Techno-economic evaluation of oxy-combustion coal-fired power plants

XIONG Jie, ZHAO HaiBo* & ZHENG ChuGuang

State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China

Received December 14, 2010; accepted July 28, 2011

Increasing attention is being paid to the oxy-combustion technique of coal-fired power plants because CO₂ produced from fossil fuel combustion can be captured and sequestered by it. However, there are many questions about the economic properties of the oxy-combustion technique. In this paper, a detailed techno-economic evaluation study was performed on three typical power plants (2 × 300 MW subcritical, 2 × 600 MW supercritical, 2 × 1000 MW ultra supercritical), as conventional air fired and oxy-combustion options in China, by utilizing the authoritative data published in 2010 for the design of coal-fired power plants. Techno-economic evaluation models were set up and costs of electricity generation, CO₂ avoidance costs as well as CO₂ capture costs, were calculated. Moreover, the effects of CO₂ tax and CO₂ sale price on the economic characteristics of oxy-combustion power plants were also considered. Finally, a sensitivity analysis for parameters such as coal sample, coal price, air separation unit price, flue gas treatment unit price, CO₂ capture efficiency, as well as the air excess factor was conducted. The results revealed that: (1) because the oxy-combustion technique has advantages in thermal efficiency, desulfurization efficiency and denitration efficiency, oxy-combustion power plants will reach the economic properties of conventional air fired power plants if, (a) the CO₂ emission is taxed and the high purity CO₂ product can be sold, or (b) there are some policy preferences in financing and coal price for oxy-combustion power plants, or (c) the power consumption and cost of air separation units and flue gas treatment units can be reduced; (2) from subcritical plants to supercritical and finally ultra-supercritical plants, the economics are improving, regardless of whether they are conventional air fired power plants or oxy-combustion power plants.

oxy-combustion, CO₂ emission control, techno-economics, sensitivity analysis, CO₂ tax, CO₂ sale, cost of electricity
from the ASU, instead of air, is used in the oxy-combustion process, and about 70%–80% of the flue gas is recycled into the furnace, keeping the combustion temperature inside the furnace within the conventional range. A schematic diagram of the oxy-combustion technology is shown in Figure 1. Because there is no nitrogen dilution, the CO₂ concentration in the oxy-combustion flue gas is high, and a high purity CO₂ product (95%–99%) can be obtained through purification, compression and separation. Moreover, efficient De-\(\text{SO}_x\) and De-\(\text{NO}_x\) can be achieved in such a system and consequently oxy-combustion has become one of the most competitive coal combustion technologies of this century. At present, oxy-combustion technology has reached the demonstration stage in many countries, and there were eight demonstration power station projects operating worldwide in 2008–2010. In this paper, techno-economic evaluations of oxy-combustion and also conventional coal-fired power plants are performed. The results of these two evaluations are compared and presented. In conventional coal-fired power plants, coal is combusted with air in the furnace and the flue gas containing about 15 mol% CO₂ is emitted directly into the atmosphere.

IHI in Japan [3], Chalmers University of Technology in Sweden [4], ALSTOM in America [5], Argonne National Laboratory in America [6], CANMET in Canada [7] and EDF in France [8] have all carried out techno-economic evaluations of the oxy-combustion technology. The results of IHI [3] show that the efficiency of the oxy-combustion power plant (1000 MW) decreases 10.5%; the results from Chalmers University of Technology [4] show that the efficiency of the oxy-combustion power plant (865 MW) decreases 9.1%, the CO₂ avoidance cost is $26/t and the cost of electricity is $64.3/kW; the results of ALSTOM [5] show that the CO₂ avoidance cost of the oxy-combustion power plant (450 MW) is $42/t and the unit investment cost is $823/kW; the results of Argonne National Laboratory [6] show that the CO₂ avoidance cost is $34/t; the results of CANMET [7] show that the CO₂ avoidance cost of the oxy-combustion power plant (400 MW) is $35/t, the cost of electricity increases 20%–30% and the unit investment cost is $791/kW; the results of EDF [8] show that the efficiency of the oxy-combustion power plant (1200 MW) decreases 10%, the investment cost increases 69%, the cost of electricity increases 48% and the CO₂ avoidance cost of the oxy-combustion system is 29% lower than that of the MEA scrubbing system. These results can be summarized as: if conventional coal-fired power plants are retrofitted to be oxy-combustion power plants, the net power output will decrease by about 25%, the cost of electricity will increase by 30%–50%, the CO₂ avoidance cost is about $30/t and about 85% CO₂ can be captured. However, the techno-economic characteristics of CO₂ emission control systems are complicated. They depend on the energy efficiency of the system, technology maturity level, pollutants (including SOₓ, NOₓ, PM10 and CO₂) emission policies in the country or the local region, and even financial policies (such as the loan interest rate and inflation rate). Since there are large differences among the evaluating system sizes and combustion conditions from various academic institutions, and the tax policies and financial policies between Western countries are usually adopted from country-specific data, the published research results are not transferable to the Chinese situation. Therefore, to provide the basis of policy decisions, it is very important to perform techno-economic evaluations for different CO₂ emission control systems based on Chinese conditions and data, for energy and power systems, by comparing various electricity costs, CO₂ avoidance costs and CO₂ capture costs for these CO₂ emission control systems.

The authors have previously performed a techno-economic evaluation of oxy-combustion coal-fired power plants retrofitted from conventional coal-fired power plants, by using a thermo-economic cost model [9] and practical investigation data [10]. However, some internal cost items (such as depreciation cost, amortization expense, material cost, etc.) were not considered in the previous evaluation. The main purpose of this paper is to provide a techno-economic evaluation of oxy-combustion power plants based on Chinese conditions and data.
cost, personnel wages and other expenses) were ignored in the previous models. Cost models for De-SO$_2$ and De-NO$_x$ technologies were very simple, and also detailed comparisons among several typical coal-fired power plants were not carried out. In this paper, a more systematic and comprehensive techno-economic evaluation of the oxy-combustion technology was thus conducted. Each factor during the electricity cost formation and detailed investment and operating costs of De-SO$_2$ and De-NO$_x$ devices, was considered. Moreover, three typical coal-fired power plants $\times 300$ MW subcritical, $\times 600$ MW supercritical and $\times 1000$ MW ultra-supercritical) in China were chosen to calculate the electricity costs in oxy-combustion power plants and conventional power plants, and CO$_2$ avoidance costs and CO$_2$ capture costs in oxy-combustion power plants. The effects of a CO$_2$ tax, and CO$_2$ sale price, on the cost results are also discussed. Finally, a sensitivity analysis of some important parameters in oxy-combustion systems, such as the coal price, ASU cost, CPU cost and CO$_2$ capture efficiency, were performed to study their influences on the economics of the oxy-combustion technology.

