Article
Chinese Science Bulletin

Engineering Thermophysics

November 2011 Vol.56 No.31: 3333–3345
doi: 10.1007/s11434-011-4707-5

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

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Received December 14, 2010; accepted July 28, 2011

Increasing attention is being paid to the oxy-combustion technique of coal-fired power plants because CO_2 produced from fossil fuel combustion can be captured and sequestrated 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, CO_2 avoidance costs as well as CO_2 capture costs, were calculated. Moreover, the effects of CO_2 tax and CO_2 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, CO_2 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 CO_2 emission is taxed and the high purity CO_2 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, CO_2 emission control, techno-economics, sensitivity analysis, CO_2 tax, CO_2 sale, cost of electricity

Citation: Xiong J, Zhao H B, Zheng C G. Techno-economic evaluation of oxy-combustion coal-fired power plants. Chinese Sci Bull, 2011, 56: 3333–3345, doi: 10.1007/s11434-011-4707-5

As a branch of practical economics, techno-economics is widely used to research the economic benefits of technology application activities, achieve the best combination of technology and economy, seek ways to enhance economy benefit, and provide a decision basis for investment decision makers. Because coal-fired power plants are technology-intensive and capital-intensive processes, a techno-economic evaluation is particularly important. Many techno-economic evaluation studies have been conducted on the desulfurization (De-SO_x) and denitration (De-NO_x) processes in conventional coal-fired power plants. CO_2 emission control has become a global issue [1], and actions to minimize emissions are a priority [2]. At present, CO_2 capture and sequestration from power plants is a feasible and effective choice. And as CO_2 emission control technologies, such as oxy-combustion technology, integrated gasification combined cycle (IGCC) technology, monoethanolamine (MEA) and MEA/MDEA (activated methyldiethanolamine) scrubbing technology, have reached the commercialization phase, greater attention has been paid to the economic costs of these new technologies. Techno-economic analysis of the emission control technologies is one of the key problems that must be solved. Oxy-combustion is a new technology that adds a cryogenic air separation process (ASU) and a flue gas clean and purification process (CPU) to a conventional combustion process. High purity oxygen product

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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 CO_2 concentration in the oxy-combustion flue gas is high, and a high purity CO_2 product (95%–99%) can be obtained through purification, compression and separation. Moreover, efficient De-SO_x and De-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% CO_2 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 CO_2 avoidance cost is $26/t and the cost of electricity is $64.3/kW; the results of ALSTOM [5] show that the CO_2 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 CO_2 avoidance cost is $34/t; the results of CANMET [7] show that the CO_2 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 CO_2 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 CO_2 avoidance cost is about $30/t and about 85% CO_2 can be captured. However, the techno-economic characteristics of CO_2 emission control systems are complicated. They depend on the energy efficiency of the system, technology maturity level, pollutants (including SO_x, NO_x, PM10 and CO_2) 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 CO_2 emission control systems based on Chinese conditions and data, for energy and power systems, by comparing various electricity costs, CO_2 avoidance costs and CO_2 capture costs for these CO_2 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

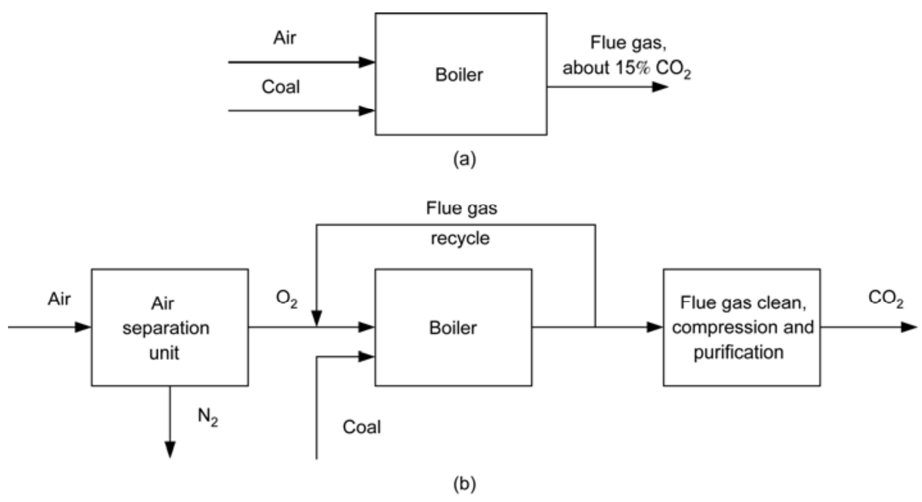

Figure 1 Schematic diagrams of the oxy-combustion technology and the conventional combustion technology. (a) Conventional combustion; (b) Oxy-combustion.

cost, personnel wages and other expenses) were ignored in the previous models. Cost models for De-SO_x 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_x and De-NO_x devices, was considered. Moreover, three typical coal-fired power plants (2 × 300 MW subcritical, 2 × 600 MW supercritical and 2 × 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_x 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_2)). Because the management expense and financial expense involve complicated financial accounting theory and industry rules, only some "hard" costs (annualized cost C_T) were considered in this paper, which can be described as

$$C_T = \sum_{i=1}^{9} C_i - C_{10} . \tag{1}$$

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

(1) Fuel cost

$$C_{1,0} = m_{F,0} \times c_F \times W \times H, \tag{2}$$

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], ¥ 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_O) for combustion can be calculated to be 1.27Nm^3/kg coal on the basis of values in Table 1 and eq. (3).

