Coal accounted for 59% of the total energy consumption in industry because of its stable supply and low price. In China, past decades, coal played a critical role in the energy utilization process and needs immediate attention. Over the past decades, coal played a critical role in the energy utilization industry because of its stable supply and low price. In China, coal accounted for 59% of the total energy consumption in 2018, while the share of renewable energy was 22.1%, even though the renewable energy, including nuclear power and biomass, are developing rapidly and becoming increasingly important. Coal will continue to play an important role in the future. The reduction of CO2 emission in the coal utilization process is an urgent issue and needs immediate attention. There are mainly three types of CO2 capture technologies widely employed and researched and include precombustion, postcombustion, and oxy-fuel combustion. In oxy-fuel combustion, fuel is combusted in a mixture of O2 and flue gas instead of air. After oxy-fuel combustion, the flue gas is mainly composed of CO2 and H2O, so that CO2 separation is much more easily realized just after purification and compression.

In recent years, many studies have been carried out on oxy-fuel combustion technology. A pressurized circulating fluidized-bed (CFB) oxy-fuel combustion power plant is proposed to increase the system efficiency and carbon capture rate. Techno-economic analysis for the oxy-fuel combustion power plant was presented by Cormos and Hanak et al. The oxy-fuel combustion technology is not only applied in the coal-fired power plant but also in the coal gasification industry. The energy and exergy efficiencies of biomass/coal co-gasification system were determined by Yan et al. The integrated gasification combined cycle (IGCC) combined with oxy-fuel combustion was proposed by Kunze et al., which catches our attention. In the referenced system, coal is completely converted into syngas at high temperatures and pressures, and the system efficiency is approximately 45%. However, the single conversion of coal results in waste of energy, and according to previous results, cascading utilization of coal has higher efficiency than single conversion. To improve the efficiency of coal utilization, a novel partial gasification combined cycle (PGCC) system based on cascading utilization of coal is proposed. The coal partial gasification technology aims not to overpursue high carbon conversion (60–85%) in the gasification process. The high-activity part of coal is gasified and converted into syngas, while the low-activity part of coal is combusted for power generation. According to our
previous results, the thermal efficiency of the PGCC system is higher than that of the IGCC and shows good feasibility.\textsuperscript{21,22} Inspired by the IGCC-Oxy system above, it is worth studying the PGCC-Oxy system, in which O\textsubscript{2} and flue gas are employed instead of air in char combustion.

In the conventional coal gasification process, O\textsubscript{2} and steam are usually used as reactant gas,\textsuperscript{23,24} and the addition of steam is beneficial for increasing the H\textsubscript{2} content of syngas. The research on coal-O\textsubscript{2}/steam gasification has also been conducted by authors\textsuperscript{25} and they found that the conversion of steam is relatively low, which means most of the steam is not involved in gasification reactions but just acts as a cooling agent. However, a lot of energy is spent for steam generation. Therefore, if there is no strict requirement for H\textsubscript{2} content, O\textsubscript{2} and CO\textsubscript{2} can also be used as reactant gases in the coal gasification process, and CO\textsubscript{2} acts as the cooling agent.\textsuperscript{26} In this study, coal-O\textsubscript{2}/CO\textsubscript{2} partial gasification and oxy-fuel combustion are combined in the PGCC-Oxy system to realize high efficiency and low carbon utilization of coal.

The PGCC-Oxy system is mainly composed of an air separation unit (ASU) unit, PGCC unit, as well as a carbon capture and storage (CCS) unit. The cryogenic distillation technology is used in the ASU,\textsuperscript{27} where high-purity (>99.5%) O\textsubscript{2} is generated. The CFB reactors are used as a gasifier and combustor due to their high fuel adaptability, low pollutant emissions, and low investment costs.\textsuperscript{28,29} Coal is partially gasified to produce syngas, which comprises CO, H\textsubscript{2}, CO\textsubscript{2}, and H\textsubscript{2}O. The ungasified char together with the circulating materials are transferred to the combustor and combusted with O\textsubscript{2} and circulating flue gas, generating 900 °C flue gas; then the heat is transferred to the feedwater through different types of heating surfaces. Supercritical power generation technology is used in the steam cycles. The temperature and pressure of the main steam is 560 °C and 24.2 MPa, respectively. After heat recovery, H\textsubscript{2}O is separated from the flue gas. Finally, H\textsubscript{2}O-free gas is purified and pressurized to obtain high-purity CO\textsubscript{2} is obtained.\textsuperscript{8}

In this study, thermodynamic and economic analysis of the PGCC-Oxy system is carried out with a aim to resolve the critical issues of high efficiency and low carbon utilization of coal as well as provide techno-economic data for further commercial application.

2. PGCC-OXY SYSTEM

2.1. Process Description. The PGCC-Oxy system is mainly composed of an ASU, a dual-CFB gasifier and a combustor unit, combined cycles unit, and a CO\textsubscript{2} separation unit. The diagram of the PGCC-Oxy system is shown in Figure 1. The Western Chinese coal is used, and the proximate and ultimate analysis is shown in Table 1. Coal and limestone are fed into the dense-phase area of the gasifier after crushing and then allowed to react with the reactant agents (O\textsubscript{2} + CO\textsubscript{2}).\textsuperscript{34} O\textsubscript{2} is provided by the ASU, and CO\textsubscript{2} is extracted from the CO\textsubscript{2} separation unit. The reactant agents are preheated to ~350 °C before entering the gasifier. Coal is partially gasified to produce syngas, which comprises CO, H\textsubscript{2}, CO\textsubscript{2}, and H\textsubscript{2}O. The ungasified char together with the circulating materials are transferred to the combustor and combusted with O\textsubscript{2} and the

