purposes.\textsuperscript{26} According to the analysis, the multigeneration solar-assisted CLC system exhibited a plant efficiency of 63.4\%, a waste heat utilization of 49\%, an electricity cost of 4.9 cents/kWh, and a return on investment of 3.98 years.

NGCC with the carbon capture function becomes even more important. To evaluate the feasibility of NGCC with CLC practically, the analysis of performance efficiency, carbon capture capability, and investment cost at the same time is required for various NGCC-CLC configurations. This study assessed the performance, economics, and environmental impact of three NGCC-CLC process schemes (Case-2: NGCC-CLC with an air reactor cooler, Case-3: NGCC-CLC with an excess air inlet, and Case-4: NGCC-CLC with excess air inlet and steam turbine integration). The NGCC-MEA scheme (Case-1) was selected as a comparative reference scheme. NG as a feed was supplied in equal amounts in all four cases, and a comparison was conducted in terms of the net power produced and plant efficiency. The investment cost, operating cost, and levelized cost of electricity (LCOE), which are considered as the key indices for economic analysis of power plants, were also evaluated. In addition, the environmental impact of each proposed case was assessed using the carbon capture efficiency and cost per ton of carbon capture.

2. PROBLEM FORMULATION

2.1. Process Configurations. The high-temperature and high-pressure gas obtained from the combustion of NG and air is used in an NGCC to generate electricity, and the pressure of the gas is decreased in the turbine. A heat recovery steam generator (HRSG) recovers heat and converts boiler feed water (BFW) into steam, and the steam turbine can generate power.\textsuperscript{4} Since flue gas from HRSG contains a large amount of CO\textsubscript{2}, it should be captured in a carbon capture facility (MEA process). The other way to prevent carbon emission is to reduce the carbon before discharging it to the atmosphere.\textsuperscript{27} This can be done with different process configurations, such as CLC, depending on...
strategies were studied: di ffe rent operating and design conditions

| Case | NGCC-MEA | NGCC-CLC | Case-3 | Case-4 |
|------|----------|----------|--------|--------|
| NGCC without carbon capture. | NGCC with MEA system | NGCC with CLC including an excess air inlet | NGCC with CLC including excess air inlet and ST integration. |

2.1. NGCC without and with an MEA System. The conventional NGCC process without carbon capture (Base case) consists of a gas turbine, an air compressor, an HRSG, and a steam turbine. MEA carbon capture technology and a CO2 compressor are added to the NGCC with the MEA system (Case-1), as shown in Figure 1. The pressurized NG generates a combustion reaction with compressed air in the gas turbine combustor, where CO2 and N2 discharge the main high-pressure and high-temperature flue gas and then generate electricity through a pressure drop in the gas turbine. The high-temperature and low-pressure flue gas is sent to the HRSG to transfer heat to the supplied BFW to produce steam, which is then sent to the steam turbine to generate electricity. The flue gas from the HRSG contains a significant quantity of CO2 and is processed in the carbon capture facility. The treated flue gas is consequently discharged into the atmosphere.

2.1.2. NGCC-CLC with an Air Reactor Cooler. When CLC is installed with NGCC technology, a gas turbine combustor and a separate CO2 capture system (MEA or cryogenic unit) are not required; instead, a chemical looping combustor unit is added. In this study, two expanders were installed instead of one gas turbine because, in CLC, flue gas is emitted from the fuel reactor and O2 and N2 are emitted from the air reactor. Since high-temperature and high-pressure gases of different compositions are emitted by these reactors, two expanders and two HRSGs were installed to utilize these gases. The steam turbine and HRSG system were operated separately.

NGCC-CLC (Case-2) was studied at the same plant capacity at the NGCC and NGCC-MEA. In addition, the same air compressor capacity was applied to the systems. However, the capacities of the expander, steam turbine, and HRSG were different between NGCC-MEA and NGCC-CLC. Chemical looping combustion has the advantage of being able to capture CO2 or other pollutants before they are emitted into the atmosphere.
CO₂ with high purity (99.9%) through oxidation and reduction reactions using metal oxides such as nickel oxide, copper oxide, and cadmium oxide as OCs, at temperatures below 1200 °C. Since the reaction proceeds at 1371 °C, there is an advantage of suppressing the generation of NOₓ. The configurations of the various NGCC-CLC processes are illustrated in Figures 2–5.

Case-2 is based on NGCC-CLC with an air reactor cooler, as depicted in Figure 2. The temperature of the CLC reactor should be below 1200 °C, which is the maximum stable temperature of the CLC carrier. Therefore, a CLC reactor cooler was installed to control the temperature. The advantages of using CLC for carbon capture in NGCC are the small amount of NOₓ and the emission of CO₂ and H₂O from the reactants. Therefore, it is highly beneficial to capture high-purity CO₂ by removing H₂O through dehydration. On the other hand, when MEA carbon capture technology using MEA or solvents is used in the NGCC process, an air separation unit (ASU) is occasionally used to deliver pure oxygen to remove the quantity of NOₓ in the gas turbine. Due to intensifying regulations on fine dust generation, NOₓ control in power plants is more concerning. In addition, many previous studies demonstrated that the amine-based CO₂ capture systems showed the optimum efficiency at the 90–95% capture rate from power plant emission gases.

### Table 5. Basis for the Economic Analysis

| economic analysis basis | 8766 | 30.0 | 0.85 | 0.1 | 0.1 | 6.3 |
|-------------------------|------|------|------|------|------|------|
| plant operating hour (h/year) | 8766 |      |      |      |      |      |
| plant operating year (year) |      | 30.0 |      |      |      |      |
| plant capacity factor |      |      | 0.85 |      |      |      |
| capital cost factor (without CCS) |      |      |      | 0.1  |      |      |
| capital cost factor (with CCS) |      |      |      |      | 0.1  |      |
| fuel cost ($/MMBtu) |      |      |      |      |      | 6.3  |

2.1.3. NGCC-CLC with excess air to the air compressor. In Case-3, excess air was supplied to control the reactor temperature, eliminating the need to install a reactor cooler as shown in Case-2. The process scheme in Figure 3 was set when the reactor temperature was controlled by excess air flow to the air compressor. Because the amount of excess air is greater, the capacity of the air compressor also increases, and the capacity of the steam turbine and HRSG changes. Because the temperature of the CLC reactor is controlled by the amount of excess air, a larger amount of air is supplied than the amount of air required by the conventional NGCC gas turbine in Case-1, as air acts as a coolant and an oxidant. Since a huge capacity of the air compressor is required, a high cost of machine investment is expected. In Case-2, when BFW is fed into the system through the internal cooler, generated steam can be used in a steam turbine. However, in Case-3, no steam is generated from CLC because no internal cooler is equipped. The steam turbine’s capacity is reduced, and the amount of electricity generated by the steam turbine is also reduced.