1 Techno-economic analysis

1.1 Basic methods

Because there are no demonstration or commercially operated oxy-combustion coal-fired power plants larger than 30 MW, the techno-economic evaluation of an oxy-combustion plant was performed based on its corresponding conventional coal-fired power plant. Keeping the gross power outputs of the oxy-combustion plant and its corresponding conventional plant equivalent, the differences in the oxy-combustion plant from the conventional plant mainly lie in: retrofitting the burner, heat exchange surface and flue gas recycle in the boiler island; an ASU and a CPU are added. Consequently, the techno-economic evaluation process of an oxy-combustion plant is as follows:

(1) Collect basic thermodynamic parameters (such as coal consumption rate, power generation load, and boiler efficiency), operational conditions (such as annual operation hours, maintenance factor, amortization rate, depreciation rate, and personnel wages), and investment and operational costs of De-SO$_2$ and De-NO$_x$ devices, in the conventional plant system, that can be obtained from a system process simulation, or investigation. In this paper, data were adopted mainly from the book “Reference cost indexes in quota design for coal-fired projects (2009 levels)” [11] published by the China Power Engineering Consulting Group Corporation in 2010. The boiler retrofit cost, investment cost and power consumption of CPU could be estimated and adjusted by referring to published papers [12,13]. The investment cost and power consumption of ASU can be obtained from oxygen production companies and by simulating the ASU system.

(2) Generally, commercial loans exist for the construction of a power plant, so it is necessary to know the market economy policies, such as interest rate, fuel price, water price, steam price, limestone price and gypsum price.

(3) From the data mentioned above, each basic cost item (such as fuel cost and investment cost) relating to the oxy-combustion and conventional plants can be calculated. Then the CO$_2$ avoidance costs and CO$_2$ capture costs of the oxy-combustion plants can be further calculated. Finally, a sensitivity analysis may be performed.

1.2 Cost calculation for power plants

The total cost of a power plant includes the power generation cost, period cost, and by-products revenue ($C_{10}$). The power generation cost includes fuel cost ($C_1$), operation and maintenance (O&M) cost ($C_3$), depreciation cost ($C_4$), amortization cost ($C_5$), pollutants’ emission tax ($C_6$), personnel wages ($C_7$), material cost ($C_8$) and other costs ($C_9$). The period cost includes a management expense and financial expense (including loan interest ($C_{10}$)). Because the management expense and financial expense involve complicated financial accounting theory and industry rules, only some “hard” costs (annualized cost $C_I$) were considered in this paper, which can be described as

$$C_I = \sum_{i=1}^{9} C_i - C_{10}. \quad (1)$$

(i) Cost calculation for conventional power plants. Conventional power plant costs can be calculated as follows:

(1) Fuel cost

$$C_{1,0} = m_{F,0} \times c_f \times W \times H, \quad (2)$$

in which, $m_{F,0}$ is the unit standard coal consumption rate for power generation (315, 299 and 275 g/(kW h) for the subcritical, supercritical and ultra-supercritical power plant, respectively in this paper) [11], $c_f$ is the unit standard coal price (680 ¥/t with tax [11], Y is the symbol of Chinese Yuan (CNY). 1 US$=6.8 CNY in 2009), $W$ is the power plant load (600, 1200 and 2000 MW for the three kinds of power plant) and $H$ is the annual operation hours (5000 h [11]).

The ultimate analysis and the lower heating value ($H_l$) of the raw coal (Shenhua coal) are listed in Table 1. The unit oxygen needed ($v_{0}$) for combustion can be calculated to be 1.27Nm$^3$/kg coal on the basis of values in Table 1 and eq. (3).

$$v_0 = (C_a/12 + H_a/4 + S_a/32 − O_a/32) \times 22.4. \quad (3)$$

(2) Loan interest cost

$$C_{2,0} = C_{IT,0} \times p_{loan} \times \xi, \quad (4)$$

in which, $C_{IT,0}$ is the total investment cost of the conventional power plant and $C_{IT,0} = C_{IT,base,0} + C_{IT,so} + C_{IT,N0}$. The $C_{IT,base,0}$ for the three kinds of power plant (excluding De-SO$_2$
and De-NOx devices) can be estimated by using 4412, 3675 and 3591 ¥/kW [11]. The device costs of the De-SOx devices (considering the wet flue gas desulfurization (FGD) technology with a 95% desulfrization efficiency (\(\eta_{SOx}\)) in the three plants are 111.43, 185.45, 247.09 ¥, respectively [11]. The device costs of the denitrification devices (considering the selective catalytic reduction (SCR) denitrification technology with a 80% denitrification efficiency (\(\eta_{NOx}\)) in the three plants are 72.99, 108 and 140 ¥, respectively [11]. In addition, the costs of De-SOx and De-NOx devices are set to be 80% of their investment costs (\(C_{IT,SOx}\) and \(C_{IT,NOx}\)) [14,15] and other costs, such as construction, installation and technical service, account for the remaining 20%; \(p_{SOx}\) is the loan percentage (80% [11]), and the “average capital method” was chosen to payback the load, the average interest rate for a period longer than 5 years (5.94% [11]). The device costs of the denitration devices (considering the selective catalytic reduction (SCR) denitrification technology with a 80% denitrification efficiency (\(\eta_{NOx}\)) in the three plants are 72.99, 108 and 140 ¥, respectively [11]. In addition, the costs of De-NOx and De-NOx devices are set to be 80% of their investment costs (\(C_{IT,SOx}\) and \(C_{IT,NOx}\)) [14,15] and other costs, such as construction, installation and technical service, account for the remaining 20%; \(p_{SOx}\) is the loan percentage (80% [11]), and the “average capital method” was chosen to payback the load, the average interest rate for a period longer than 5 years (5.94% [11]).

(3) Operation and maintenance cost

\[
C_{OM,0} = C_{OM,base,0} \times p_{OM,base,0} + C_{OM,SOx} + C_{OM,NOx},
\]

in which, \(p_{OM,base,0}\) is the O&M coefficient (2.5% [7], including the major maintenance expense) for the conventional power plants (excluding De-SOx and De-NOx devices); \(C_{OM,SOx}\) is the O&M cost for the FGD device, including limestone consumption rate in each power plant, C\(_{OM,SOx}\) is the O&M coefficient (2.5% [7], in-

(4) Depreciation cost

\[
C_{d,0} = C_{IT,0} \times p_{d,0} \times (1 - p_{d,0})/Y_d, \quad (6)
\]

in which, \(p_{d,0}\) is the fixed assets formation percentage (95% [11]), \(p_{d,0}\) is the residual value percentage (5% [11]) and the \(Y_d\) is the depreciation period (15 years).