![Figure 1. Diagram of the PGCC-Oxy system.](https://dx.doi.org/10.1021/acsomega.0c05277)

| Table 1. Proximate and Ultimate Analysis of Western Chinese Coal |
|------------------------------------------------------------------|
| ultimate analysis | proximate analysis |
| w(C) 61.14 | w(M) 7.55 |
| w(H) 3.18 | w(A) 20.94 |
| w(N) 1.23 | w(V) 25.12 |
| w(S) 0.56 | w(FC) 46.39 |
| w(O) 12.95 | Q\textsubscript{net,ar}/(MJ·kg\textsuperscript{-1}) 21.93 |
recirculated flue gas. Then, the flue gas is generated after char combustion. The flue gas is split into two flows after the heat exchanger: one is recirculated into the combustor and the other is sent to the CO₂ separation unit. Supercritical steam is generated in the heat recovery steam generation (HRSG) and expands in the steam turbines for power generation.

The high-temperature syngas from the gasifier is first sent to the heat recovery and then to the syngas compressor. The pressurized syngas is combusted with O₂ and the recirculating flue gas in the combustor of GT to produce the high-temperature and high-pressure exhausted gas that expands in GT for power generation. Similarly, the exhausted CO₂-rich flue gas is split into two flows: one is recirculated to the combustor of GT and the other is sent to the CO₂ separation unit. In the CO₂ separation unit, CO₂-rich gas flows into the acid condenser where H₂O is removed. Then, the H₂O-free flue gas is pressurized to 11 MPa after the de-NOₓ process and high-purity CO₂ is obtained. The main parameters of the system are listed in Table 2. The Peng-Robinson with Boston-Mathias (PR-BM) model is adopted as the thermodynamic model.

### Table 2. Primary Parameters of the Oxy-Fuel PGCC System

| parameters                        | value           |
|-----------------------------------|-----------------|
| coal feed rate, kg/s              | 50              |
| gasification temperature, °C      | 980             |
| combustion temperature, °C        | 900             |
| superheated steam                 | 560 °C, 24.2 MPa|
| reheated steam                    | 560 °C, 3.69 MPa|
| discharge temperature, °C         | 37              |
| CO₂ compression pressure, MPa     | 11              |

2.2. Air Separation Unit. As essential auxiliary equipment, the ASU, aims at providing high-purity O₂ for gasification and combustion. It is one of the most energy-consuming units and has a great effect on system's performance. Cryogenic technology similar to Zhang's research is used, and the diagram of the ASU is shown in Figure 2. The ASU is mainly composed of several heat exchangers, compressors, a high-pressure turbine (HP) column, and a low-pressure turbine (LP) column. The pressures in the HP and LP columns are 1 and 0.25 MPa, respectively. The air is first pressurized to 1 MPa and then passes through two heat exchangers. Finally, the air is separated in the HP column and LP column in turns, and high-purity (>99 wt %) O₂ is generated.

2.3. Dual-CFB Gasifier and Combustor. The diagram of dual-CFB gasifier and combustor is shown in Figure 3. Silica is employed as the bed and recirculated materials in the CFB gasifier and combustor. It is different from the entrained-flow gasifier in that the CFB gasifier has higher fuel adaptability, especially suitable for low-rank coal and other low heating fuels. In this scheme, coal is crushed into particles and mixed with limestone. Then, the solid mixture is continuously fed into the dense-phase region of the gasifier and allowed to react with O₂ and CO₂. The reactions of coal particles in the gasifier are very complicated and include devolatilization, char gasification, NOₓ and SOₓ transformation, and desulfurization, as shown in the following reactions.

1. Devolatilization
   \[ C_mH_n + (m + n/4)O_2 = mCO_2 + (n/2)H_2O \] (1)
   \[ C_mH_n + (m/2)O_2 = mCO + (n/2)H_2 \] (2)
   \[ 2CO + O_2 = 2CO_2 \] (3)
   \[ 2H_2 + O_2 = 2H_2O \] (4)
   \[ CH_4 + 2O_2 = 2H_2O + CO_2 \] (5)

2. Gas–solid heterogeneous reactions
   \[ C + O_2 = CO_2 \] (6)
   \[ 2C + O_2 = 2CO \] (7)
As coal particles together with limestone are fed into the furnace where the gasification temperature rises to more than 950 °C, coal is decomposed into coal char and volatiles. Limestone is decomposed into CaO, and CaO reacts with H₂S. Then, the char and volatiles react with O₂ and CO₂, and syngas is generated. O₂ is from the ASU and CO₂ is from the CO₂ separation unit. The syngas mainly consists of CO, H₂, CO₂, and H₂O, and it is different from the conventional coal-O₂/H₂O gasification in that the CO content is higher and the H₂ content is lower. The syngas goes through the cyclone, and the solid material is separated. The separated solid material is sent through a loop-seal. In the meantime, there is a char outlet set in the dense phase of the gasifier, and the char would also flow into the combustor through the char outlet. Oxygen-enriched combustion technology is used in the char combustion process. Char is combusted with O₂ and the recycled flue gas (RFG), and CO₂-rich flue gas is generated. To ensure stable operation of the CFB combustor, the combustion temperature is maintained at around 900 °C.