2.1.4. NGCC-CLC with an Air Inlet to a Gas Turbine (GT) and Steam Turbine (ST) Integration. The motivation for Case-4 is to increase the economic efficiency of Case-3 by integrating two single STs and an HRSG. Stream-205 fed to the first HRSG.
Table 6. Summary of the Performance and Cost Analysis of Five Cases and Comparison with Other Works

| contents                        | USDOE 2011 | case-1 | case-2 | case-3 | case-4 |
|---------------------------------|------------|--------|--------|--------|--------|
| plant description               |            |        |        |        |        |
| CCS technology                  | econamine FG+ | MEA | CLC | CLC | CLC |
| net power without CCS (MW)      | 512         | 580.4  | N/A   | N/A   | N/A   |
| net power with CCS (MW)         | 435         | 484.2  | 459.4 | 510.1 | 510.1 |
| annual operating hours (h)      | 8766        | 8766   | 8766  | 8766  | 8766  |
| plant capacity factor           | 0.85        | 0.85   | 0.85  | 0.85  | 0.85  |
| fuel                            | natural gas | natural gas | natural gas | natural gas | natural gas |
| power plant efficiency          |            |        |        |        |        |
| without capture (%)             | 50.5        | 52.6   | N/A   | N/A   | N/A   |
| with capture (%)                | 42.9        | 43.8   | 39.9  | 44.3  | 44.3  |
| cost of electricity             |            |        |        |        |        |
| without capture (LCOE) ($/MWh)  | 65          | 67.5   | N/A   | N/A   | N/A   |
| with capture (LCOE) ($/MWh)     | N/A         | 82     | 84.8  | 76.3  | 75.8  |
| with capture (LCOE) ($/MWh)     | 95.9        | 98.4   | 101.7 | 91.5  | 90.9  |
| CO2 capture                     |            |        |        |        |        |
| CO2 generation (ton/h)           | N/A         | 210.5  | 205.6 | 205.6 | 205.6 |
| CO2 capture (ton/h)              | N/A         | 200.2  | 205.5 | 205.5 | 205.5 |
| cost of CO2 capture ($/CO2 ton)  | 80          | 76.2   | 77.9  | 60.7  | 59.2  |

contains primarily nitrogen and is discharged to the atmosphere. Stream-104, on the other hand, is fed to the second HRSG and contains CO2. Therefore, it is sent to the CO2 capture unit. Combined feeding of two streams into one HRSG is not vital because the device load of the CO2 capture unit increases. Since a method for independently placing two flue gas streams into a single HRSG is not typical in the common HRSG, it is excluded in the study. When CLC is applied to NGCC, effluents of different compositions are produced in the air reactor and fuel reactor; these products are used to produce electricity in Case-2 and Case-3 using two gas turbines, two HRSGs, and two steam turbine sets. In Case-4, a system that generates electricity by integrating two steam turbine sets into a single steam turbine set was studied. While exhibiting the same performance as Case-3, Case-4 has the advantage of reduced investment cost because of the reduction in the number of steam turbine sets as shown in Figure 4. The main design difference between Case-3 and Case-4 results from an economic aspect. However, it is expected that the operation of Case-4 may be relatively difficult because it must be operated by connecting one steam turbine set with two HRSGs.

2.2. Combustion Reactions and Thermodynamics. In this study, NiO as an OG is selected because of its outstanding physical property and reactivity at high temperatures. NG is supplied to the fuel reactor, and NiO at high temperature in the reactor generates H2O and CO2. Furthermore, Ni is transferred to the air reactor. The generated H2O and CO2 are transferred to the gas turbine. Electricity is generated through a pressure drop of 31 bar/1.2 bar, and a gas at 650 °C or higher is generated by supplying heat from the HRSG to the BFW to generate steam. When H2O is removed from the dehydrator, the remaining CO2 is compressed and transported.32,54

In the fuel reactor,

\[
2\text{Ni} + \text{O}_2 \rightarrow 2\text{NiO}
\]

\[
\text{CH}_4 + 4\text{NiO} \rightarrow \text{CO}_2 + \text{2H}_2\text{O} + 4\text{Ni}
\]

\[
\text{C}_2\text{H}_6 + 7\text{NiO} \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} + 7\text{Ni}
\]

\[
\text{C}_2\text{H}_8 + 10\text{NiO} \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + 10\text{Ni}
\]

\[
\text{C}_4\text{H}_{10}(i - \text{C}_4) + 13\text{NiO} \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O} + 13\text{Ni}
\]

\[
\text{C}_4\text{H}_{10}(n - \text{C}_4) + 13\text{NiO} \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O} + 13\text{Ni}
\]

\[
\text{C}_4\text{H}_{12} + 16\text{NiO} \rightarrow 5\text{CO}_2 + 6\text{H}_2\text{O} + 16\text{Ni}
\]

In the air reactor,

\[
2\text{Ni} + \text{O}_2 \rightarrow 2\text{NiO}
\]

In the air reactor, an exothermic reaction, converting Ni to NiO, occurs by combining Ni with oxygen in the supplied air. Unreacted oxygen and nitrogen at high temperature and high pressure from the air reactor generate electricity in the expander. This supplies heat to the HRSG to generate steam from the BFW, which is discharged to the atmosphere. Ni and NiO are contained with 60 wt % Al2O3 support to circulate through the fuel and air reactors.35 To obtain Ni in the above equation, NiO is injected back into the fuel reactor through a cyclone.