$$v_O = \left(C_{ar}/12 + H_{ar}/4 + S_{ar}/32 - O_{ar}/32\right) \times 22.4 . \tag{3}$$

(2) Loan interest cost

$$C_{2,0} = C_{IT,0} \times p_{loan} \times \xi, \tag{4}$$

in which, $C_{IT,0}$ is the total investment cost of the conventional power plant and $C_{IT,0} = C_{IT,base,0} + C_{IT,S,0} + C_{IT,N,0}$. The $C_{IT,base,0}$ for the three kinds of power plant (excluding De-SO_x

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

M_{ar}(%)	A_{ar}(%)	C_{ar}(%)	H_{ar}(%)	O_{ar}(%)	N_{ar}(%)	S_{ar}(%)	H_i(kJ/kg)
13.8	11	60.51	3.62	9.94	0.7	0.43	22768

and De-NO_x devices) can be estimated by using 4412, 3675 and 3591 ¥/kW [11]. The device costs of the De-SO_x devices (considering the wet flue gas desulfurization (FGD) technology with a 95% desulfurization efficiency ($\eta_{S,0}$)) in the three plants are 111.43, 185.45, 247.09 M¥, respectively [11]. The device costs of the denitration devices (considering the selective catalytic reduction (SCR) denitration technology with a 80% denitration efficiency ($\eta_{N,0}$)) in the three plants are 72.99, 108 and 140 M¥, respectively [11]. In addition, the costs of De-SO_x and De-NO_x devices are set to be 80% of their investment costs ($C_{IT,S,0}$ and $C_{IT,N,0}$) [14,15] and other costs, such as construction, installation and technical service, account for the remaining 20%; p_{loan} is the loan percentage (80% [11]), and the "average capital method" was chosen to payback the load, the average interest rate can be calculated by $\xi = i\times(1+1/P)/2$, P is the loan period (15, 18 and 18 years, respectively [11]), i is the loan interest rate for a period longer than 5 years (5.94% [11]).

(3) Operation and maintenance cost

$$C_{3,0} = C_{IT,base,0} \times p_{OM,base,0} + C_{OM,S,0} + C_{OM,N,0}, \tag{5}$$

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-SO_x and De-NO_x devices); $C_{OM,S,0}$ is the O&M cost for the FGD device, including limestone expense ($C_{OMS0,1}$), process water expense ($C_{OMS0,2}$), effluent processing expense ($C_{OMS0,3}$) and equipment maintenance expense ($C_{OMS0,4}$). Personnel wages, depreciation cost, amortization cost and electricity consumption cost for the De-SO_x device and the following De-NO_x device are considered from the viewpoint of the whole power plant. Furthermore, $C_{OMS0,1} = c_{CaCO_3} \times S_{ar} \times M_{F,0} \times H_n/H_i \times W \times H \times 100/32 \times r_{Ca_2S}/P_{CaCO_3}$, in which, H_n is the lower heating value of the standard coal, 29270 kJ/kg, c_{CaCO_3} is the unit price of limestone (60 ¥/t [11]), r_{CaCO_3} is the mole ratio of Ca to S (1.03 [14]), P_{CaCO_3} is the purity of limestone (90% [14]); $C_{OMS0,2}=c_{pw}\times M_{pw,0}\times H$, where c_{pw} is the unit price of process water (1.54¥/t [14]), $M_{pw,0}$ is the process water consumption rate (10 t/h [14] for the 2×300 MW power plant); $C_{OMS0,3} = c_{ef}\times M_{ef,0}\times H$, where c_{ef} is the unit effluent processing cost (1.6 ¥/t [14]), $M_{ef,0}$ is the effluent discharge rate (120 t/h [14] for the 2×300 MW power plant); $C_{OMS0,4} = C_{IT,S,0}\times p_{OM,S,0}$, $p_{OM,S,0}$ is the O&M coefficient (1.5% [14], including the major maintenance expense) for the De-SO_x device. And for the 2×600 MW supercritical and 2×1000 MW ultra-supercritical power plants, the $C_{OMS0,2}$ and $C_{OMS0,3}$ are proportional to the limestone consumption rate in each power plant, respectively. $C_{OM,S,0}$ is the O&M cost for the SCR device, including ammonia expense, catalyst expense, steam expense and equipment maintenance expense [15,16]. Adjusted for the annual operation hours, the ammonia expense, catalyst expense and steam expense for the 2 × 300 MW power plant considered in this paper are 4.62, 13.34 and 0.11 M¥/y, respectively [16]. The corresponding data for the 2×600 MW power plant are 9.15, 26.43 and 0.22 M¥/y, respectively [15]. However, because 2 × 1000 MW ultra-supercritical power plants with SCR devices are very limited in China, data for this size of SCR device is very difficult to obtain. In this paper, the corresponding data for the 2×1000 MW power plant (14, 40.42 and 0.35 M¥/y, respectively) were proportional to those of the 2×600 MW power plant. The O&M coefficient of the SCR device used in this paper is 1.5%.