### 2.4 Steam Cycle Unit

The diagram of the steam cycle unit is shown in Figure 4, and the water and steam flows are shown with their temperatures and pressures. The heat from the char combustion is used for the steam generation, which is much higher than that of the flue gas from GT. Thus, supercritical power generation technology is used in the steam cycle unit and it is widely employed in the coal-fired power plants because of its higher power generation efficiency when compared to that in the subcritical power generation technology. The feedwater is pumped at an increased pressure and goes through the deaerator, low-pressure heaters,
and high-pressure heaters in order. There are three low-pressure heaters and three high-pressure heaters. Then preheated water flows through the heating surfaces that are distributed on the char combustor, and water is evaporated into supercritical steam. The temperature and pressure of the steam are 560 °C and 24.2 MPa, respectively. After doing work in the HP, the exhaust steam from the HP is sent back to the reheater where it is converted to subcritical steam and then expands in the intermedia pressure turbine (IP) and LP. The temperature and pressure of the reheated steam are 560 °C and 3.69 MPa, respectively. The exhaust steam from the LP is condensed in the condenser and mixed with the feedwater in the deaerator. Then, another water recirculation begins.  

### 2.5. CO₂ Purification and the Compression Unit

The diagram of the carbon dioxide compression and purification unit (CPU) is shown in Figure S, which is based on Xiong and Yan’s work. The flue gas is sent to the flash reactor, where water is separated. The water-free gas is pressurized to 3 MPa in the multistage compressor and then NO is converted into HNO₃ in the de-NOₓ process. Since N₂ is not involved in GT, NO₂ emission from oxy-fuel combustion is much lower than that from air combustion. The de-NOₓ process is still needed and the reactions in the de-NOₓ process are shown below. After the de-NOₓ process, the gas is sent to the heat exchanger where it is cooled and the separated products are heated. Finally, more than 92% CO₂ of the flue gas is separated and CO₂ of 95% purity is obtained.  

\[
\begin{align*}
\text{NO} + 1/2\text{O}_2 &= \text{NO}_2 \\
2\text{NO}_2 + \text{H}_2\text{O} &= \text{HNO}_3 + \text{HNO}_2 \\
3\text{HNO}_2 + \text{HNO}_3 &= 2\text{NO} + \text{H}_2\text{O}
\end{align*}
\]

### 3. METHODOLOGY

The methods of thermodynamic and economic analysis, including energy efficiency analysis, exergy efficiency analysis, and economic analysis, are presented in this section.  

#### 3.1. Thermodynamic Evaluation Criteria

Energy and exergy efficiencies are commonly used to evaluate the thermodynamic performance of the energy conversion system. Energy analysis is based on the first law of thermodynamics, while exergy efficiency analysis is based on the second law of thermodynamics. The energy efficiency \( \eta \) (%) of the system is calculated as follows  

\[
\eta = \frac{E}{m_{\text{coal}} \cdot \text{LHV}_{\text{coal}}}
\]

where \( E \) (MW) is the electricity production, \( m_{\text{coal}} \) (kg/h) is the mass flow rate of coal, and \( \text{LHV}_{\text{coal}} \) (MJ/kg) is the lower calorific value of coal. The exergy efficiency \( \varepsilon \) (%) of the system is calculated as follows  

\[
\varepsilon = \frac{\text{EX}_{\text{electricality}}}{\text{EX}_{\text{coal}}}
\]

where \( \text{EX}_{\text{electricality}} \) (MW) is the exergy of electricity and is equal to \( E \) (MW) and \( \text{EX}_{\text{coal}} \) (MW) is the exergy of coal. The specific exergy of the inlet coal is calculated by \( S - S \) equations, which are developed by Szargut and Styrińska.  

\[
\text{EX}_{\text{coal}} = \text{LHV}_{\text{coal}} \left( 1.0438 + 0.0013 \frac{H}{C} + 0.1083 \frac{O}{C} + 0.0549 \frac{N}{C} \right) + 6.17 \cdot S
\]

where C, H, O, N, and S represent the mass fractions of carbon, hydrogen, O₂, nitrogen, and sulfur, respectively.

#### 3.2. Economic Evaluation Criteria

The fixed capital investment (FCI), the internal rate of return (IRR), and the payback period are employed to describe the economic performance of the combined cycle system. The FCI is calculated using the production capacity index method. In the case of the single equipment, it can be expressed by the following equation  

\[
C_i = E^*(S_i/S_f)^\delta
\]

where \( C_o \) and \( b_i \) are the capital investment of the equipment and the capital investment of the referenced equipment, and the production capacity index, respectively. When 0 < \( S_i/S_f < 1 \), \( b_i = 1 \). When \( S_i/S_f < 50 \) and the expansion of the proposed projects is achieved by increasing the size of the equipment, \( 0.6 < b_i < 0.7 \). When \( S_i/S_f < 50 \) and the expansion of the proposed projects is achieved by increasing the number of equipments, \( 0.8 < b_i < 0.9 \). The price of each equipment is according to thermal power engineering limit design reference cost index.  

The IRR is commonly used to evaluate the feasibility of the engineering project. which is expressed as follows  

\[
\sum_{t=0}^{n} C_i (1 + \text{IRR})^{-t} = 0
\]

where \( C_t \) represents the cash flow of the year \( t \) and \( n \) denotes the calculation year.  

The net cash flow can be obtained as follows  

\[
C_t = C_p - (\text{FCI}^* (\text{CRF}^*(1 + \alpha) + \text{O&M}) + C_p + C_M)
\]

where \( C_{\text{op}} \) and \( C_{\text{Sm}} \) represent the annual income of products, material cost, and fuel cost, respectively. \( \text{O&M} \) denotes the ratio of the annual operation and management cost to FCI, \( \alpha \) is the interest rate during the construction period, and the CRF represents the ratio of annual average investment.  

\[
\text{CRF} = i/1 - (1 + i)^{-n}
\]

The payback period is used here  

\[
\sum_{k=1}^{P} C_i = 0
\]

where \( P_i \) is the payback period and \( n \) is the time.