In this study, the yield of reaction/reduction was predicted by modeling using a Gibbs reactor since the reactions take place at high temperatures in the gas phase, which guaranteed an equilibrium reaction. The Gibbs reactor tries to find the reaction path to minimize Gibbs free energy, which corresponds to equilibrium conditions. As a matter of fact, a similar method using the Gibbs reactor was reported from other studies.2,36

The Soave—Redlich—Kwong modified (SRKM) equation is one of the most widely used model equations to examine the behavior of hydrocarbons and gases. A modified Panagiotopoulos mixing rule is introduced to the SRK equation.37 The SRKM equation, used in this study, is known to simulate the behavior of a gas accurately. In addition, since the binary parameters of the feed stream in the SRKM are embedded to the simulator in this study, the calculation accuracy can be guaranteed.
Table A1. Heat and Material Balance for Case-1

| stream name | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 201 | 202 | 203 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| stream description | NF feed | air feed | HRSG feed | FG to CC treated GAS | captured CO₂ | compressed CO₂ | HP ST inlet | IP ST inlet | LP ST inlet |
| phase | vapor | vapor | vapor | vapor | vapor | vapor | vapor | vapor | vapor |
| temperature (°C) | 38.0 | 15.0 | 689.4 | 45.0 | 50.4 | 21.0 | 115.0 | 565.6 | 561.3 | 335.3 |
| pressure (bar) | 31.0 | 1.0 | 1.2 | 1.1 | 1.1 | 1.1 | 1.6 | 75.0 | 166.5 | 24.8 | 5.2 |
| mass rate (kg/h) | 3,154,732 | 113,867 | 115,940 | 111,520 | 5258 | 4628 | 21,475 | 24,8 |
| molar rate (kg mol/h) | 3,015,043 | 201,722 | 386,876 | 463,184 | 234,088 |

Molar component percentage

| CH₄ | 91.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C₂H₆ | 5.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C₃H₈ | 2.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IC₄ | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| N₂ | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CO₂ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CO | 0 | 0 | 0 | 4.2 | 4.6 | 0 | 98.3 | 98.3 | 0 | 0 |
| H₂O | 0.2 | 0 | 0 | 0 | 0 | 0 | 1.5 | 1.5 | 100.0 | 100.0 | 100.0 |
| O₂ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MEA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

3. RESULTS AND DISCUSSION

3.1. Simulation Basis. The PRO/II simulation package was used for the process modeling and simulation of Base and the four cases discussed in the previous chapter. The feed conditions are summarized in Table 1. Methane, ethane, and propane are the main components of NG. The simulation basis for GT and ST is also shown in Table 2. Table 3 summarizes the major equipment used in this study.

3.2. Simulation Results. The same quantities of NG and feed conditions were applied for all five cases: NGCC without carbon capture (Base case), NGCC with an MEA system (Case-1), NGCC with CLC including an air reactor cooler (Case-2), NGCC with CLC including an excess air inlet (Case-3), and NGCC with CLC including excess air inlet and ST integration (Case-4). The amounts of produced power and steam were calculated and recorded using a simulation based on the process scheme. The detailed heat and material balance are given in Appendix.

The process conditions and simulation results of the Base and four cases are summarized in Table 4. The NG feed had the same pressure, temperature, and flow rate in all cases. Since Base, Case-1, and Case-2 were supplied with an equal amount of air (109,348 kg mol/h), the capacity of the installed air compressor is the same for these three cases. On the other hand, in Case-3 and Case-4, a large amount of air (158,229 kg mol/h) was supplied as excess air to control the temperature of the CLC reactor.

One advantage of NGCC-CLC schemes is that they allow for utilization of heat obtained from the CLC reactor, which can be used to produce steam from BFW and for the ST. In Case-2, an air reactor cooler is installed to supply BFW to produce steam, the total amount of which (788.8 ton/h) is 54.9% greater than those (509 ton/h) in Base and Case-1. In Case-3 and Case-4, excess air is used to control the reactor temperature, and the amount of air supplied is 44% greater than that in Case-1. The amount of CO₂ emission from NGCC-CLC is 140 kg/h, which is smaller than that of NGCC with MEA (10,279 kg/h).

Due to the interaction force between CO₂ and other components of the flue gas, it is thermodynamically impossible to capture 100% CO₂ using an amine. As shown in Table 4, the MEA process could capture 95.1% CO₂ from flue gas. When CLC is used, CO₂ and H₂O are produced by the reaction in the fuel reactor. Since only H₂O is required to be separated from CO₂, the CLC process was able to capture about 99.93% of generated CO₂. In this study, about 5 wt % total generated CO₂ from the MEA process is emitted into the atmosphere, whereas in the case of CLC, about 0.07% is discharged into the atmosphere. Since CLC can contribute to reducing CO₂ generation and enhancing CO₂ capture efficiency, it can be described as environmentally friendly.

3.3. Power Generation and Plant Efficiency. Figure 5 shows the gross and net power produced in each case. The Base case produced a net power of 580.4 MW, whereas the amount of power generated in Case-1 was 484.2 MW, which was a 16.6% reduction. This was because the steam consumption by the regenerator of the MEA process in Case-2 reduced the amount of power produced from the steam turbine, and the power consumption of the CO₂ compressor decreased the net power. Case-2 produced 3.5% less power than Case-1, when an equal amount of air was supplied. In addition, since installing internal coils or wall piping in a FBR can change the flow patterns of the particles and fluid, the reactor efficiency should be carefully evaluated. In Case-3 and Case-4, where the temperature of the CLC reactor was adjusted with excess air, the GT produced an additional electricity of 6.4%. The net power produced was 510.1 MW, which was a 12.1% reduction from the Base case. However, with respect to carbon capture requirement, NGCC with CLC (Case-3 and Case-4) could produce an additional 5.4% of net powder compared with Case-2. In the NGCC-CLC, the GT produced more power, resulting from the greater amount of air supplied to the air compressor. In addition, a regeneration energy for carbon capture was not necessary.