(5) Amortization cost

\[
C_{a,0} = C_{IT,0} \times p_{a,0}/Y_a, \quad (7)
\]

in which \(p_{a,0}\) is the percentage of intangible and deferred assets (5%) [17] and \(Y_a\) is the amortization period (5 years).

(6) Pollutants emission tax

\[
C_{e,0} = E_{S,0} \times T_S + E_{N,0} \times T_N, \quad (8)
\]

in which \(E_{SOx}\) is the SOx emission amount in the conventional power plant, which can be estimated by referring to [18]. \(E_{SOx} = 32/16 \times m_{SOx}/H_i \times W \times H \times S_{ar} \times i_{SOx} \times (1-\eta_{SOx})\), where \(i_{SOx}\) is the ratio of \(S_{ar}\) transformed to SO2 after coal combustion (80% [18]); \(E_{NOx}\) is the NOx emission amount in the conventional power plant, \(E_{NOx} = 30.8/14 \times m_{NOx}/W \times H_i \times H \times N_{ar} \times i_{NOx} \times m_{NOx} \times (1-\eta_{NOx})\), in which 30.8/14 is the ratio of NOx (95 m% NO and 5 m% N2O) molecular weight to that of N element [18], \(\eta_{SOx}\) is the transforming rate (25% [18]) of fuel N, \(m_{SOx}\) is the percentage of NOx coming from fuel N to total NOx (80% [18]), \(T_S\) and \(T_N\) are the unit pollutant emission tax (0.6 ¥/0.95 kg) for SO2 and NOx, respectively. In addition, pollutant emission taxes for CO and particles were not considered in this paper and tax differences from different regions and environment functions were also not considered. If the emission tax of CO2 is considered, then eq. (8) should be modified to be

\[
C_{e,0} = E_{S,0} \times T_S + E_{N,0} \times T_N + E_{CO2,0} \times T_{CO2}, \quad (9)
\]

in which, \(E_{CO2,0}\) is the CO2 emission amount, \(E_{CO2,0}=44/12 \times m_{CO2}/H_i \times W \times H \times C_{ar} \times i_{CO2} \times (1-\eta_{CO2})\), and \(T_{CO2}\) is the unit CO2 emission tax (¥/tCO2). \(i_{CO2}\) is the ratio of \(C_{ar}\) transformed to be CO2 after coal combustion (usually 100%). \(\eta_{CO2}\) is the CO2 capture ratio (for conventional plants, \(\eta_{CO2}=0\); and for

### Table 1 Ultimate analysis and lower heating value of the Shenhua coal

| M (%) | A (%) | C (%) | H (%) | O (%) | N (%) | S (%) | \(H_i\) (kJ/kg) |
|-------|-------|-------|-------|-------|-------|-------|---------------|
| 13.8  | 11    | 60.51 | 3.62  | 9.94  | 0.7   | 0.43  | 22768         |

\(\eta_{SOx}\) is the transforming rate (25% [18]) of fuel N, \(m_{SOx}\) is the percentage of NOx coming from fuel N to total NOx (80% [18]), \(T_S\) and \(T_N\) are the unit pollutant emission tax (0.6 ¥/0.95 kg) for SO2 and NOx, respectively. In addition, pollutant emission taxes for CO and particles were not considered in this paper and tax differences from different regions and environment functions were also not considered. If the emission tax of CO2 is considered, then eq. (8) should be modified to be

\[
C_{e,0} = E_{S,0} \times T_S + E_{N,0} \times T_N + E_{CO2,0} \times T_{CO2}, \quad (9)
\]

in which, \(E_{CO2,0}\) is the CO2 emission amount, \(E_{CO2,0}=44/12 \times m_{CO2}/H_i \times W \times H \times C_{ar} \times i_{CO2} \times (1-\eta_{CO2})\), and \(T_{CO2}\) is the unit CO2 emission tax (¥/tCO2). \(i_{CO2}\) is the ratio of \(C_{ar}\) transformed to be CO2 after coal combustion (usually 100%). \(\eta_{CO2}\) is the CO2 capture ratio (for conventional plants, \(\eta_{CO2}=0\); and for...
oxy-combustion plants, $\eta_C; i=90\%$).

(7) Personnel wages

$$C_{7,0} = (N_{base,0} + N_{S,0} + N_{N,0}) \times c_{pay} \times (1 + r_w),$$

(10)
in which, $N_{base,0}$, $N_{S,0}$, $N_{N,0}$ are personnel numbers for the base power plant, the FGD system and the SCR system, respectively. For the three kinds of plant, $N_{base,0}$ is 234, 247 and 300 [11], respectively; $N_{S,0}$ is 15, 18, 21 (three groups, and each of 5, 6 and 7 persons), respectively; $N_{N,0}$ is 15, 18, 21 (three groups, and each of 5, 6 and 7 persons), respectively. $c_{pay}$ is the annual wage for each person (50000 ¥/y), and $r_w$ is the welfare and labor insurance coefficient (60% [11]).

(8) Material cost

$$C_{8,0} = p_{m,0} \times W \times H,$$

(11)
in which, $p_{m,0}$ is the material cost ratio (6, 5, 4 ¥/(MW h) [11] for each plant, respectively).

(9) Other costs

$$C_{9,0} = p_{o,0} \times W \times H,$$

(12)
in which, $p_{o,0}$ is the other costs ratio (12, 10, 8 ¥/(MW h) [11] for each plant, respectively).

(10) By-products revenue

$$C_{10,0} = M_{CaSO_4} \times c_{CaSO_4},$$

(13)
in which, $M_{CaSO_4} = S_o \times M_{F,0} \times H_e/H_i \times W \times H \times \eta_{SO_2,0} \times 172/32/P_{CaSO_4}$. $P_{CaSO_4}$ is the purity of gypsum (90% [14], viz. 10% water content), and $c_{CaSO_4}$ is the market price of gypsum (50 ¥/t). It should be mentioned that it is only the revenue for gypsum (by-product from desulfurization) that was considered for conventional plants in this paper.

(ii) Cost calculation for oxy-combustion power plants.