### 4. RESULTS AND DISCUSSION

#### 4.1. Effects of RFG Ratio on the System Performance

Since there are pressure drops along the flue gas flow, the recirculation compressors are arranged to compensate for the pressure drops. The energy consumption of the flue gas recirculation processes would have a significant effect on energy efficiency. In contrast to the conventional oxy-fuel combustion system, there are two flue gas recirculation processes in this study: the char oxy-fuel combustion and gas oxy-fuel combustion. With some constant parameters, the
energy consumptions of different processes are listed in Table 3 and Figure 6.

| parameters                                | 1       | 2       | 3       | 4       | 5       | 6       |
|-------------------------------------------|---------|---------|---------|---------|---------|---------|
| mass flow rate of coal, kg/h              | 180 000 | 180 000 | 180 000 | 180 000 | 180 000 | 180 000 |
| O₂/coal ratio                             | 0.36    | 0.36    | 0.36    | 0.36    | 0.36    | 0.36    |
| CO₂/coal ratio                            | 0.34    | 0.34    | 0.34    | 0.34    | 0.34    | 0.34    |
| inlet O₂ of char combustion, kg/s         | 6.5     | 8       | 16      | 24      | 32      | 40      |
| inlet O₂ of gas combustion, kg/s          | 46      | 46      | 46      | 46      | 46      | 46      |
| RFG ratio of char combustion              | 0.31    | 0.35    | 0.43    | 0.46    | 0.48    | 0.50    |
| mass fraction of O₂ in char combustion, kg/kg | 0.44 | 0.44    | 0.44    | 0.44    | 0.44    | 0.44    |
| volume fraction of O₂ in char combustion, m³/m³ | 36%  | 36%     | 36%     | 36%     | 36%     | 36%     |
| RFG ratio of GT                           | 0.34    | 0.34    | 0.34    | 0.34    | 0.34    | 0.34    |
| ST                                        | 544.28  | 558.43  | 633.27  | 636.27  | 639.29  | 642.32  |
| ASU                                       | 59.22   | 60.48   | 67.2    | 73.92   | 80.64   | 87.36   |
| GT                                        | 129.51  | 129.51  | 129.51  | 129.51  | 129.51  | 129.51  |
| CPU                                       | 77.94   | 77.99   | 78.04   | 83.16   | 88.29   | 93.43   |
| Gross power generation                    | 673.80  | 687.94  | 762.79  | 765.79  | 768.80  | 771.83  |
| Power Consumption (MW)                    | 55.44   | 55.49   | 56.06   | 56.52   | 56.98   | 57.54   |
| total                                     | 224.97  | 226.45  | 234.44  | 246.51  | 258.59  | 270.69  |
| energy efficiency, %                      | 40.93   | 40.93   | 40.93   | 40.93   | 40.93   | 40.93   |
| exergy efficiency, %                      | 38.32   | 38.32   | 38.32   | 38.32   | 38.32   | 38.32   |

Figure 6. Effects of RFG ratios of char combustion on the energy efficiency and exergy efficiency.

In the first part, the effects of the RFG ratio of char combustion on system performances are studied. The mass fraction of O₂ in char combustion is maintained at 0.44. The power generation of ST increases from 544.28 to 642.32 MW, while the power generation of GT is almost constant when the RFG ratio of char combustion varies from 0.31 to 0.5. The O₂ supply to char combustion needs to be increased to keep the mass fraction of O₂ constant as the RFG ratio of char combustion increases. Thus, the energy consumption of the ASU increases from 59.22 to 87.36 MW and the increased amplitude is almost 47.51%. The energy consumption of the CPU increases from 77.94 to 93.43 MW and the increased amplitude is 19.87%, which is much smaller than that of the ASU. When the mass flow rate of O₂ is lower than 16 kg/s, the char is in the anoxic condition and part of the carbon in char is converted into CO instead of CO₂. When the mass flow rate of O₂ is more than 16 kg/s, the carbon in the char is converted to CO₂ completely, which leads to a significant increase in the CO₂ content. Therefore, the power consumption of the CPU increases sharply from case 3 to case 4. The total energy consumption of the ASU and CPU is more than half of the total energy consumption. The total pressure drops of heat exchangers and recirculated pipes are approximately 0.004 MPa. Therefore, when the RFG ratio of char combustion increases from 0.31 to 0.50, the energy consumption of compressors only increases from 224.97 to 270.69 MW. Similarly, the energy consumption of other processes differs slightly when the RFG ratio of char combustion varies. In view of energy and exergy efficiencies of the system, both of them have an increasing/decreasing tendency. Thus, when the RFG ratio of char combustion is 0.43, both energy and exergy efficiencies have maximum values of 48.18 and 45.11%, respectively.

The RFG ratio of char combustion is set as 0.43 according to the above results. The effects of the RFG ratio of GT on system performance are determined and are shown in Table 4 and Figure 7. The recirculated flue gas needs to be pressurized before sending to GT, and higher combustion pressure results in larger pressure drops. The power consumption of compressors increases from 67.38 to 123.38 MW when the RFG ratio of GT varies from 0.29 to 0.52 and the increased amplitude is around 83.54%. To maintain the mass fraction of O₂ in GT, the mass flow rate of O₂ increases with the increase in the RFG ratio of GT, resulting in the energy consumption of the ASU increasing from 55.44 to 105.84 MW. From the view of power generation, both power generation of ST and GT varies significantly, from 508.61 to 626.19 MW and from 116.63 to 218.61 MW, respectively, with the increase in the RFG ratio of GT. Combining with the above analysis, both the energy and exergy efficiencies have an increasing/decreasing tendency. When the RFG ratio of GT is 0.34, both the energy and exergy efficiencies reach the maximum values of 48.18 and 45.11%, respectively.