(4) Depreciation cost

$$C_{4,0} = C_{IT,0} \times p_{fa} \times (1-p_{lv})/Y_d, \tag{6}$$

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

(5) Amortization cost

$$C_{5,0} = C_{IT,0} \times p_{ia}/Y_a, \tag{7}$$

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

(6) Pollutants emission tax

$$C_{6,0} = E_{S,0} \times T_S + E_{N,0} \times T_N, \tag{8}$$

in which $E_{S,0}$ is the SO_2 emission amount in the conventional power plant, which can be estimated by referring to [18]. $E_{S,0}$ = 32/16 × $m_{F,0}$ × H_n/H_i × W × H × S_{ar} × $t_{S,0}$ × (1−$\eta_{S,0}$), where $t_{S,0}$ is the ratio of S_{ar} transformed to SO_2 after coal combustion (80% [18]); $E_{N,0}$ is the NO_x emission amount in the conventional power plant, $E_{N,0}$ = 30.8/14 × $m_{F,0}$ × W × H_n/H_i × H × N_{ar} × $\eta_{n,0}/m_{n,0}$ × (1−$\eta_{N,0}$), in which 30.8/14 is the ratio of NO_x (95 m% NO and 5 m% N_2O) molecular weight to that of N element [18], $\eta_{N,0}$ is the transforming rate (25% [18]) of fuel N, $m_{n,0}$ is the percentage of NO_x coming from fuel N to total NO_x (80% [18]), T_S and T_N are the unit pollutant emission tax (0.6 ¥/0.95 kg) for SO_2 and NO_x, 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 CO_2 is considered, then eq. (8) should be modified to be

$$C_{6,0} = E_{S,0} \times T_S + E_{N,0} \times T_N + E_{CO_2,0} \times T_{CO_2}, \tag{9}$$

in which, $E_{CO_2,0}$ is the CO_2 emission amount, $E_{CO2,0}$ = 44/12 × $m_{F,0}$ × H_n/H_i × W × H × C_{ar} × t_C × (1−$\eta_{C,0}$), and T_{CO_2} is the unit CO_2 emission tax (¥/t), t_C is the ratio of C_{ar} transformed to be CO_2 after coal combustion (usually 100%), $\eta_{C,0}$ is the CO_2 capture ratio (for conventional plants, $\eta_{C,0}$=0; and for oxy-combustion plants, $\eta_{C,1}$=90%).

(7) Personnel wages

$$C_{7,0} = \left(N_{\text{base},0} + N_{\text{S},0} + N_{\text{N},0}\right) \times c_{\text{pay}} \times \left(1 + r_{\text{w}}\right), \tag{10}$$

in which, $N_{\text{base},0}$, $N_{\text{S},0}$, $N_{\text{N},0}$ are personnel numbers for the base power plant, the FGD system and the SCR system, respectively. For the three kinds of plant, $N_{\text{base},0}$ is 234, 247 and 300 [11], respectively; $N_{\text{S},0}$ is 15, 18, 21 (three groups, and each of 5, 6 and 7 persons), respectively; $N_{\text{N},0}$ 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

$$C_{8,0} = p_{\text{m},0} \times W \times H, \tag{11}$$

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

(9) Other costs

$$C_{9,0} = p_{\text{o},0} \times W \times H, \tag{12}$$

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

(10) By-products revenue

$$C_{10,0} = M_{\text{CaSO}_4} \times c_{\text{CaSO}_4}, \tag{13}$$

in which, $M_{\text{CaSO}_4} = S_{\text{ar}} \times M_{\text{F},0} \times H_{\text{n}}/H_{\text{i}} \times W \times H \times \eta_{\text{S},0} \times 172/32/P_{\text{CaSO}_4}$, 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. $m_{\text{n},1}$ = 100%) and at the same time, the flue gas recycle, low air excess factor (tiny positive pressure combustion, air excess factor $\alpha_1 = 1.05$) and adopting low NO_x air staging burners can effectively suppress the fuel NO_x generation (considering the fuel N transforming efficiency $\eta_{\text{n},1}$ is 15%). Also, NO_x in the flue gas can be co-removed in the CPU (assuming the De-NO_x efficiency $\eta_{\text{N},1}$ = 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 $\eta_{\text{e}} = \eta_b/(\eta_b + 0.02)$ is applicable, and this reduces coal consumption. The unit standard coal consumption rate in the oxy-combustion plant is $m_{\text{F},1} = m_{\text{F},0} \times \eta_{\text{e}}$, and its fuel cost $C_{1,1} = C_{1,0} \times \eta_{\text{e}}$. The boiler efficiencies (η_b) for the three kinds of plant are set to be 92%, 94% and 95%, respectively.

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

$$C_{\text{IT},1} = C_{\text{IT,base},0} + C_{\text{I,bioler},0} \times 7\% + C_{\text{IT,S},0}/3 + C_{\text{ASU}} + C_{\text{IT,base},0} \times 2.5\%, \tag{14}$$

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 ($C_{\text{I,bioler},0}$), and the $C_{\text{I,bioler},0}$ for the three sizes of boilers are 652.75, 1299.9 and 2800 M¥ [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 $V_{\text{O},1} = v_{\text{O}} \times \alpha_1 \times m_{\text{F},1} \times W \times H_{\text{n}}/H_{\text{i}}$. Therefore, the $C_{\text{ASU}} = V_{\text{O},1}/60000 \times 120$ 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 $C_{\text{IT},1}$.