The net plant efficiency is defined as the ratio of the electrical power sent out of the power station to the rate at which heat is supplied to the reactor. The plant efficiency of the Base case was 52.6% and that of Case-1 was 43.8%. The energy consumption in the amine regenerator (Case-1) naturally led to a lower plant efficiency and net power produced when...
compared with the Base case. Case-2 and Case-3 showed plant efficiencies of 39.9% and 44.3%, respectively, since the net power generation of Case-2 (459.4 MWh) was lower than that of Case-3. Since both Case-3 and Case-4 were designed to have the same net power, they had the same plant efficiency of 44.3%.

As shown in Figure 5, NGCC-CLC with excess air demonstrated the highest performance with 510.1 MWh net power and 44.3% plant efficiency. The economic analysis will outline the reason that Case-4, which incorporated an integrated steam turbine, is economically superior to Case-3 in terms of CO₂, COE, LCOE, and CO₂ capture cost per ton.

4. ECONOMIC ANALYSIS

4.1. Basis for the Economic Analysis. An economic analysis was carried out to measure the costs of investment and operation. Whereas the investment cost includes total capital cost and owner’s cost, the operating cost consists of the fixed operating cost, variable operating cost, and fuel cost. In addition,
this study also discussed the COE, LCOE, and carbon capture cost to evaluate the economic advantages of each case.

COE is the net income per net MWh received during the plant’s first year of operation under the assumption of its increase at the same nominal annual inflation rate. LCOE refers to the revenue received per net MWh during the plant’s first year of operation, assuming that the COE remains constant in nominal terms over the operational period of the plant. It was calculated as the product of COE and levelized factor. The CO2 capture cost was the revenue to capture per ton of CO2. The formulas for COE, LCOE, and CO2 capture cost are shown below:

$$\text{COE} = \frac{(\text{CCF})^*(\text{TOC}) + \text{OC}_{\text{FIX}} + (\text{CF})(\text{OC}_{\text{VAR}})}{(\text{CF})(\text{MWH})}$$

$$\text{LCOE} = \text{LF} \times \text{COE}$$

$$\text{CO}_2 \text{ capture cost} = \frac{\$}{\text{tCO}_2} = \frac{\left(\text{LCOE}\right)_{\text{cc}} - \left(\text{LCOE}\right)_{\text{ref}}}{(\text{tCO}_2/\text{MWH})_{\text{cc}}}$$
Table 5 shows the basis for the economic analysis. AACE Class 4 for cost estimation was employed with the expected range. The accuracy range was 30−50% for the lower range and 30−100% for the upper range.42

4.2. Investment and Operating Cost. The detailed breakdown of the investment and operating cost is given in Table A5. The investment cost is the ratio of the total capital cost to the new power in each case, i.e., the nominator is the total capital cost with net power being the denominator. The investment cost per net MWh of each unit was calculated by referring to the NETL report;4 the results are shown in Figure 6. The investment cost for CLC was calculated based on ref36 and the amount of feed gas and operating pressure from heat and material balance. The investment cost of the Base case was 88.2 $/net MWh, while that of Case-1 was the highest (191.3 $/net MWh) due to the use of MEA-based carbon capture and CO₂ compression. On the other hand, the NGCC-CLC-based schemes showed a reduction in investment costs of 8.9−13.9% compared to Case-1.

The total capital costs of Case-1, Case-2, Case-3, and Case-4 were $698,937,189, $544,824,279, $540,684,744, and $526,305,068, respectively (discussed more later in Figure 8). The net power of Case-1 was 484.2 MW, while those of Case-2, Case-3, and Case-4 were 459.4, 510.1, and 510.1 MW, respectively, in Figure 5. The investment cost per net MWh for Case-4 was the lowest, making it economically superior to the others.

Figure 7 shows the resulting operating cost, and the details are shown in Tables A5 and A6 in the Appendix. The fuel for plant operation accounts for about 90% of the total operating cost.

| stream name | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 201 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| stream description | NG feed circulation NIO CO₂ capture CO₂ from second GT CO₂ from HRSG captured CO₂ compressed CO₂ air supply |
| temperature (°C) | 38.0 | 1047 | 1047 | 500.2 | 110.0 | 101.2 | 120.0 | 25.0 |
| pressure (bar) | 31.0 | 31.0 | 31.0 | 1.0 | 1.0 | 1.0 | 75.0 | 1.0 |
| mass rate (kg/h) | 75,901 | 5,757,096 | 365,127 | 365,127 | 365,127 | 206,223 | 206,223 | 4,564,959 |
| molar rate (kg mol/h) | 4246 | 74,473 | 13,703 | 13,703 | 13,703 | 4887 | 4887 | 158,229 |
| molar component percentage | | | | | | | | |
| CH₄ | 91.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| O₂ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.0 |
| N₂ | 0.2 | 0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 79.0 |
| CO₂ | 0 | 0 | 34.1 | 34.1 | 34.1 | 95.6 | 95.6 | 0 |
| H₂O | 0 | 0 | 64.3 | 64.3 | 64.3 | 0 | 0 | 0 |
| C₂ | 5.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C₃ | 2.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NC₄ | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IC₅ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ni | 0 | 24.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| NIO | 0 | 51.7 | 4.7 × 10⁻¹⁴ | 4.7 × 10⁻¹⁴ | 4.7 × 10⁻¹⁴ | 0 | 0 | 0 |
| Al₂O₃ | 0 | 23.9 | 0 | 0 | 0 | 0 | 0 | 0 |
| H₂ | 0 | 0 | 1.5 | 1.5 | 1.5 | 4.2 | 4.2 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| stream name | 202 | 203 | 204 | 205 | 206 | 301 | 302 | 303 | 304 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| stream description | compressed air AR effluent FG FG to HRSG FG to stack BFW HP steam to HP ST IP steam to IP ST LP steam to LPST |
| temperature (°C) | 545.4 | 1200 | 1200 | 442.5 | 110.0 | 148.0 | 400.0 | 403.5 | 223.4 |
| pressure (bar) | 31.0 | 31.0 | 31.0 | 1.0 | 1.0 | 5.1 | 166.5 | 24.8 | 5.2 |
| mass rate (kg/h) | 4,564,959 | 10,322,054 | 4,274,411 | 4,274,411 | 4,274,411 | 627,263 | 5.6 | 501,816 | 627,263 |
| molar rate (kg mol/h) | 158,229 | 223,622 | 149,149 | 149,149 | 149,149 | 34,818 | 0.3 | 27,855 | 34,818 |
| molar component percentage | | | | | | | | | |
| CH₄ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| O₂ | 21.0 | 10.8 | 16.2 | 16.2 | 16.2 | 0 | 0 | 0 |
| N₂ | 79.0 | 55.9 | 83.8 | 83.8 | 83.8 | 0 | 0 | 0 |
| CO₂ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| H₂O | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C₂ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C₃ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IC₄ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NC₅ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IC₆ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ni | 0 | 24.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| NIO | 0 | 51.7 | 4.7 × 10⁻¹⁴ | 4.7 × 10⁻¹⁴ | 4.7 × 10⁻¹⁴ | 0 | 0 | 0 |
| Al₂O₃ | 0 | 23.9 | 0 | 0 | 0 | 0 | 0 | 0 |
| H₂ | 0 | 0 | 1.5 | 1.5 | 1.5 | 4.2 | 4.2 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
Table A5. Investment Cost and Operating Cost per Net MWh of Base and Each Case