4.2. Effects of O₂/CO₂ Ratio of Coal Gasification on the System Performance. In recent years, CO₂ and O₂ have been proposed as gasification agents instead of steam and O₂ in
the coal/biomass gasification, which would greatly improve the CO₂ enrichment.53 Moreover, the efficiency of gasification with CO₂ and O₂ is higher than that with air or O₂-steam at the same O₂ concentration.54 Therefore, it is meaningful to study the effect of the O₂/CO₂ ratio on the system performance26 and the results are listed in Table 5.

The influence of O₂/CO₂ ratio on the gasification temperature, energy efficiency, and exergy efficiency is shown in Figure 8. The gasification temperature increases with the O₂/CO₂ ratio because more O₂ results in higher combustible part consumption thereby releasing more heat. Both the energy and exergy efficiencies increase from 48.11% to 48.18% and from 45.05% to 45.11%, respectively, when the O₂/CO₂ ratio varies from 0.78 to 1.06. The tendency of energy and exergy efficiencies differ indistinctively. The energy consumption in several units is shown in Figure 9. Since the O₂ supply in the ASU is constant, the energy consumption is constant and it is the minimum among the three units, while the coal/biomass gasification, which would greatly improve the CO₂ enrichment.53 Moreover, the efficiency of gasification with CO₂ and O₂ is higher than that with air or O₂-steam at the same O₂ concentration.54 Therefore, it is meaningful to study the effect of the O₂/CO₂ ratio on the system performance26 and the results are listed in Table 5.

Table 4. System Performance under Different RFG Ratios of GT

| parameters                  | 1   | 2   | 3   | 4   | 5   |
|-----------------------------|-----|-----|-----|-----|-----|
| mass flow rate of coal, kg/h| 180.000 | 180.000 | 180.000 | 180.000 | 180.000 |
| O₂/coal ratio               | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| CO₂/coal ratio              | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| inlet O₂ of char combustion, kg/s | 16  | 16  | 16  | 16  | 16  |
| inlet O₂ of GT, kg/s        | 32  | 46  | 68  | 80  | 92  |
| RFG ratio of char combustion| 0.43 | 0.43 | 0.43 | 0.43 | 0.43 |
| mass fraction of O₂ in char combustion, kg/kg | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 |
| volume fraction of O₂ in char combustion, m³/m³ | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| mass fraction of O₂ in GT, kg/kg | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 |
| volume fraction of O₂ in GT, m³/m³ | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| RFG ratio of GT              | 0.29 | 0.34 | 0.40 | 0.46 | 0.52 |

Table 5. Parameters under Different CO₂/Coal Ratios

| parameters                  | 1   | 2   | 3   | 4   |
|-----------------------------|-----|-----|-----|-----|
| mass flow rate of coal, kg/h| 180.000 | 180.000 | 180.000 | 180.000 |
| gasification temperature, °C | 982 | 926 | 887 | 859 |
| O₂/coal ratio               | 0.36 | 0.36 | 0.36 | 0.36 |
| CO₂/coal ratio              | 0.3  | 0.34 | 0.38 | 0.42 |
| O₂/CO₂ ratio                | 1.06 | 0.95 | 0.86 | 0.78 |
| inlet O₂ of char combustion, kg/s | 16  | 16  | 16  | 16  |
| inlet O₂ of GT, kg/s        | 46  | 46  | 46  | 46  |
| mass fraction of O₂ in char combustion, kg/kg | 0.44 | 0.44 | 0.44 | 0.44 |
| volume fraction of O₂ in char combustion, m³/m³ | 0.36 | 0.36 | 0.36 | 0.36 |
| RFG ratio of char combustion| 0.43 | 0.43 | 0.43 | 0.43 |
| RFG ratio of GT              | 0.34 | 0.34 | 0.34 | 0.34 |

Figure 7. Energy and exergy efficiencies of the system under different RFG ratios of GT.

Figure 8. The gasification temperature increases with the O₂/CO₂ ratio because more O₂ results in higher combustible part consumption thereby releasing more heat. Both the energy and exergy efficiencies increase from 48.11% to 48.18% and from 45.05% to 45.11%, respectively, when the O₂/CO₂ ratio varies from 0.78 to 1.06. The tendency of energy and exergy efficiencies differ indistinctively. The energy consumption in several units is shown in Figure 9. Since the O₂ supply in the ASU is constant, the energy consumption is constant and it is the minimum among the three units, while
the energy consumption of the CPU is slightly higher than that of compressors. The energy consumption of compressors decreases from 77.33 to 79.25 MW because of the decrease in the CO₂ input. Since a multistage compressor is arranged in the CPU to pressurize the flue gas, an increase in the O₂/CO₂ ratio results in low power consumption of compressors. Therefore, the energy consumption of the CPU decreases from 81.02 to 78.04 MW.

4.3. Comparison of the Proposed System with the Referenced System. The proposed system is compared with an IGCC-Oxy system, and the mass flow rate of the main streams of the PGCC-Oxy system is shown in Figure 10. Since some data are not provided by authors of ref 17, only some necessary data are listed in Table 6. It can be seen that the energy efficiency of the PGCC-Oxy system is approximately 3% higher than that of the IGCC-Oxy system indicating that cascading utilization of coal is more advantageous than the single conversion of coal. To evaluate the quantity of pollutant emission of the flue gas, the content of SO₂ and NOₓ in the flue gas are listed in Table 7, showing that the emission of SO₂ and NOₓ can meet the national standard.