We can calculate the $C_T$ in oxy-combustion plants similarly to that of the conventional plants, and the differences lie in the boiler retrofit, ASU and CPU additions. Also, the DE-

SO$_x$ and De-NO$_x$ devices can be simplified significantly in the oxy-combustion plants. Because of the N$_2$-lean combustion environment and flue gas recycle, a lower cost De-SO$_x$ technology (such as limestone injection into the furnace and the activation of unreacted calcium, LIFAC) could be adopted to reach a satisfactory De-SO$_x$ result. In addition, SO$_x$ in the flue gas can also be removed in the CPU, thus a total 95% De-SO$_x$ efficiency was used in this paper. On the other hand, because of the N$_2$-lean environment, it can be considered that there is only fuel NO$_x$ generated (viz. $m_{n,1} \equiv 100\%$) and at the same time, the flue gas recycle, low air excess factor (tiny positive pressure combustion, air excess factor $\alpha_1 \equiv 1.05$) and adopting low NO$_x$ air staging burners can effectively suppress the fuel NO$_x$ generation (considering the fuel N transforming efficiency $\eta_{n,1} \equiv 15\%$). Also, NO$_x$ in the flue gas can be co-removed in the CPU (assuming the De-NO$_x$ efficiency $\eta_{SO_x,1} \equiv 30\%$), so an additional SCR is not needed. In general, costs for the oxy-combustion plants can be calculated as follows:

(1) Because the flue gas recycle can effectively reduce the heat loss from the flue gas, the efficiency increase ratio $\eta_r = \eta_p/(\eta_p + 0.02)$ is applicable, and this reduces coal consumption. The unit standard coal consumption rate in the oxy-combustion plant is $m_{n,1} = m_{n,0} \times \eta_r$, and its fuel cost $C_{1,1} = C_{1,0} \times \eta_r$. The boiler efficiencies ($\eta_p$) for the three kinds of plant are set to be 92%, 94% and 95%, respectively.

(2) The total investment cost ($C_{IT,1}$) for oxy-combustion plants can be calculated as

$$C_{IT,1} = C_{IT,base,0} + C_{L,bioler,0} \times 7% + C_{IT-S,0}/3 + C_{ASU}$$

$$+ C_{IT,CPU,0} \times 2.5%,$$

(14)
in which, the second item on the right side of the equation is the boiler retrofit cost, which can be estimated to be 7% [12] of the boiler cost ($C_{L,bioler,0}$), and the $C_{bioler,0}$ for the three sizes of boilers are 652.75, 1299.9 and 2800 ¥ [11], respectively; the third item on the right side is the cost of the LIFAC De-SO$_x$ device, which is assumed to be 1/3 of that of the FGD; while the fourth item is the cost of the ASU. According to the investigation data from some oxygen production companies (such as Hangzhou Oxygen Production and the Sichuan Air Separation), the investment cost of large-scale oxygen production machines (60000 N m$^3$/h) satisfying the oxygen concentration demand of oxy-combustion technology is 120 M¥, and the actual oxygen consumption rate (N m$^3$/h) for oxy-combustion is $V_{O,1} = V_0 \times \alpha_1 \times m_{n,1} \times W \times H_e/H_i$. Therefore, the $C_{ASU} = V_{O,1}/60000 \times 120$ M¥; and the fifth item on the right side is the cost of the CPU, which is about 2.5% of the total investment cost of the whole base power plant [13]. Similar to that of the base plant, and the loan interest cost, depreciation cost and amortization cost can be calculated based on the $C_{IT,1}$.

(3) The O&M cost of the oxy-combustion plant includes the O&M cost of the base plant (excluding De-SO$_x$ device, ASU and CPU), the O&M cost of the De-SO$_x$ device, the O&M cost of ASU and the O&M cost of CPU, can be estimated as

$$C_{3,1} = (C_{IT,base,0} + C_{L,bioler,0} \times 7\%) \times p_{OM,base,1} + C_{OM-S,0}/3 + C_{ASU}$$

$$\times p_{OM,ASU} + C_{IT,CPU,0} \times 2.5\% \times p_{OM,CPU},$$

(15)
in which, $p_{OM,base,1}$ is the O&M coefficient of the oxy-combustion base plant (also 2.5%, including the major maintenance expense); the O&M cost of the De-SO$_x$ device (LIFAC) is set to be 1/3 of that of FGD; $p_{OM,ASU}$ is the O&M coefficient of ASU (1.5%) and the $p_{OM,CPU}$ is the O&M coefficient of CPU (1.5%).

(4) Each pollutant emission amount and corresponding emission tax can be estimated by using methods introduced for conventional power plants.

(5) The personnel wages for an oxy-combustion base plant (including LIFAC) are considered to be equivalent to
that of the conventional plant.

(6) The material cost ratio and other cost ratios in oxy-combustion plants are equivalent to that of conventional plants.

(7) There is no gypsum revenue in oxy-combustion plants, but the high purity CO₂ may be considered as a product. So in that case, the by-products revenue could be 

\[ C_{CO_2} = M_{CO_2} \times c_{CO_2}, \]

in which \( M_{CO_2} \) is the amount of CO₂ capture, \( c_{CO_2} \) is the unit price of CO₂ product.

1.3 Cost of electricity

The cost of electricity (\( c_{COE} \)) for coal-fired power plants can be calculated as

\[ c_{COE} = C_T \left( C_{net} \times H \right), \] (16)

in which, \( W_{net} \) is the net power output. For conventional power plants, \( W_{net} = W \times (1 - r_{pe,0}) - W_{ASU} \), \( r_{pe,0} \) is the auxiliary power ratio (5.5%, 5.2% and 4.5% [11] for the three sizes of plant, respectively), \( W_{ASU} \) is the power consumption of the De-SO₂ device (1.5%, 1.1% and 0.7% [11] of the total load, respectively). \( W_{S0} \) is the power consumption of the De-NOx device (1.3, 1.6 and 2.0 MW [15,16], respectively). For oxy-combustion power plants, \( W_{net} = W \times (1 - r_{pe,1}) - W_{ASU} \) - \( W_{CPU} \). \( r_{pe,1} \) is equivalent to \( r_{pe,0} \), the power consumption of the De-SO₂ device is \( W_{S0} = W_{S0}/3 \), the power consumption of ASU is \( W_{ASU} = V_{O_2}/60000 \times 21 \) MW (the power consumption of the 60000 Nm³/h ASU is 21 MW) and the power consumption of CPU, \( W_{CPU} \), is estimated to be 8% [13] of the gross power output.

The \( c_{COE} \) values of the conventional (four cases: without De-SO₂ or De-NOx device; with De-SO₂ device; with De-NOx device; with De-SO₂ and De-NOx devices) and oxy-combustion plants (two cases: with LIFAC and without De-SO₂ device, the CO₂ tax and the CO₂ sale price are not considered) under the three different loads are listed in Table 2. Figure 2 gives a comparison of the \( c_{COE} \) in different cases.