(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

$$C_{3,1} = \left(C_{\text{IT,base},0} + C_{\text{I,bioler},0} \times 7\%\right) \times p_{\text{OM,base},1} + C_{\text{OM,S},0}/3 + C_{\text{ASU}} \times p_{\text{OM,ASU}} + C_{\text{IT,base},0} \times 2.5\% \times p_{\text{OM,CPU}}, \tag{15}$$

in which, $p_{\text{OM,base},1}$ 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; $p_{\text{OM,ASU}}$ is the O&M coefficient of ASU (1.5%) and the $p_{\text{OM,CPU}}$ 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 CO_2 may be considered as a product. So in that case, the by-products revenue could be $C_{10,1}=M_{CO_2}\times c_{CO_2}$, in which CO_2 capture amount $M_{CO_2}=C_{ar}\times m_{F,1}\times H_n/H_i\times H\times W\times \eta_C\times 44/12$, and c_{CO_2} is the unit price of CO_2 product.

1.3 Cost of electricity

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

$$c_{COE}=C_T/\left(W_{net}\times H\right), \tag{16}$$

in which, W_{net} is the net power output. For conventional power plants, $W_{net,0}=W\times(1-r_{pe,0})-W_{S,0}-W_{N,0}$, $r_{pe,0}$ is the auxiliary power ratio (5.5%, 5.2% and 4.5% [11] for the three sizes of plant, respectively), $W_{S,0}$ is the power consumption of the De-SO_x device (1.5%, 1.1% and 0.7% [11] of the total load, respectively), $W_{N,0}$ is the power consumption of the De-NO_x device (1.3, 1.6 and 2.0 MW [15,16], respectively). For oxy-combustion power plants, $W_{net,1}=W\times(1-r_{pe,1})-W_{S,1}-W_{ASU}-W_{CPU}$, $r_{pe,1}$ is equivalent to $r_{pe,0}$, the power consumption of the De-SO_x device is $W_{S,1}=W_{S,0}/3$, the power consumption of ASU is $W_{ASU}=V_{O,1}/60000\times 21$ MW (the power consumption of the 60000 Nm^3/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-SO_x or De-NO_x device; with De-SO_x device; with De-NO_x device; with De-SO_x and De-NO_x devices) and oxy-combustion plants (two cases: with LIFAC and without De-SO_x device, the CO_2 tax and the CO_2 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 341.04–358.72, 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-SO_x and De-NO_x devices are added. In comparison to the conventional power plants with De-SO_x and De-NO_x devices, the c_{COE} of oxy-combustion plants (with LIFAC) increase 39.4%, 38.39% and 36.47%, 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_{IT} (M¥)	C_T (M¥/y)	W_{net} (MW)	SO_x 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)	341.04	2647.2	966.86	567	0/8358.3	0/5846.56	0/2695431.08
Conventional (FGD, no SCR)	349.36	2786.49	974.72	558	7940.39/417.92	0/5846.56	0/2695431.08
Conventional (SCR, no FGD)	350.23	2738.44	990.63	565.7	0/8358.3	4677.25/1169.31	0/2695431.08
Conventional (FGD and SCR)	358.72	2877.72	998.49	556.7	7940.39/417.92	4677.25/1169.31	0/2695431.08
Oxy-combustion (no LIFAC)	495.06	3391.13	1010.88	408.39	3343.32/5014.98	748.36/1122.54	2374273.33/263808.15
Oxy-combustion (with LIFAC)	500.04	3437.56	1013.56	405.39	7940.39/417.92	748.36/1122.54	2374273.33/263808.15
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)	324.50	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	1420.70/2131.04	4509392.02/501043.56
Oxy-combustion (with LIFAC)	449.09	5888.97	1857.26	827.12	15074.13/793.38	1420.70/2131.04	4509392.02/501043.56
2×1000 MW ultra-supercritical							
Conventional (no FGD or SCR)	280.19	7182	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	2177.77/3266.65	6913906.42/768211.82
Oxy-combustion (with LIFAC)	395.93	9480.48	2817.50	1423.23	23106.95/1216.16	2177.77/3266.65	6913906.42/768211.82

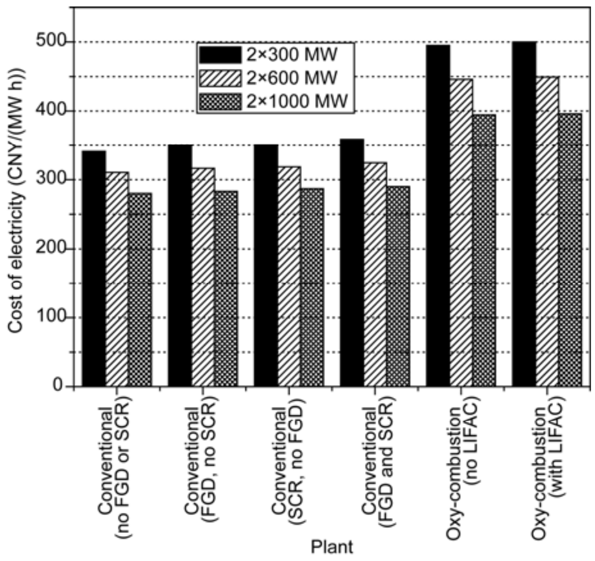

Figure 2 Costs of electricity for different cases.