| contents                        | base  | case-1 | case-2 | case-3 | case-4 |
|---------------------------------|-------|--------|--------|--------|--------|
| TCC ($/MWh-net)                 | 9.72  | 13.08  | 13.53  | 12.18  | 12.19  |
| feed water and MISC.            | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| BOP systems                     | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| gasifier and accessories        | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| gas cleanup and piping          | 0.00  | 67.87  | 4.03   | 3.63   | 3.63   |
| CO2 removal and compression     | 0.00  | 0.00   | 19.22  | 17.31  | 17.31  |
| chemical looping system         | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| combustion turbine/ accessories | 22.54 | 26.75  | 27.46  | 26.43  | 25.94  |
| HRSG, ducting, and stack        | 11.02 | 11.66  | 13.12  | 10.45  | 10.45  |
| steam turbine generator         | 11.55 | 11.80  | 13.31  | 10.56  | 7.27   |
| cooling water system            | 3.91  | 7.17   | 7.42   | 6.68   | 6.68   |
| ash/spent sorbent handling SYS  | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| accessory electric plant        | 8.03  | 12.96  | 13.41  | 12.07  | 12.07  |
| instrumentation and control     | 3.12  | 4.33   | 4.48   | 4.03   | 4.03   |
| improvements to site            | 2.19  | 2.67   | 2.77   | 2.49   | 2.49   |
| buildings and structures        | 2.46  | 2.84   | 2.94   | 2.65   | 2.65   |
| TCC                             | 74.55 | 161.13 | 121.68 | 108.49 | 104.71 |
| owner’s cost ($/MWh-net)        | 3.33  | 5.98   | 6.18   | 5.57   | 5.57   |
| preproduction costs             | 0.42  | 0.92   | 0.95   | 0.86   | 0.86   |
| inventory capital               | 0.00  | 0.23   | 0.24   | 0.22   | 0.22   |
| initial cost for catalyst and chemicals | 0.07 | 0.08   | 0.09   | 0.08   | 0.08   |
| initial cost for land           | 11.25 | 24.60  | 25.45  | 22.92  | 22.92  |
| other owner’s costs             | 2.03  | 4.43   | 4.58   | 4.13   | 4.13   |
| financing cost                  | 13.76 | 30.26  | 31.31  | 28.20  | 28.20  |
| fixed operating cost ($/MWh-net-year) | 0.46 | 0.71   | 0.73   | 0.66   | 0.66   |
| annual operating labor cost     | 0.61  | 1.18   | 1.22   | 1.10   | 1.10   |
| maintenance labor cost          | 0.27  | 0.47   | 0.49   | 0.44   | 0.44   |
| administrative and support labor cost | 1.50 | 3.28   | 3.39   | 3.06   | 3.06   |
| properties taxes and insurance  | 2.83  | 5.63   | 5.83   | 5.25   | 5.25   |
| fixed operating cost            | 0.91  | 1.76   | 1.82   | 1.64   | 1.64   |
| variable operating cost ($/MWh-net-year) | 0.34 | 0.79   | 0.81   | 0.73   | 0.73   |
| annual maintenance material cost | 0.00 | 0.00   | 0.00   | 0.00   | 0.00   |
| catalysts                       | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| chemicals and others            | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| waste disposal                  | 0.00  | 0.00   | 0.00   | 0.00   | 0.00   |
| byproducts and emissions        | 1.26  | 2.55   | 3.37   | 3.11   | 3.11   |
| variable operating cost         | 42.54 | 51.95  | 53.75  | 48.40  | 48.40  |
| fuel cost ($/MWh-net-year)       | 42.54 | 51.95  | 53.75  | 48.40  | 48.40  |
| economic analysis               | 56.3  | 82.0   | 84.8   | 76.3   | 75.8   |
| (COE) capture + compression     | 67.5  | 98.4   | 101.7  | 91.5   | 90.9   |
| (LCOE) capture + compression    | N/A   | 0.4    | 0.4    | 0.4    | 0.4    |
| (tCO2/MWh) capture + compression| N/A   | 76.2   | 77.9   | 60.7   | 59.2   |
| cost of CO2 capture and compression ($/tCO2) | N/A | N/A   | N/A   | N/A   | N/A    |
The fuel cost of 6.55 $/MMBtu was obtained from ref 4. The total operating costs were similar (~21 million dollars) for all cases because of the fuel cost as shown in Table A6. However, the difference in operating costs ($/net MWhh year) resulted from the net power produced in each case. Case-3 and Case-4 showed a similar operating cost of $6.7 $/net MWhh year, which was lower than those of Case-1 and Case-2.

The total investment cost and the operation cost were compared among all cases in Figure 8, and a detailed summary is given in Table A6. Total costs were calculated based on the investment cost per net MWh (Figure 6 and Table A5), the operating cost per net MWh-year (Figure 7 and Table A5), and the material balances (Tables A1–A4). The investment cost of Case-1 was 22.426% more expensive than NGCC with CLC schemes due to the higher cost of the MEA process. The investment cost of Case-4 was 2.6% lower than that of Case-3 due to the integration of STs, thereby making it economically efficient.