The results in Table 2 and Figure 2 show that (the descriptions in the following paragraph all correspond to the 2 × 300 MW subcritical, 2 × 600 MW supercritical and 2 × 1000 MW ultra-supercritical plants sequentially):

(1) The \( c_{COE} \) ranges for conventional power plants are 311.04–358.72, 310.57–324.50 and 280.19–290.12 ¥/MW h, respectively. The \( c_{COE} \) increases 5.18%, 4.49% and 3.54% if the De-SO₂ and De-NOx devices are added. In comparison to the conventional power plants with De-SO₂ and De-NOx devices, the \( c_{COE} \) of oxy-combustion plants (with LIFAC) increase 39.4%, 38.39% and 36.74%, respectively. The investor’s profit-sharing and income tax were not considered during the \( c_{COE} \) calculation. This part of the cost accounts

| Table 2 | Techno-economic analysis results for different plants under three loads |
|--------|---------------------------------------------------------------|
| Plant | \( c_{COE} \) (¥/MW h) | \( C_T \) (MW) | \( C_T \) (MW/y) | \( W_{net} \) (MW) | \( SO_2 \) capture/ emission (t/y) | \( NO_x \) capture/ emission (t/y) | \( CO_2 \) capture/ emission (t/y) |
| 2×300 MW subcritical | | | | | | | |
| Conventional (no FGD or SCR) | 310.57 | 4140 | 1776.53 | 1137.6 | 0/15867.51 | 0/11099.18 | 0/5117040.59 |
| Conventional (FGD, no SCR) | 316.38 | 4641.81 | 1778.70 | 1124.4 | 15074.13/793.38 | 0/11099.18 | 0/5117040.59 |
| Conventional (SCR, no FGD) | 318.59 | 4545 | 1809.59 | 1136 | 0/15867.51 | 8879.35/2219.84 | 0/5117040.59 |
| Conventional (FGD and SCR) | 320.50 | 4776.81 | 1821.76 | 1122.8 | 15074.13/793.38 | 8879.35/2219.84 | 0/5117040.59 |
| Oxy-combustion (no LIFAC) | 445.86 | 5811.70 | 1853.69 | 831.52 | 6347.00/9520.50 | 4120.70/1213.04 | 4509392.02/501043.56 |
| Oxy-combustion (with LIFAC) | 450.04 | 4337.56 | 1013.56 | 405.39 | 7940.39/417.92 | 4777.25/1169.31 | 4509392.02/501043.56 |
| 2×600 MW supercritical | | | | | | | |
| Conventional (no FGD or SCR) | 310.57 | 4410 | 1766.53 | 1137.6 | 0/15867.51 | 0/11099.18 | 0/5117040.59 |
| Conventional (FGD, no SCR) | 316.38 | 4641.81 | 1778.70 | 1124.4 | 15074.13/793.38 | 0/11099.18 | 0/5117040.59 |
| Conventional (SCR, no FGD) | 318.59 | 4545 | 1809.59 | 1136 | 0/15867.51 | 8879.35/2219.84 | 0/5117040.59 |
| Conventional (FGD and SCR) | 320.50 | 4776.81 | 1821.76 | 1122.8 | 15074.13/793.38 | 8879.35/2219.84 | 0/5117040.59 |
| Oxy-combustion (no LIFAC) | 445.86 | 5811.70 | 1853.69 | 831.52 | 6347.00/9520.50 | 4120.70/1213.04 | 4509392.02/501043.56 |
| Oxy-combustion (with LIFAC) | 450.04 | 4337.56 | 1013.56 | 405.39 | 7940.39/417.92 | 4777.25/1169.31 | 4509392.02/501043.56 |
| 2×1000 MW ultra-supercritical | | | | | | | |
| Conventional (no FGD or SCR) | 280.19 | 7185 | 2675.81 | 1910 | 0/24323.10 | 0/17013.80 | 0/7843847.06 |
| Conventional (FGD, no SCR) | 283.20 | 7429.09 | 2684.76 | 1896 | 23106.95/1216.16 | 0/17013.80 | 0/7843847.06 |
| Conventional (SCR, no FGD) | 287.05 | 7357 | 2738.49 | 1908 | 0/24323.10 | 13611.04/3402.76 | 0/7843847.06 |
| Conventional (FGD and SCR) | 290.12 | 7604.09 | 2747.44 | 1894 | 23106.95/1216.16 | 13611.04/3402.76 | 0/7843847.06 |
| Oxy-combustion (no LIFAC) | 394.37 | 9398.12 | 2815.60 | 1427.90 | 9729.24/14593.86 | 21777.77/1266.65 | 6913906.42/768211.82 |
| Oxy-combustion (with LIFAC) | 395.93 | 9480.48 | 2817.50 | 1423.23 | 23106.95/1216.16 | 21777.77/1266.65 | 6913906.42/768211.82 |
for about 12%–14% [11] of the total $c_{\text{COE}}$. If these effects are considered, the $c_{\text{COE}}$ of conventional power plants are approximately the same according to the results presented in [11], which indicates that the techno-economic analysis performed in this paper is in reasonable agreement.

(2) The static investment cost increases by 8.7%, 8.32% and 5.88% if the De-SO$_x$ and De-NO$_x$ devices are added in the conventional power plants; in comparison to the conventional power plants with De-SO$_x$ and De-NO$_x$ devices, the static investment costs for oxy-combustion plants (with LIFAC) increase by 19.45%, 23.28% and 24.68%, respectively. From the subcritical to the supercritical and finally the ultra-supercritical, the material upgrade and some special imported parts make the boiler cost increase rapidly.

(3) Even if the De-SO$_x$ and De-NO$_x$ devices are not included in the oxy-combustion power plants, a low SO$_x$ and NO$_x$ emission level can still be achieved. However, if the LIFAC system is installed, the static investment costs of the oxy-combustion plants increase by only about 1%, the annualized total costs remain nearly unchanged, power outputs decrease about 0.5% and $c_{\text{COE}}$ increases no more than 1%, and a De-SO$_x$ efficiency similar to the FGD technology can be realized.

(4) The static investment costs for oxy-combustion plants increase mainly because of the high commercial price of ASU, and the investment in the CPU system. Further developments to the oxygen production technology and increasing the scale of the ASU market should decrease the costs of ASU systems significantly, and then the economic characteristics of the oxy-combustion technology will improve significantly.