5. ECONOMIC ANALYSIS

Economic analysis is conducted to evaluate the economic performance of the PGCC-Oxy system. The basic data of economic analysis are listed in Table 8. The total investment cost of the PGCC-Oxy system is 3272.71 million RMB and is shown in Table 9. The investment cost per kW electricity is 6194.21 RMB/kW, which is almost twice that of 660 MW-supercritical coal-fired power plant (3367 RMB/kW). This is because there are two extra expensive facilities in the PGCC-Oxy system: one is the ASU, the cost of which is almost 634.71 million RMB since O₂ instead of air is used as gasification and combustion reactants; the other is the CPU, the cost of which is almost 575.57 million RMB. The total investment cost is greatly increased by these two units. The dual-CFB reactors, HRSG, and CPU are the most expensive facilities in the system that account for more than 80% of the total investment cost. Based on the data in Tables 8 and 9, the IRR and payback time are 8.07% and 12.38 years, respectively. Even though they are lower than that of PGCC without CCS, it is still a promising technology that can be applied in the industry.

Figure 8. Influence of O₂/CO₂ ratio on the gasification temperature, energy efficiency, and exergy efficiency.

Figure 9. Energy consumption of compressors and the CPU under different O₂/CO₂ ratios.

Figure 10. Mass flow rate of main streams in the PGCC-Oxy system.
6. CONCLUSIONS

In this work, thermodynamic and economic analysis of a novel energy conversion system based on coal partial gasification and oxy-fuel combustion is conducted. The conclusions are as follows.

(1) When the RFG of char combustion and GT increase, both the energy efficiency and exergy efficiency have an increasing/decreasing tendency and they reach the maximum values when the RFG of char combustion and GT are 0.43 and 0.34, respectively.

(2) When the CO2/O2 ratio increases from 0.78 to 1.06, the gasification temperature, energy efficiency, and exergy efficiency have an ever-increasing tendency.

(3) When compared with the IGCC-Oxy system, the energy efficiency of the proposed system is approximately 3% higher.

(4) The total investment cost of the PGCC-Oxy system is 3272.71 million RMB, and the IRR and payback time of the system are 8.07% and 12.38 years, respectively, which shows a promising prospect.

AUTHOR INFORMATION

Corresponding Author
Qinhui Wang  –  State Key Laboratory of Clean Energy Utilization, Zhejiang University, Zhejiang, Hangzhou 310027, China; orcid.org/0000-0002-5190-6932; Email: qhwang@zju.edu.cn

Authors
Chao Ye  –  Department of Energy and Environmental System Engineering, Zhejiang University of Science and Technology, Zhejiang, Hangzhou 310023, China
Zefu Ye  –  Shanxi Gemeng US-China Clean Energy R&D Center Co. Ltd., Shanxi, Taiyuan 030000, China
Zhujun Zhu  –  Shanxi Gemeng US-China Clean Energy R&D Center Co. Ltd., Shanxi, Taiyuan 030000, China

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.0c05277

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work is supported by Shanxi Gemeng US-China Clean Energy R&D Center, National Key R&D Program of China (2016YFE0102500-05), Science and Technology Major...
Project of Shanxi Province (20181101005), and Zhejiang Provincial Natural Science Foundation of China under Grant No. LQ21E060002.

■ ABBREVIATIONS

CFB circulating fluidized bed
ASU air separation unit
CPU carbon dioxide compression and purification unit
RFG recirculating flue gas
PGCC partial gasification combined cycle
GTC gas turbine
HP high-pressure turbine
IP intermediate pressure turbine
LP low-pressure turbine
IGCC integrated gasification combined cycle
HRSG heat recovery steam generation
IRR internal rate of return