for about 12%–14% [11] of the total c_{COE}. If these effects are considered, the c_{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_{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_{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_{CAC}) can be used to evaluate the economic property of controlling the CO_2 emission. c_{CAC} is defined as the ratio of the c_{COE} difference to the unit CO_2 emission amounts 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

$$c_{\mathrm{CAC}} = \frac{c_{\mathrm{COE},1} - c_{\mathrm{COE},0}}{e_{\mathrm{CO_2},0} - e_{\mathrm{CO_2},1}} = \frac{c_{\mathrm{COE},1} - c_{\mathrm{COE},0}}{\dfrac{E_{\mathrm{CO_2},0}}{W_{\mathrm{net},0}H} - \dfrac{E_{\mathrm{CO_2},1}}{W_{\mathrm{net},1}H}}, \tag{17}$$

in which, $e_{\mathrm{CO_2}}$ is the CO_2 emission amount per unit of power (t/MWh). The c_{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

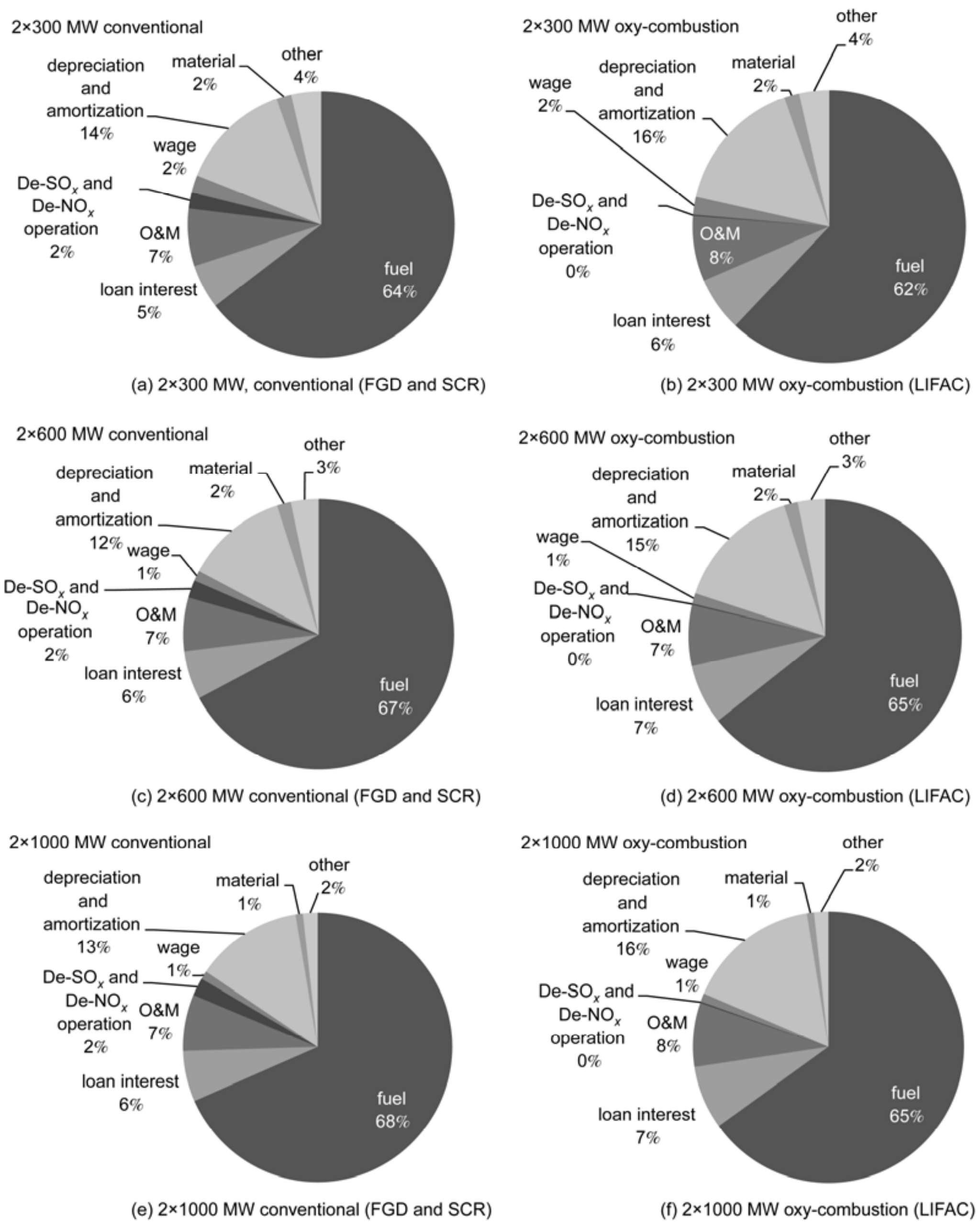

Figure 3 Structure diagrams of annualized total costs for three different load plants under conventional combustion and oxy-combustion.