(5) In comparison to the conventional power plants with De-SO$_x$ and De-NO$_x$ devices, the annualized total costs for oxy-combustion plants (with LIFAC) increase by 1.51%, 1.95% and 2.55%, respectively. The increases are slight because the De-SO$_x$ and De-NO$_x$ devices with high O&M costs are removed and coal consumption decreases because of the enhanced boiler efficiency in oxy-combustion plants. However, the net power outputs for oxy-combustion plants decrease substantially in comparison to conventional plants because of the high power consumptions of ASU and CPU systems, which also increase the $c_{\text{COE}}$ of oxy-combustion plants substantially. Therefore, developing low cost and low power consumption ASU and CPU systems is the key to enhance the economic characteristics of the oxy-combustion technology. The components and corresponding proportions of annualized total costs for three different load plants under conventional combustion and oxy-combustion are shown in Figure 3. The results show that fuel costs, the depreciation and amortization costs affect the distributions of the annualized total costs remarkably. Because the unit investment costs of base plants reduce sequentially from the subcritical plants to the supercritical plants and finally the ultra-supercritical plants, although the unit coal consumptions also reduce sequentially, the ratios of fuel costs increase sequentially, and are 64%, 67% and 68%, respectively. Because the ASU and CPU systems are added in oxy-combustion plants, the ratios of investment costs and O&M costs increase, accordingly, but the ratios of fuel costs reduce 2%–3%. Also, it is worth emphasizing, the ratios of De-SO$_x$ and De-NO$_x$ costs in oxy-combustion plants decrease greatly, and become almost negligible.

1.4 CO$_2$ avoidance cost

Oxy-combustion technology has been considered to control the CO$_2$ emission from fossil fuel combustion, and this is the reason why so much attention has been paid to it. The CO$_2$ avoidance cost ($c_{\text{CAC}}$) can be used to evaluate the economic property of controlling the CO$_2$ emission. $c_{\text{CAC}}$ is defined as the ratio of the $c_{\text{COE}}$ difference to the unit CO$_2$ emission difference between the CO$_2$ emission control system (oxy-combustion plant with LIFAC in this paper) and the corresponding CO$_2$ emission non-control system (conventional plant with De-SO$_x$ and De-NO$_x$ devices in this paper). It means the additional economic cost of avoiding one ton CO$_2$ emission, which can be described as

\[
c_{\text{CAC}} = \frac{c_{\text{COE},1} - c_{\text{COE},0}}{W_{\text{act},1} - W_{\text{act},0}} = \frac{c_{\text{COE},1} - c_{\text{COE},0}}{E_{\text{CO}_2,0} - E_{\text{CO}_2,1}} = \frac{E_{\text{CO}_2,0} - E_{\text{CO}_2,1}}{W_{\text{act},1}H - W_{\text{act},0}H},
\]

in which, $E_{\text{CO}_2}$ is the CO$_2$ emission amount per unit of power (t/MWh). The $c_{\text{CAC}}$ of oxy-combustion plants (with LIFAC) for three different loads are given in Table 3.

Large amounts of CO$_2$ emission can be reduced in oxy-combustion plants, producing an environmental benefit. Some countries have already begun to tax the CO$_2$ emission.
Figure 3  Structure diagrams of annualized total costs for three different load plants under conventional combustion and oxy-combustion.

Table 3  $c_{CAC}$ and $c_{CCC}$ for oxy-combustion plants

| Item | 2×300 MW | 2×600 MW | 2×1000 MW |
|------|----------|----------|----------|
| $c_{COE,1}(¥/(MW h))$ | 500.04 | 449.09 | 395.93 |
| $c_{COE,0}(¥/(MW h))$ | 358.72 | 324.50 | 290.12 |
| $c_{CO2,1}(t/(MW h))$ | 0.13 | 0.12 | 0.11 |
| $c_{CO2,0}(t/(MW h))$ | 0 | 0 | 0 |
| $m_{CO2,0}(t/(MWh))$ | 1.17 | 1.09 | 0.97 |
| $c_{CAC}(¥/t)$ | 168.61 | 157.64 | 146.89 |
| $c_{CCC}(¥/t)$ | 120.65 | 114.26 | 108.90 |

from conventional power plants. The CO₂ tax has a significant influence on the economic performance of conventional and oxy-combustion plants, and the cost of electricity ($c'_{COE}$) and CO₂ avoidance cost ($c'_{CAC}$) when considering the CO₂ tax is

\[
c'_{COE} = c_{COE} + T_{CO2} c_{COE} = c_{COE} + \frac{E_{CO2} T_{CO2}}{W_{net} H},
\]

(18)

\[
c'_{CAC} = c'_{COE,1} - c'_{COE,0} = c_{CAC} - T_{CO2}.
\]

(19)
Figure 4 shows the effect of the unit CO$_2$ emission tax ($T_{\text{CO}_2}$) on the $c_{\text{COE}}$ of conventional and oxy-combustion plants and the results show that the oxy-combustion technology could be competitive with the conventional mode if the CO$_2$ emission is taxed at 140–170 ¥/t. When the $T_{\text{CO}_2}$ equals the $c_{\text{CAC}}$ without CO$_2$ emission taxation, the $c_{\text{COE}}$ of the oxy-combustion plant is equivalent to that of the corresponding conventional plant. The $c_{\text{CAC}}$ calculation relates to the CO$_2$ emission reduction (the emission difference between the two plants), and the total tax cost difference of the two plants is also related to the CO$_2$ emission reduction. This makes the $T_{\text{CO}_2}$ value when the oxy-combustion plant and the corresponding conventional plant have equivalent economic property (named as critical $T_{\text{CO}_2}$) is equal to the $c_{\text{CAC}}$ without CO$_2$ emission taxation (see equation (19) and Figure 4).

1.5 CO$_2$ capture cost

Another parameter required to evaluate the economic property of the oxy-combustion technology is the CO$_2$ capture cost ($c_{\text{CCC}}$). $c_{\text{CCC}}$ is defined as the ratio of the $c_{\text{COE}}$ difference to the unit CO$_2$ capture amounts difference between the CO$_2$ emission control system and the corresponding CO$_2$ emission non-control system. It means the additional economic cost of capturing one ton CO$_2$ can be described as

$$c_{\text{CCC}} = \frac{c_{\text{COE},1} - c_{\text{COE},0}}{m_{\text{CO}_2,1} - m_{\text{CO}_2,0}} = \frac{c_{\text{COE},1} - c_{\text{COE},0}}{M_{\text{CO}_2} r_{\text{CO}_2}} \frac{1}{W_{\text{net}} H},$$

in which, $m_{\text{CO}_2}$ is the CO$_2$ capture amount per unit of power (t/(MW h)), $r_{\text{CO}_2}$ is the CO$_2$ capture efficiency. The $c_{\text{CCC}}$ of oxy-combustion plants (with LIFAC) for three different loads are also given in Table 3.