■ REFERENCES

(1) Mehrpooya, M.; Sharifzadeh, M. M. M. A novel integration of oxy-fuel cycle, high temperature solar cycle and LNG cold recovery—energy and exergy analysis. Appl. Therm. Eng. 2017, 114, 1090–1104.
(2) Xiang, Y.; Cai, L.; Guan, Y.; Liu, W.; Han, Y.; Liang, Y. Study on the configuration of bottom cycle in natural gas combined cycle power plants integrated with oxy-fuel combustion. Appl. Energy 2018, 212, 465–477.
(3) Plaza, M. G.; Pevida, C. Current Status of CO2 Capture from Coal Facilities. In New Trends in Coal Conversion; Publishing, 2019; pp 31–58.
(4) Chu, F.; Xiao, G.; Yang, G. Mass Transfer Characteristics and Energy Penalty Analysis of MEA Regeneration Process in Packed Column. Sustainable Energy Fuels 2020, No. 01251.
(5) Houghton, J. T.; Ding, Y.; Griggs, D. J.; Noguer, M.; van der Linden, P. J.; Dai, X.; Maskell, K.; Johnson, C. Climate Change. In The Scientific Basis; The Press Syndicate of the University of Cambridge, 2001.
(6) Szulczewski, M. L.; MacMinn, C. W.; Herzog, H. J.; Juanes, R. Lifetime of carbon capture and storage as a climate-change mitigation technology. Proc. Natl. Acad. Sci. U.S.A. 2012, 109, $185–5189$.
(7) Statistics NBo. Statistical Communique on National Economic and Social Development. 2018.
(8) Rizza, J.; Gil, M. V.; Álvarez, L.; Pevida, C.; Pis, J. J.; Rubiera, F. Oxy-fuel combustion of coal and biomass blends. Energy 2012, 41, 429–435.
(9) Chen, S.; Yu, R.; Soomro, A.; Xiang, W. Thermodynamic assessment and optimization of a pressurized fluidized bed oxy-fuel combustion power plant with CO2 capture. Energy 2019, 175, 445–455.
(10) Mathenge, H. I.; Oboirien, B. O.; North, B. C. A review of oxy-fuel combustion in fluidized bed reactors. Int. J. Energy Res. 2016, 40, 878–902.
(11) Scheffknecht, G.; Al-Mahkadmeh, L.; Schnell, U.; Maier, J. Oxy-fuel coal combustion—A review of the current state-of-the-art. Int. J. Greenhouse Gas Control 2011, S16-S33.
(12) Kanniche, M.; Gros-Bonnivard, R.; Jaud, P.; Valle-Marcos, J.; Amanum, J.-M.; Bouallou, C. Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture. Appl. Therm. Eng. 2010, 30, 53–62.
(13) Shi, Y.; Zhong, W.; Shao, Y.; Liu, X. Energy efficiency analysis of pressurized oxy-coal combustion system utilizing circulating fluidized bed. Appl. Therm. Eng. 2019, 150, 1104–1115.
(14) Hanak, D. P.; Powell, D.; Manovic, V. Techno-economic analysis of oxy-combustion coal-fired power plant with cryogenic oxygen storage. Appl. Energy 2017, 191, 193–203.
(15) Cormos, C.-C. Oxy-combustion of coal, lignite and biomass: A techno-economic analysis for a large scale Carbon Capture and Storage (CCS) project in Romania. Fuel 2016, 169, 50–57.
(16) Yan, L.; Yue, G.; He, B. Thermodynamic analyses of biomass-coal co-gasification power generation system. Bioresour. Technol. 2016, 205, 133–141.
(17) Kunze, C.; Spielfthoef, H. Assessment of oxy-fuel, pre- and post-combustion-based carbon capture for future IGCC plants. Appl. Energy 2012, 94, 109–116.
(18) Ye, C.; Wang, Q.; Zheng, Y.; Li, G.; Zhang, Z.; Luo, Z. Techno-economic analysis of methanol and electricity poly-generation system based on coal partial gasification. Energy 2019, 185, 624–632.
(19) Guo, Z.; Wang, Q.; Fang, M.; Luo, Z.; Cen, K. Thermodynamic and economic analysis of polygeneration system integrating atmospheric pressure coal pyrolysis technology with circulating fluidized bed power plant. Appl. Energy 2014, 113, 1301–1314.
(20) Zhou, H.; Jing, B.; Zhong, Z.; Huang, Y.; Xiao, R. Air and Steam Coal Partial Gasification in an Atmospheric Fluidized Bed. Energy Fuels 2005, 19, 1619–1623.
(21) Ye, C.; Wang, Q.; Luo, Z.; Fang, M.; Cen, K. Techno-economic analysis of novel power generation system based on coal partial gasification technology. Asia-Pac. J. Chem. Eng. 2019, No. e2377.
(22) Ye, C.; Wang, Q.; Zheng, Y.; Li, G.; Zhang, Z.; Luo, Z. Techno-economic analysis of methanol and electricity poly-generation system based on coal partial gasification. Energy 2019, 185, 624–632.
(23) Xiao, Y.; Xu, S.; Song, Y.; Wang, C.; Ouyang, S. Gasification of low-rank coal for hydrogen-rich gas production in a dual loop gasification system. Fuel Process. Technol. 2018, 171, 110–116.
(24) Gao, D.; Qiu, X.; Zhang, Y.; Liu, P. Life cycle analysis of coal based methanol-to-olefins processes in China. Comput. Chem. Eng. 2018, 109, 112–118.
(25) Ye, C.; Wang, Q.; Luo, Z.; Xie, G.; Jin, K.; Siyil, M.; Cen, K. Characteristics of Coal Partial Gasification on a Circulating Fluidized Bed Reactor. Energy Fuels 2017, 31, 2557–2564.
(26) Ye, C.; Wang, Q.; Yu, L.; Luo, Z.; Cen, K. Characteristics of coal partial gasification experiments on a circulating. Appl. Therm. Eng. 2018, 130, 814–821.
(27) Zhang, R.; Chen, Y.; Lei, K.; Ye, B.; Cao, J.; Liu, D. Thermodynamic and economic analyses of a novel coal pyrolysis-gasification-combustion staged conversion utilization polygeneration system. Asia-Pac. J. Chem. Eng. 2018, 13, No. e2171.
(28) Yue, G.; Cai, R.; Lu, J.; Zhang, H. From a CFB reactor to a CFB boiler—the review of R&D progress of CFB coal combustion technology in China. Powder Technol. 2017, 316, 18–28.
(29) Chen, S.; Yu, R.; Soomro, A.; Xiang, W. Thermodynamic assessment and optimization of a pressurized fluidized bed oxy-fuel combustion power plant with CO2 capture. Energy 2019, 175, 445–455.
(30) Emun, F.; Gadalla, M.; Jiménez, L. Integrated Gasification Combined Cycle (IGCC) process simulation and optimization. Comput.-Aided Chem. Eng. 2008, 25, 1059–1064.
(31) Liang, C.; Zhang, H.; Zhu, Z.; Na, Y.; Lu, Q. CO2–O2 gasification of a bituminous coal in circulating fluidized bed. Fuel 2017, 200, 81–88.
(32) Yang, Z.; Zheng, C.; Zhang, X.; Zhou, H.; Silva, A. A.; Liu, C.; Snyder, B.; Wang, Y.; Gao, X. Challenge of SOx removal by wet electrostatic precipitator under simulated flue gas with high SOx concentration. Fuel 2018, 217, 597–604.
(33) Kez, V.; Liu, F.; Consalvi, J. L.; Strohle, J.; Eppe, B. A comprehensive evaluation of different radiation models in a gas turbine combustor under conditions of oxy-fuel combustion with dry recycle. J. Quant. Spectrosc. Radiat. Transfer 2016, 172, 121–133.
(34) Kodama, T.; Kondohe, Y.; Tamagawa, T.; Funatohe, A.; Shimizu, K.; Kitayama, Y. Fluidized bed coal gasification with CO2 under direct irradiation with concentrated visible light. Energy Fuels 2002, 16, 1264–1270.
(35) Harris, D.; Roberts, D.; Henderson, D. Gasification behaviour of Australian coals at high temperature and pressure. Fuel 2006, 85, 134–142.
(36) Liu, Q.; Zhong, W.; Yu, A. Oxy-fuel combustion behaviors in a fluidized bed: A combined experimental and numerical study. Powder Technology 2019, 349, 40–51.