### 4.3. COE, LCOE, and Carbon Capture Cost

COE is the actual cost to buy electricity, while LCOE is the break-even cost to generate the electricity. The LCOE is the widely accepted calculation of the total life cycle cost per unit of electricity produced in the lifetime of a project. Figure 9 shows the economic analysis on the COE, LCOE, and CO₂ capture cost per ton. The Base case had the lowest LCOE of 67.5 $/MWh, whereas Case-2 showed the highest LCOE of 101.7 $/MWh, which was 34.2% higher than the Base case. Case-4 was economically efficient since its LCOE was 2% lower than that of Case-3 and 3.8% lower than that of Case-2.

The carbon capture potential of a power plant serves as an important basis for economic analysis. Conventional NGCC (Base) is unable to capture CO₂ because any capture process was not equipped. In this study, Case-1 was used to capture about 95.1% of CO₂ and 4.9% was released into the atmosphere, while NGCC-CLC schemes captured about 99.93% of CO₂ and a small amount (about 0.07%) was discharged into the atmosphere. The CLC schemes have a higher rate of carbon capture than the MEA because the CLC fuel reactor emits only CO₂ and H₂O. In conclusion, the CO₂ capture cost of Case-4 was 13.9% lower than that of NGCC-MEA.

Table 6 summarizes the findings of the study and compares them with the relation. The reference NGCC process employs Econamine for carbon capture. NGCC-Econamine has a net capacity of 435 MW, which is less than the results of the analysis. Although Case-1 and Case-2 have LCOEs of 98.4 and 101.7 $/MWh, respectively, NGCC-Econamine has an LCOE of 95.9 $/MWh, which is more efficient than the other two scenarios. Case-3 and Case-4 have LCOEs of 91.5 and 90.9 $/MWh, respectively. This means that when the NGCC-CLC configuration is correctly built, it produces better economic performance. As previously said, since the investment cost for a CO₂ absorber and regenerator in an amine-based carbon capture operation is typically very high, the LCOEs increase. In addition, NGCC-Econamine has a carbon capture cost of 80 $/ton, while
NGCC/CLC Case-4 has a CO₂ capture cost of 59.2 $/ton, which is 25.5% cheaper.

5. CONCLUSIONS

With NGCC being a major player in the generation of electricity, this study evaluated four cases of NGCC-based process schemes: NGCC with an MEA system (Case-1), NGCC-CLC with an air reactor cooler (Case-2), NGCC-CLC with an excess air inlet (Case-3), and NGCC-CLC with excess air inlet and ST integration (Case-4). A comparative analysis of the performance, cost, and carbon capture capability was performed on all four cases in view of the feasibility study. Performance and environmental analyses included net power, plant efficiency, and carbon capture capability. Economic assessment was also performed on the investment cost, operating cost, carbon capture cost, and LCOE. The results of this study are summarized as follows:

- Simulation: Detailed heat and material balance results for the studied processes were obtained under the condition of an equal amount of NG feed (4264 kg mol/h). An internal cooler was installed in Case-2 to produce steam when BFW was fed through it. The BFW flow rate in Case-2 was higher than that in the other cases. One the other hand, air was fed at a flow rate of 158,229 kg mol/h in Case-3 and Case-4, which was greater than the other cases. The excess air was used to control the temperature of the CLC reactor in these cases.

- Performance: The performance of a power plant was described by its net power and efficiency. Case-1 produced a net power of 484.2, which represented a 16.6% reduction when compared to 580.4 MW in the Base Case. The net power of Case-3 was low because the steam consumed by the operation of the regenerator in the MEA process resulted in a reduction in the amount of power produced by the steam turbine. Both Case-3 and Case-4 produced a net power of 510.1 MW, which was 5.4% more than that produced in Case-2. A plant efficiency of 44.3% made them more efficient than the other cases proposed. The excess air fed in both cases helped the turbine to generate more power.

- Economics: The economic analysis was conducted using the investment cost, operating cost, and LCOE as the basis. Case-1 had the highest investment cost (191.3 $/net MWh) due to the use of MEA-based carbon capture and CO₂ compression. The investment and operating costs of Case-4 were 132.9 and 56.7 $/net MWh year, respectively. Case-4 had a lower investment cost than Case-3 because of the ST integration. Although both Case-3 and Case-4 produced the same amount of net power, Case-4 had a lower LCOE.

- Carbon capture capability: The carbon capture ratio was used as the basis for the environmental impact analysis. NGCC-CLC-based schemes had a better carbon capture ratio of about 99.93%. The CLC carbon capture rate was higher than that of MEA because the fuel reactor in the CLC emitted only CO₂ and H₂O. Additionally, the carbon capture cost per ton in Case-4 (59.2 $/CO₂-ton) was the lowest among all four cases.

With regard to the results and discussion from our study, Case-4 (NGCC-CLC with the ST integration) was considered the most efficient process scheme for generating power from NG with regard to performance, economics, and the environment impact. The detailed results of this study were subject to change due to several factors such as investment cost, levelized factor, and operating condition. This study demonstrated that combining CLC with NGCC is a promising technology for mitigating the amount of CO₂ emitted by power plants. If commercially reliable advanced OCs can be applied, further enhancement can be achieved. In addition, it can be developed with further modification for full-scale operation. In the scaled FBR, more detailed design and operation difficulties are expected because it is operated at high pressures.

APPENDIX

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Notes
The authors declare no competing financial interest.