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

Item	2×300 MW	2×600 MW	2×1000 MW
$c_{\rm COE,1}$(¥/(MW h))	500.04	449.09	395.93
$c_{\rm COE,0}$(¥/(MW h))	358.72	324.50	290.12
$e_{\rm CO2,0}$(t/(MW h))	0.97	0.91	0.83
$e_{\rm CO2,1}$(t/(MW h))	0.13	0.12	0.11
$m_{\rm CO2,1}$(t/(MW h))	0	0	0
$m_{\rm CO2,0}$(t/(MWh))	1.17	1.09	0.97
$c_{\rm CAC}$(¥/t)	168.61	157.64	146.89
$c_{\rm CCC}$(¥/t)	120.65	114.26	108.90

from conventional power plants. The CO_2 tax has a significant influence on the economic performance of conventional and oxy-combustion plants, and the cost of electricity ($c'_{\rm COE}$) and CO_2 avoidance cost ($c'_{\rm CAC}$) when considering the CO_2 tax is

$$\begin{aligned} c'_{\rm COE} &= \frac{C'_{\rm T}}{W_{\rm net}H} = \frac{C_{\rm T}+E_{\rm CO_2}T_{\rm CO_2}}{W_{\rm net}H} \\ &= c_{\rm COE}+T_{\rm CO_2}e_{\rm CO_2} = c_{\rm COE}+\frac{E_{\rm CO_2}T_{\rm CO_2}}{W_{\rm net}H}, \end{aligned} \tag{18}$$

$$c'_{\rm CAC} = \frac{c'_{\rm COE,1}-c'_{\rm COE,0}}{e_{\rm CO2,0}-e_{\rm CO2,1}} = c_{\rm CAC}-T_{\rm CO2}. \tag{19}$$

Figure 4 shows the effect of the unit CO_2 emission tax (T_{CO_2}) on the c_{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_{CO_2} equals the c_{CAC} without CO_2 emission taxation, the c_{COE} of the oxy-combustion plant is equivalent to that of the corresponding conventional plant. The c_{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_{CO_2} value when the oxy-combustion plant and the corresponding conventional plant have equivalent economic property (named as critical T_{CO_2}) is equal to the c_{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_{CCC}). c_{CCC} is defined as the ratio of the c_{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

$$c_{CCC}=\frac{c_{COE,1}-c_{COE,0}}{m_{CO_2,1}-m_{CO_2,0}}=\frac{c_{COE,1}-c_{COE,0}}{m_{CO_2,1}}=\frac{c_{COE,1}-c_{COE,0}}{\dfrac{M_{CO_2,1}r_{CO_2}}{W_{net,1}H}},\quad (20)$$

in which, m_{CO_2} is the CO_2 capture amount per unit of power (t/(MW h)), r_{CO_2} is the CO_2 capture efficiency. The c_{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_{COE} of oxy-combustion plants may be further reduced and the CO_2 capture cost will change. The cost of electricity (c''_{COE}) and the CO_2 capture cost (c''_{CCC}) when considering the CO_2 sale are

$$\begin{aligned}c''_{COE}&=C''_T/(W_{net}H)=\left(C_T-M_{CO_2}c_{CO_2}\right)/(W_{net}H)\\&=c_{COE}-c_{CO_2}m_{CO_2}=c_{COE}-M_{CO_2}c_{CO_2}/(W_{net}H)\end{aligned}\quad (21)$$

$$c''_{CCC}=\frac{c''_{COE,1}-c''_{COE,0}}{m_{CO_2,1}}=c_{CCC}-c_{CO_2}\,.\quad (22)$$

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_{CO_2}). From eq. (22), we can see that the critical c_{CO_2} equals the c_{CCC} without a CO_2 sale. Figure 5 shows the effect of the c_{CO_2} on the c_{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_{CO2} (viz. c_{CCC}) that makes the c_{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 ($e_{CO_2,0}$–$e_{CO_2,1}$) and relative CO_2 capture amounts ($m_{CO_2,1}$–$m_{CO_2,0}$) 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_{CO_2} and the critical c_{CO_2}, and the critical T_{CO_2} is generally greater than the critical c_{CO_2}.

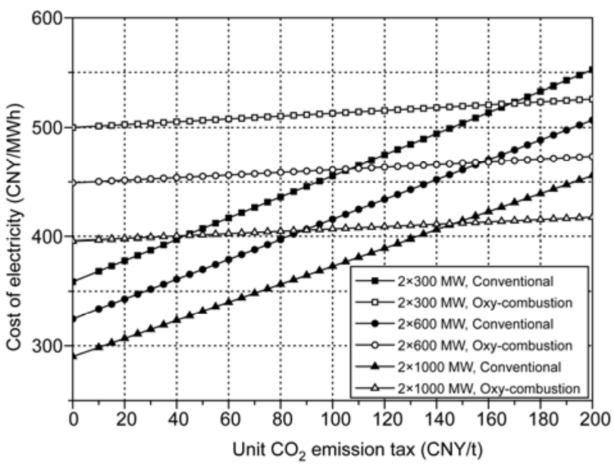

Figure 4 Relations between c_{COE} and T_{CO_2}.

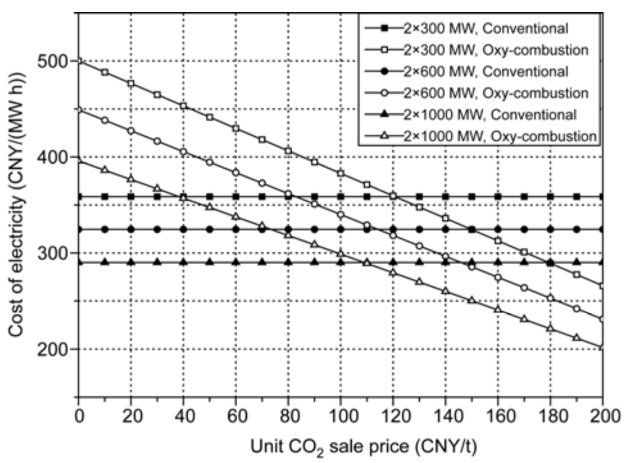

Figure 5 Relations between c_{COE} and c_{CO_2}.