The high purity CO$_2$ captured from oxy-combustion plants can be used in enhancing oil recovery (EOR), carbon fertilizer and beverage production. Therefore, if the CO$_2$ sale is considered, the $c_{\text{COE}}$ of oxy-combustion plants may be further reduced and the CO$_2$ capture cost will change. The cost of electricity ($c_{\text{COE}}^*$) and the CO$_2$ capture cost ($c_{\text{CCC}}^*$) when considering the CO$_2$ sale are

$$c_{\text{COE}}^* = c_{\text{COE}} + \frac{C_T}{W_{\text{net}}} = \left( C_T - M_{\text{CO}_2} c_{\text{CO}_2} \right) / W_{\text{net}} H$$

$$c_{\text{CCC}}^* = \frac{c_{\text{COE},1} - c_{\text{COE},0}}{m_{\text{CO}_2,1}} = c_{\text{CCC}} - c_{\text{CO}_2}^*.$$ (21)

The CO$_2$ capture cost is related to the CO$_2$ capture amount, and the CO$_2$ sale revenue equals the CO$_2$ capture amount multiplied by the unit CO$_2$ sale price ($c_{\text{CO}_2}$). From eq. (22), we can see that the critical $c_{\text{CCC}}$ equals the $c_{\text{CCC}}$ without a CO$_2$ sale. Figure 5 shows the effect of the $c_{\text{CO}_2}$ on the $c_{\text{COE}}$ of conventional and oxy-combustion plants. Obviously, the economic characteristics of the oxy-combustion technology will enhance significantly if there are organizations who will purchase the high purity CO$_2$ product. The critical $c_{\text{CO}_2}$ (viz. $c_{\text{CCC}}$) that makes the $c_{\text{COE}}$ of oxy-combustion plants equivalent to those of conventional plants is 110–120 ¥/t.

It is worth noting that the relative CO$_2$ emission amounts ($e_{\text{CO}_2,0}$–$e_{\text{CO}_2,1}$) and relative CO$_2$ capture amounts ($m_{\text{CO}_2,0}$–$m_{\text{CO}_2,1}$) are not equivalent when the oxy-combustion plants are compared with conventional plants. This is because the thermal efficiencies of the oxy-combustion plant increase, and there is increased CO$_2$ emitted from oxy-combustion plants. The non-equivalence between the relative CO$_2$ emission amount and relative CO$_2$ capture amount (the relative CO$_2$ emission amount is generally less than the relative CO$_2$ capture amount) leads to non-equivalence between the critical $T_{\text{CO}_2}$ and the critical $c_{\text{CO}_2}$, and the critical $T_{\text{CO}_2}$ is generally greater than the critical $c_{\text{CO}_2}$.
1.6 CO₂ tax and CO₂ sale

The economic characteristics of the oxy-combustion technology were evaluated when the CO₂ tax and the CO₂ sale were considered together. Both the CO₂ tax and the CO₂ sale price significantly affect the $c_{COE}$, $c_{CAC}$ and $c_{CCC}$ of oxy-combustion plants. If they are considered together, the cost of electricity ($c_{COE}$), CO₂ avoidance cost ($c_{CAC}$) and CO₂ capture cost ($c_{CCC}$) are given by

$$c_{COE} = \frac{C_T + E_{CO,1}T_{CO,1} - M_{CO,1}E_{CO,1}}{W_{net,1}}$$

$$c_{CAC} = \frac{E_{CO,0,T_{CO,0}}}{W_{net,0}} - \frac{E_{CO,1,T_{CO,1}}}{W_{net,1}}$$

$$c_{CCC} = \frac{E_{CO,2,T_{CO,2}}}{W_{net,2}} - \frac{E_{CO,3,T_{CO,3}}}{W_{net,3}}$$

in which the critical coefficient $\beta = W_{net,0}/(W_{net,0} + \eta_{L,1} - (1 - \eta_{L,1})/\eta_{L,1})$, is actually the ratio of the critical $c_{COE}$ to the critical $T_{COE}$. Usually, $\beta < 1$.

The critical lines where the $c_{COE}$ of oxy-combustion plants equal those of conventional plants for three different loads are shown in Figure 6. Points on a line correspond to critical $c_{COE}$ and critical $T_{COE}$ values for a particular case. Above the line, the economic characteristics of oxy-combustion plants are better, whereas below the line, the economic characteristics of conventional plants are better. For example, for the critical line of the 2 × 300 MW subcritical case, the point A is above the line and it corresponds to 60 ¥/t $T_{CO2}$ and 80 ¥/t $c_{COE}$. In this case, the $c_{COE}$ of the oxy-combustion plant is smaller and its economic characteristic is better; on the other hand, the point B is below the line and it corresponds to 80 ¥/t $T_{CO2}$ and 60 ¥/t $c_{COE}$. In this case, the $c_{COE}$ of the oxy-combustion plant is greater and its economic characteristic is worse. This result also reveals the difference between the $c_{CO2}$ and $T_{CO2}$.

2 Sensitivity analysis

2.1 Effects of parameters

A sensitivity analysis of some important parameters in the oxy-combustion plant, such as coal price, ASU cost, ASU power consumption and CO₂ capture efficiency, was performed under the 2 × 300 MW subcritical plant model, and the results are shown in Figure 7. This shows that $c_{COE}$ is most correlated with $c_{ASU}$ and that is because fuel costs contribute 62%–65% of $c_{COE}$ of oxy-combustion plants. The following parameters are $\alpha$ and $W_{ASU}$, because the net power outputs of oxy-combustion plants decrease significantly because of the ASUs (power consumptions are 16%–18.5% of total loads), and the $\alpha$ directly relates to the oxygen demand and the ASU power consumption. The influences of ASU cost, CPU power consumption, interest rate, loan percentage on the $c_{COE}$ are also obvious, but the influence of CPU cost on the $c_{COE}$ is slight, because its cost amounts to only about 2% of the static investment cost of the oxy-combustion plants. For $c_{CAC}$ and $c_{CCC}$, the nine parameters considered have similar influences on them; and $r_{CO2}$ influences them most because it directly affects unit CO₂ capture amounts and unit CO₂ emission amounts in oxy-combustion plants. The other important parameters are $\alpha$ and $W_{ASU}$. The influences of coal price, ASU cost, CPU power consumption, interest rate, loan percentage on them are also obvious. Similarly, the influences of CPU cost on them are slight. In
In general, the influences of the parameters on these three costs are similar. The results show that the influences of $\alpha$ and $W_{ASU}$ on the $c_{COE}$ of the oxy-combustion plant are less than that of the coal price. But the influences of $\alpha$ and $W_{ASU}$ on the $c_{CAC}$ and $c_{CCC}$ are greater than that of the coal price because ASU consumes much power and the influences of coal price on $c_{COE}$ of conventional plants and oxy-combustion plants are similar. In addition, the influences of $SO_x$ and $NO_x$ emission taxes, S and N contents of coal on the three costs were also analyzed in the paper. The results show that the influences are slight, so they are not shown in Figure 7.