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NOMENCLATURE

ASU air separation unit
BFW boiler feed water
CC carbon capture
CF plant capacity factor
CCF capital charge factor
CCS carbon capture and sequestration
CCU carbon capture and utilization
CHP combined heat and power
CLC chemical looping combustion
COE cost of electricity ($/MWh)
GT gas turbine
HP high pressure (kPa)
HRSG heat recovery steam generator
IGCC integrated gasification combined cycle
IOU investor owned utility
IP intermediate pressure (kPa)
LCOE levelized COE ($/MWh)
LP low pressure (kPa)
MEA monoethanolamine
MW net plant capacity (MW)
NG natural gas
NGCC natural gas combined cycle
OC oxygen carrier

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21056
OC\textsubscript{fix} the sum of all fixed annual operating costs

\( P \) pressure (kPa)

\( P_c \) critical pressure (kPa)

\( R \) gas constant (J/kmol)

SRK Soave–Redlich–Kwong

SRKM Soave–Redlich–Kwong modified

ST steam turbine

\( T \) temperature (K)

\( T_c \) critical temperature (K)

TCC total capital cost ($)

TOC total ownership cost ($)

TS&M transporting, storing, and monitoring

\( V \) molar volume (m\(^3\)/mol)

\( W \) acentric factor

LF levelization factor

\[ \text{REFERENCES} \]

(1) France—Countries & Regions, IEA. https://www.iea.org/countries/france (accessed 2021-04-22).

(2) Zhu, L.; Chen, H.; Fan, J.; Jiang, P. Thermo-Economic Investigation: An Insight Tool to Analyze NGCC with Calcium-Looping Process and with Chemical-Looping Combustion for CO\textsubscript{2} Capture. Int. J. Energy Res. 2016, 40, 1908–1924.

(3) Lee, W. S.; Kang, J. H.; Lee, J. C.; Lee, C. H. Enhancement of Energy Efficiency by Exhaust Gas Recirculation with Oxygen-Rich Combustion in a Natural Gas Combined Cycle with a Carbon Capture Process. Energy 2020, 200, No. 117586.

(4) James, R. E., III PhD; Kearins, D.; Turner, M.; Woods, M.; Kuehn, N.; Zoelle, A. Cost and Performance Baseline for Fossil Energy Plants Volume I: Bituminous Coal and Natural Gas to Electricity; NETL-PUB-22638, 2019. DOI: 10.2172/1569246

(5) Industrial Construction Estimating Manual—1st ed. https://www.elsevier.com/books/industrial-construction-estimating-manual/storm/978-0-12-83362-7 (accessed 2021-04-22).

(6) Hu, Y.; Xu, G.; Xu, C.; Yang, Y. Thermodynamic Analysis and Techno-Economic Evaluation of an Integrated Natural Gas Combined Cycle (NGCC) Power Plant with Post-Combustion CO\textsubscript{2} Capture. Appl. Therm. Eng. 2017, 111, 308–316.

(7) Farooqui, A.; Bose, A.; Ferrero, D.; Llorca, J.; Santarelli, M. Techno-Economic and Exergetic Assessment of an Oxygen-Fuel Power Plant Fueled by Syngas Produced by Chemical Looping CO\textsubscript{2} and H\textsubscript{2}O Dissociation. J. CO\textsubscript{2} Util. 2018, 27, 500–517.

(8) Peeters, A. N. M.; Faaij, A. P. C.; Turkenburg, W. C. Techno-Economic Analysis of Natural Gas Combined Cycles with Post-Combustion CO\textsubscript{2} Absorption, Including a Detailed Evaluation of the Development Potential. Int. J. Greenhouse Gas Control 2007, 1, 396–417.

(9) Oh, H. T.; Ju, Y.; Chung, K.; Lee, C. H. Techno-Economic Analysis of Advanced Stripped Configurations for Post-Combustion CO\textsubscript{2} Capture Amine Processes. Energy 2020, 206, No. 118164.

(10) Ju, Y.; Oh, H. T.; Lee, C. H. Sensitivity Analysis of CO\textsubscript{2} Capture Process in Cyclic Fluidized-Bed with Regeneration of Solid Sorbent. Chem. Eng. J. 2020, 379, No. 122291.

(11) Ju, Y.; Lee, C. H. Dynamic Modeling of a Dual Fluidized-Bed System with the Circulation of Dry Sorbent for CO\textsubscript{2} Capture. Appl. Energy 2019, 241, 640–651.

(12) Berstad, D.; Anantharaman, R.; Blom, R.; Jordal, K.; Arstad, B. NGCC Post-Combustion CO\textsubscript{2} Capture with Ca/Carbonate Looping: Efficiency Dependency on Sorbent Properties, Capture Unit Performance and Process Configuration. Int. J. Greenhouse Gas Control 2014, 24, 43–53.

(13) Cormos, C. C. Assessment of Chemical Absorption/Adsorption for Post-Combustion CO\textsubscript{2} Capture from Natural Gas Combined Cycle (NGCC) Power Plants. Appl. Therm. Eng. 2015, 82, 120–128.

(14) Liu, Y.; Guo, Q.; Cheng, Y.; Ryu, H. J. Reaction Mechanism of Coal Chemical Looping Process for Syngas Production with CaSO\textsubscript{4} Oxygen Carrier in the CO\textsubscript{2} Atmosphere. Ind. Eng. Chem. Res. 2012, 51, 10364–10373.

(15) Liu, Y.; Jia, W.; Guo, Q.; Ryu, H. J. Effect of Gasifying Medium on the Coal Chemical Looping Gasification with CaSO\textsubscript{4} as Oxygen Carrier. Chin. J. Chem. Eng. 2014, 22, 1208–1214.

(16) Guo, Q.; Hu, X.; Liu, Y.; Jia, W.; Yang, M.; Wu, M.; Tian, H.; Ryu, H. J. Coal Chemical-Looping Gasification of Ca-Based Oxygen Carriers Decorated by CaO. Powder Technol. 2015, 275, 60–68.

(17) Ryu, H. J.; Lee, D.; Nam, H.; Jo, S.-H.; Baek, J.-I. Solid Circulation Characteristics of Two Oxygen Carriers for Chemical Looping Combustion System. Trans. Korean Hydrogen New Energy Soc. 2018, 29, 393–400.

(18) Idziak, K.; Czakiert, T.; Krzywanski, J.; Zyłka, A.; Kozłowska, M.; Nowak, W. Safety and Environmental Reasons for the Use of Ni-, Co-, Cu-, Mn- and Fe-Based Oxygen Carriers in CLC/CLOU Applications: An Overview. Fuel 2020, 268, No. 117245.