1.6 CO_2 tax and CO_2 sale

The economic characteristics of the oxy-combustion technology were evaluated when the CO_2 tax and the CO_2 sale were considered together. Both the CO_2 tax and the CO_2 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}), CO_2 avoidance cost (c'''_{CAC}) and CO_2 capture cost (c''_{CCC}) are given by

$$\begin{aligned} c'''_{COE} &= C'''_{T}/(W_{net}H) \\ &= \left(C_T + E_{CO_2}T_{CO_2} - M_{CO_2}c_{CO_2}\right)/(W_{net}H) \\ &= c_{COE} + T_{CO_2}e_{CO_2} - c_{CO_2}m_{CO_2} \\ &= c_{COE} + E_{CO_2}T_{CO_2}/(W_{net}H) - M_{CO_2}c_{CO_2}/(W_{net}H), \end{aligned} \quad (23)$$

$$\begin{aligned} c'''_{CAC} &= c_{CAC} + \left(\frac{E_{CO_2,1}T_{CO_2} - M_{CO_2,1}c_{CO_2}}{W_{net,1}H} - \frac{E_{CO_2,0}T_{CO_2}}{W_{net,0}H}\right) \Big/ \left(\frac{E_{CO_2,0}}{W_{net,0}H} - \frac{E_{CO_2,1}}{W_{net,1}H}\right) \\ &= c_{CAC} + \left[\frac{(1-\eta_{C,1})\eta_e E_{CO_2,0}T_{CO_2} - \eta_{C,1}\eta_e E_{CO_2,0}c_{CO_2}}{W_{net,1}} - \frac{E_{CO_2,0}T_{CO_2}}{W_{net,0}}\right] \Big/ \left[\frac{E_{CO_2,0}}{W_{net,0}} - \frac{(1-\eta_{C,1})\eta_e E_{CO_2,0}}{W_{net,1}}\right] \\ &= c_{CAC} - T_{CO_2} - c_{CO_2}/\beta, \end{aligned} \quad (24)$$

$$\begin{aligned} c'''_{CCC} &= c_{CCC} + \left(\frac{E_{CO_2,1}T_{CO_2} - M_{CO_2,1}c_{CO_2}}{W_{net,1}H} - \frac{E_{CO_2,0}T_{CO_2}}{W_{net,0}H}\right) \Big/ \left(\frac{M_{CO_2,1}}{W_{net,1}H}\right) \\ &= c_{CCC} + \left[\frac{(1-\eta_{C,1})\eta_e E_{CO_2,0}T_{CO_2} - \eta_{C,1}\eta_e E_{CO_2,0}c_{CO_2}}{W_{net,1}} - \frac{E_{CO_2,0}T_{CO_2}}{W_{net,0}}\right] \Big/ \left[\frac{\eta_{C,1}\eta_e E_{CO_2,0}}{W_{net,1}}\right] \\ &= c_{CCC} - c_{CO_2} - T_{CO_2}\beta, \end{aligned} \quad (25)$$

in which the critical coefficient $\beta = W_{net,1}/(W_{net,0}\eta_{C,1}\eta_e) - (1-\eta_{C,1})/\eta_{C,1}$, is actually the ratio of the critical c_{CO_2} to the critical T_{CO_2}. 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_{CO_2} and critical T_{CO_2} 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_{CO_2} and 80 ¥/t c_{CO_2}. 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_{CO_2} and 60 ¥/t c_{CO_2}. 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_{CO_2} and T_{CO_2}.

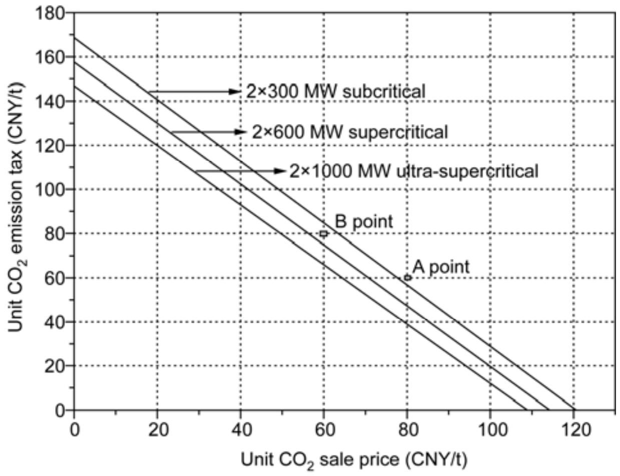

Figure 6 Relations between T_{CO_2} and c_{CO_2} when $c_{COE,0}$ equals $c_{COE,1}$.