2.2 Effects of coal samples

To analyse the influence of different coal samples on the economic characteristics of the oxy-combustion technology, three different coal samples were further chosen to conduct a similar calculation process. The ultimate analysis results and lower heating values of these coal samples are all listed in Table 4.

Considering the $2 \times 300$ MW subcritical plant for example, the $c_{COE}$, $c_{CAC}$ and $c_{CCC}$ results corresponding to the four coal samples are listed in Table 5. The results show that the influence of different coal samples on the economic characteristics of the oxy-combustion technology is not obvious, and the results obtained in this paper are universally significant.

3 Conclusion

In this paper, a techno-economic evaluation of $2 \times 300$ MW subcritical, $2 \times 600$ MW supercritical and $2 \times 1000$ MW ultra-supercritical oxy-combustion coal-fired power plants was performed. The results indicate that the electricity cost of a $2 \times 300$ MW oxy-combustion plant (with LIFAC desulphurization device) is $500.04 \, ¥/(MW \cdot h)$ ($449.09 \, ¥/(MW \cdot h)$, $395.93 \, ¥/(MW \cdot h)$, are the equivalent values for the $2 \times 600$ MW and $2 \times 1000$ MW plants), which is 1.39 (similarly 1.38, 1.36) times that of the corresponding conventional plant (equipped with the limestone-gypsum desulfurization system and SCR denitration system); its static investment cost is 1.19 (1.23, 1.25) times that of the corresponding conventional plant; its net power output is 0.73 (0.74, 0.75) times that of the corresponding conventional plant. The increase in the static investment cost is mainly because of the high commercial price of ASU, and the significant decrease of the net power output is mainly because of the high power consumption of the ASU and CPU systems. However, without considering the power consumption of the ASU and the CPU, the annualized costs of oxy-combustion plants increase slightly in comparison to conventional plants. This is because the desulfurization and denitration devices with low efficiency and high consumption increase the costs of oxy-combustion plants.

Table 4 Ultimate analysis results and lower heating values of three other coal samples

| Coal sample | $M$ (%) | $A$ (%) | $C$ (%) | $H$ (%) | $O$ (%) | N (%) | S (%) | $H_i$ (kJ/kg) |
|-------------|---------|---------|---------|---------|---------|-------|-------|---------------|
| Huangshi    | 6       | 26.18   | 59.21   | 2.56    | 2.12    | 0.82  | 3.11  | 22310         |
| Datong      | 9.1     | 21.94   | 55.78   | 3.34    | 8.11    | 1.14  | 0.59  | 21326         |
| Huangling   | 7.27    | 26.48   | 53.06   | 2.88    | 8.79    | 0.81  | 0.71  | 20890         |
Table 5  
$c_{COE}$, $c_{CAC}$ and $c_{CCC}$ results corresponding to the four coal samples

| Coal sample  | $c_{COE}$ (¥ (MW h)$^{-1}$) | $c_{CAC}$ (¥/t) | $c_{CCC}$ (¥/t) |
|-------------|-----------------------------|-----------------|-----------------|
| Conventional (FGD, SCR) |                         |                 |                 |
| Shenhua      | 358.72                      | 500.04          | 168.61          |
| Huangshi     | 360.07                      | 504.84          | 173.04          |
| Datong       | 359.01                      | 499.15          | 169.83          |
| Huangling    | 358.95                      | 491.39          | 164.94          |
| Oxy-combustion (LIFAC) |                         |                 |                 |

high O&M costs are avoided and the coal consumption amount may be reduced.

If the CO$_2$ tax and CO$_2$ sale price are considered, the economic property of the oxy-combustion technology could be competitive with the conventional combustion technology. For the oxy-combustion plants, the CO$_2$ avoidance cost (viz. critical unit CO$_2$ emission tax) is 168.61 ¥/t (157.64 ¥/t, 146.89 ¥/t), and the CO$_2$ capture cost (viz. critical CO$_2$ sale price) is 120.65 ¥/t (114.26 ¥/t, 108.90 ¥/t).

The comparison of economic performance of the three plants with different loads shows that from the subcritical system to the supercritical system and finally the ultra-supercritical system, the economic characteristics increase significantly because of the decrease in the unit investment cost and the increase in the systems thermal efficiency. Sensitivity analysis shows that coal price, air excess factor, ASU power consumption and CO$_2$ capture efficiency are the four parameters that most influence the economic performance of the oxy-combustion technology. The influence of the coal sample on the economic performance of the oxy-combustion technology is not obvious.

Nomenclature

Abbreviations

| Abbreviation | Description                        |
|--------------|-----------------------------------|
| ASU          | Air separation unit               |
| CAC          | CO$_2$ avoidance cost             |
| CCC          | CO$_2$ capture cost               |
| COE          | Cost of electricity               |
| CPU          | Flue gas clean and purification unit |
| FGD          | Wet flue gas desulfurization      |
| IT           | Total investment cost             |
| OM           | Operation and maintenance cost    |
| SCR          | Selective catalytic reduction     |

Scalars

| Scalar | Description                               |
|--------|------------------------------------------|
| $C, c$ | Cost and unit cost                       |
| $E, e$ | Emission and unit emission amount        |
| $H$    | Annual operation hours                   |
| $H_l$  | Lower heating value of raw coal          |

Greek letters

| Letter | Description |
|--------|-------------|
| $\alpha$ | Air excess factor |
| $\beta$  | Critical coefficient |
| $\eta$   | Efficiency |
| $\xi$    | Average interest rate |

Subscripts

| Subscript | Description|
|-----------|------------|
| 0         | Base (conventional) plant |
| 1         | Oxy-combustion plant    |
| ar        | As-received basis       |
| b         | Boiler                  |
| ef        | Effluent                |
This work was supported by the National Basic Research Program of China (2011CB707300), National Natural Science Foundation of China (50936001 and 50721005) and New Century Excellent Talents in University of China (NECT-10-0395).

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