(19) Cho, P.; Mattisson, T.; Lyngfelt, A. Comparison of Iron-, Nickel-, Copper- and Manganese-Based Oxygen Carriers for Chemical-Looping Combustion. Fuel 2004, 83, 1215–1225.

(20) Mantiripragada, H. C.; Rubin, E. S. Performance Model for Evaluating Chemical Looping Combustion (CLC) Processes for CO\textsubscript{2} Capture in Gas-Fired Power Plants. Energy Fuels 2016, 30, 2257–2267.

(21) Schnellmann, M. A.; Heuberger, C. F.; Scott, S. A.; Dennis, J. S.; Mac Dowell, N. Quantifying the Role and Value of Chemical Looping Combustion in Future Electricity Systems via a Retrosynthetic Approach. Int. J. Greenhouse Gas Control 2018, 73, 1–15.

(22) Fernández, J. R.; Abanades, J. C. Conceptual Design of a Ni-Based Chemical Looping Combustion Process Using Fixed-Beds. Appl. Energy 2014, 135, 309–319.

(23) Lee, W. S.; Lee, J. C.; Oh, H. T.; Baek, S. W.; Oh, M.; Lee, C. H. Performance, Economic and Exergy Analyses of Carbon Capture Processes for a 300 MW Class Integrated Gasification Combined Cycle Power Plant. Energy 2017, 134, 731–742.

(24) Scott, M. Technical Economic Analysis Guide—DRAFT; U.S. Department of Energy, 2015.

(25) Petriz-Prieto, M. A.; Rico-Ramirez, V.; Gonzalez-Alatorre, G.; Gómez-Castro, F. I.; Diwekar, U. M. A Comparative Simulation Study of Power Generation Plants Involving Chemical Looping Combustion Systems. Comput. Chem. Eng. 2016, 84, 434–445.

(26) Ogidiama, O. V.; Abu-Zahra, M. R. M.; Shamim, T. Techno-Economic Analysis of a Poly-Generation Solar-Assisted Chemical Looping Combustion Power Plant. Appl. Energy 2018, 228, 724–735.

(27) Rubín, E. S.; Davison, J. E.; Herzog, H. J. The Cost of CO\textsubscript{2} Capture and Storage. Int. J. Greenhouse Gas Control 2015, 40, 378–400.

(28) Mathieu, P.; Bolland, O. Comparison of Costs for Natural Gas Power Generation with CO\textsubscript{2} Capture. Energy Procedia 2013, 37, 2406–2419.

(29) Porrazzo, R.; White, G.; Ocone, R. Techno-Economic Investigation of a Chemical Looping Combustion Based Power Plant. Faraday Discuss. 2016, 192, 437–457.

(30) Sit, S. P.; Reed, A.; Hohenwarter, U.; Horn, V.; Marx, K.; Proell, T. Cenovus 10 MW CLC Field Pilot. Energy Procedia 2013, 37, 671–676.

(31) Naqvi, R. Analysis of Natural Gas-Fired Power Cycles with Chemical Looping Combustion for CO\textsubscript{2} Capture. Doctoral Thesis, Norwegian University of Science and Technology, 2006.

(32) Petarakopoulou, F.; Tsatsaronis, G.; Morosuk, T. Conventional Exergetic and Exergoeconomic Analyses of a Power Plant with Chemical Looping Combustion for CO\textsubscript{2} Capture. Int. J. Thermodynamics 2010, 13, 77–86.

(33) He, Z.; Ricardez-Sandoval, L. A. Dynamic Modelling of a Commercial-Scale CO\textsubscript{2} Capture Plant Integrated with a Natural Gas Combined Cycle (NGCC) Power Plant. Int. J. Greenhouse Gas Control 2016, 55, 23–35.

(34) Marx, K.; Bertsch, O.; Pröll, T.; Hofbauer, H. Next Scale Chemical Looping Combustion: Process Integration and Part Load Investigations for a 10 MW Demonstration Unit. Energy Procedia 2013, 37, 635–644.
(35) Mantripragada, H. C.; Rubin, E. S. Chemical Looping for Pre-Combustion and Post-Combustion CO₂ Capture. *Energy Procedia* 2017, 114, 6403–6410.

(36) IECM Technical Documentation: Chemical Looping Combustion for Pre-Combustion CO₂ Capture; 2012.

(37) Valderrama, J. O.; Silva, A. Modified Soave-Redlich-Kwong Equations of State Applied to Mixtures Containing Supercritical Carbon Dioxide. *Korean J. Chem. Eng.* 2003, 20, 709–715.

(38) de Beer, J.; Depew, C. The Role of Process Engineering in the Digital Transformation. *Comput. Chem. Eng.* 2021, 107423.

(39) http://mafra-win.korcham.net/Service/appl/index.asp (accessed 2021-04-27).

(40) Lee, J. C.; Lee, H. H.; Joo, Y. J.; Lee, C. H.; Oh, M. Process Simulation and Thermodynamic Analysis of an IGCC (Integrated Gasification Combined Cycle) Plant with an Entrained Coal Gasifier. *Energy* 2014, 64, 58–68.

(41) Winterton, R. H. S. Steam Cycles. In *Thermal Design of Nuclear Reactors*; Elsevier, 1981, pp 146–162. DOI: 10.1016/b978-0-08-024215-6.50013-9

(42) Cost Estimating & Project Controls, *Cost Engineering*. https://www.costengineering.eu/ (accessed 2021-04-27).

(43) Bruck, M.; Sandborn, P.; Goudarzi, N. A Levelized Cost of Energy (LCOE) Model for Wind Farms That Include Power Purchase Agreements (PPAs). *Renewable Energy* 2018, 122, 131–139.

(44) DOE NETL Cost and Performance Baseline for Fossil Energy Plants; Volume 3c: Natural Gas Combined Cycle at Elevation; 2011.

(45) Copeland, R. J.; Alptekin, G.; Cesario, M.; Gebhard, S.; Gershonovich, Y. A Novel CO₂ Separation System; Federal Energy Technology Center: Pittsburgh, PA, and Morgantown, WV, 1999. DOI: 10.2172/766698