(37) Wei, H.; Yang, X.; Ge, Z.; Yang, L.; Du, X. Anti-freezing of natural draft dry cooling system of power generation by water redistribution during winter. Int. J. Heat Mass Transfer 2020, 149, No. 119194.

(38) Xiong, J.; Zhao, H.; Chen, M.; Zheng, C. Simulation Study of an 800 MWeOxy-combustion Pulverized-Coal-Fired Power Plant. Energy Fuels 2011, 25, 2405–2415.

(39) Chu, F.; Gao, Q.; Li, S.; Yang, G.; Luo, Y. Mass transfer characteristic of ammonia escape and energy penalty analysis in the regeneration process. Appl. Energy 2020, 258, No. 113975.

(40) Lasek, J. A.; Janusz, M.; Zuwala, J.; Głód, K.; Iluk, A. Oxy-fuel combustion of selected solid fuels under atmospheric and elevated pressures. Energy 2013, 62, 105–112.

(41) Duan, L.; Duan, Y.; Zhao, C.; Anthony, E. J. NO emission during co-firing coal and biomass in an oxy-fuel circulating fluidized bed combustor. Fuel 2015, 150, 8–13.

(42) Tøftegaard, M. B.; Brix, J.; Jensen, P. A.; Glarborg, P.; Jensen, A. D. Oxy-fuel combustion of solid fuels. Prog. Energy Combust. Sci. 2010, 36, 581–625.

(43) Han, X.; Liu, M.; Wu, K.; Chen, W.; Xiao, F.; Yan, J. Exergy analysis of the flue gas pre-dried lignite-fired power system based on the boiler with open pulverizing system. Energy 2016, 106, 285–300.

(44) Han, X.; Chen, N.; Yan, J.; Liu, J.; Liu, M.; Karellas, S. Thermodynamic analysis and life cycle assessment of supercritical pulverized coal-fired power plant integrated with No. 0 feedwater preheater under partial loads. J. Cleaner Prod. 2019, 233, 1106–1122.

(45) Zhang, G.; Yang, Y.; Jin, H.; Xu, G.; Zhang, K. Proposed combined-cycle power system based on oxygen-blown coal partial gasification. Appl. Energy 2013, 102, 735–745.

(46) Govin, O.; Díky, V.; Kabo, G.; Blokhin, A. Evaluation of the chemical exergy of fuels and petroleum fractions. J. Therm. Anal. Calorim. 2000, 62, 123–133.

(47) Design Quota of Thermal Power Project Reference Cost Index-2014; Institute EPPaE, 2014.

(48) Cormos, A.-M.; Cormos, C.-C. Techno-economic assessment of combined hydrogen & power co-generation with carbon capture: The case of coal gasification. Appl. Therm. Eng. 2019, 147, 29–39.

(49) Gao, D.; Qiu, X.; Zheng, X.; Zhang, Y. Life cycle analysis of coal-based synthetic natural gas for heat supply and electricity generation in China. Chem. Eng. Res. Des. 2018, 131, 709–722.

(50) Wright, M. M.; Daugaard, D. E.; Satrio, J. A.; Brown, R. C. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 2010, 89, S2–S10.

(51) Yi, Q.; Feng, J.; Li, W. Y. Optimization and efficiency analysis of polygeneration system with coke-oven gas and coal gasified gas by Aspen Plus. Fuel 2012, 96, 131–140.

(52) Wang, F.; Zeng, X.; Wang, Y.; Yu, J.; Xu, G. Characterization of coal char gasification with steam in a micro-fluidized bed reaction analyzer. Fuel Process. Technol. 2016, 141, 2–8.

(53) Kumabe, K.; Hanoka, T.; Fujimoto, S.; Minowa, T.; Sakanishi, K. Co-gasification of woody biomass and coal with air and steam. Fuel 2007, 86, 684–689.

(54) Prabowo, B.; Umeki, K.; Yan, M.; Nakamura, M. R.; Castaldi, M. J.; Yoshikawa, K. CO2–steam mixture for direct and indirect gasification of rice straw in a downdraft gasifier: Laboratory-scale experiments and performance prediction. Appl. Energy 2014, 113, 670–679.

(55) Li, S.; Gao, L.; Zhang, X.; Lin, H.; Jin, H. Evaluation of cost reduction potential for a coal based polygeneration system with CO2 capture. Energy 2012, 45, 101–106.

(56) Tang, Z.; Wang, Y. Efficient and environment friendly use of coal. Fuel Process. Technol. 2000, 62, 137–141.