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 CO_2 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_F, and that is because fuel costs contribute 62%–65% of c_{COE} of oxy-combustion plants. The following parameters are α 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 α 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 CO_2 capture amounts and unit CO_2 emission amounts in oxy-combustion plants. The other important parameters are α 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

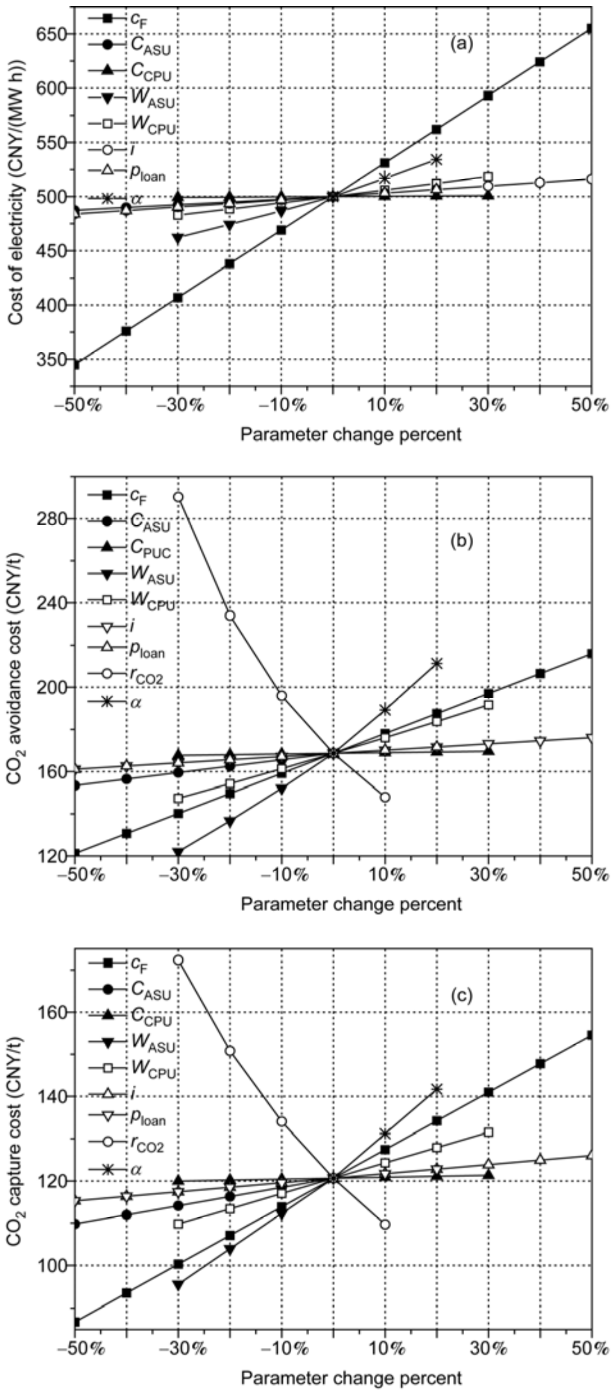

Figure 7 Results of the sensitivity analysis. (a) Influences of parameters on c_{COE}; (b) influences of parameters on c_{CAC}; (c) influences of parameters on c_{CCC}.

general, the influences of the parameters on these three costs are similar. The results show that the influences of α and W_{ASU} on the c_{COE} of the oxy-combustion plant are less than that of the coal price. But the influences of α 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 2×300 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 2×300 MW subcritical, 2 × 600 MW supercritical and 2 × 1000 MW ultra-supercritical oxy-combustion coal-fired power plants was performed. The results indicate that the electricity cost of a 2×300 MW oxy-combustion plant (with LIFAC desulphurization device) is 500.04 ¥/(MW h) (449.09 ¥/(MW h), 395.93 ¥/(MW h), are the equivalent values for the 2×600 MW and 2×1000 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

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

Coal sample	M_{ar} (%)	A_{ar} (%)	C_{ar} (%)	H_{ar} (%)	O_{ar} (%)	N_{ar} (%)	S_{ar} (%)	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)	Oxy-combustion (LIFAC)		
Shenhua	358.72	500.04	168.61	120.65
Huangshi	360.07	504.84	173.04	123.34
Datong	359.01	499.15	169.83	121.84
Huangling	358.95	491.39	164.94	120.15

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

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

C, c	Cost and unit cost
E, e	Emission and unit emission amount
H	Annual operation hours
H_i	Lower heating value of raw coal
H_n	Lower heating value of standard coal
i	Interest rate
M, m	Mass flowrate and unit mass flowrate
N	Personnel numbers
P	Loan period
p	O&M coefficient
P_{caco3}	Purity of limestone
P_{CaSO4}	Purity of gypsum
p_{fa}	Fixed assets formation percentage
p_{ia}	Intangible and deferred assets percentage
p_{loan}	Loan percentage
p_{lv}	Residual value percentage
p_m	Material cost ratio
p_O	Other costs ratio
r_{ca2s}	Mole ratio of Ca to S
r_{CO2}	CO_2 capture efficiency
r_{pe}	Auxiliary power ratio
r_W	Welfare and labor insurance coefficient
T	Pollutant emission tax
t_C	Ratio of C_{ar} transformed to be CO_2
t_S	Ratio of S_{ar} transformed to be SO_2
V, v	Volume and unit volume
W	Power
Y_d	Depreciation period

Greek letters

α	Air excess factor
β	Critical coefficient
η	Efficiency
ξ	Average interest rate

Subscripts

0	Base (conventional) plant
1	Oxy-combustion plant
ar	As-received basis
b	Boiler
ef	Effluent

F	Fuel
N	NO_x
net	Net power output
O	Oxygen
pay	Payment
pw	Process water
S	SO_x

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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