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An economic feasibility study of O_2/CO_2 recycle combustion technology based on existing coal-fired power plants in China

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ABSTRACT

In order to reduce the CO_2 emission from the coal-fired power plants, O_2/CO_2 recycle combustion (Oxy-combustion) technique has been proposed through combining a conventional combustion process with a cryogenic air separation process. The technique is capable of enriching CO_2 concentration and then allowing CO_2 sequestration in an efficient and energy-saving way. Taking into account the CO_2 taxation and CO_2 sale, the paper evaluates the economic feasibility of Oxy-combustion plants retrofitted from two typical existing conventional coal-fired power plants (with capacities of 2×300 MW and 2×600 MW, respectively) with Chinese data. The cost of electricity (COE) and the CO_2 avoidance cost (CAC) are also considered in the evaluation. The COE of the retrofitted Oxy-combustion plant is nearly the same as that of the corresponding conventional plant if the unit price of CO_2 sale reaches 17–22 \$/t (different cases). The CAC of the retrofitted 2×300 MW Oxy-combustion plant is 1–3 \$/t bigger than that of the retrofitted 2×600 MW Oxy-combustion plant. Supercritical plants are more economical and appropriate for Oxy-combustion retrofit. The result indicates that Oxy-combustion technique is not only feasible for CO_2 emission control based on existing power plants but is also cost-effective.

1. Introduction

In 2004, the emission of CO_2 in China ranks second in the world, reaching about 4.8 Gt (18% of world CO_2 emission) [1]. The largest CO_2 emission source is from coal combustion power plants since over 60% of the total energy is supplied by coal combustion in China. Oxy-combustion technique, which is based on existing coal-fired power plant through combining a conventional combustion process with a cryogenic air separation process (as shown in Fig. 1), is one approach to produce high purity CO_2 gas stream from coal-fired plant.

As far as Oxy-combustion is considered, oxygen with greater than 95% purity is used rather than air in conventional coal-fired combustion. About 70–80% of the flue gas is recycled to make up the volume fraction of missing N_2 to ensure there is enough gas to carry heat through boiler [2]. The remaining flue gas, where the CO_2 concentration exceeds 95% in bench-scale experiments [3], is first cooled to remove water, then compressed, followed by separation of non-condensable gases (Ar, O_2 and N_2) from CO_2, and finally boosted to pipeline pressure [4]. Compared with air combustion plant, Oxy-combustion generally produces smaller amount of NO_x, but emits similar amount of SO_x. With the use of low sulphur coals, Oxy-combustion power station may omit flue gas denitrification plant or even flue gas desulphurisation (FGD) plant [4,5]. However, it is generally accepted that Oxy-combustion plant would require a de-SO_x plant when burning coal with significant amount of sulphur. Generally speaking, the Oxy-combustion technique exhibits high-efficiency and low cost in the removal of SO_x as the continually-recycled flue gas results in higher-concentration SO_x than conventional air combustion technique. Unfortunately, the addition of air separation unit (ASU) and CO_2 post-treatment unit increases the investment cost of base power plant and decreases the net electricity output. Thus, it is necessary to have a techno-economic evaluation on the new combustion process.

Chalmers University has evaluated a retrofitted 865 MWe lignite-fired power plant in Germany [2,6]. In the study, a cryogenic ASU was integrated into the power plant to produce pure O_2 required for combustion. Andersson and Johnsson [6] found that the cost of electricity (COE) increased from 42.1 \$/MWh in the reference plant to 64.3 \$/MWh in the O_2/CO_2 plant with a lignite price of 5.2 \$/MWh and an interest rate of 10%.

ALSTOM simulated the Oxy-combustion process to evaluate its technical and economic issues, including boiler performance, plant efficiency, heat transfer characteristics, etc [7]. The ALSTOM study on an existing 450 MW US bituminous coal-fired power plant showed that the boiler efficiency increased from 88.13% for conventional air firing to 90.47% for Oxy-combustion because of flue gas recycle. At the same time, as a result of energy requirement

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Nomenclature

c_{ASU}	unit price of air separation unit (M$)
c_C	unit price of CO_2 sale ($/t)
c_{CAC}	CO_2 avoidance cost ($/t)
c'_{CAC}	CO_2 avoidance cost when the CO_2 taxation and the CO_2 sale are considered ($/t)
c_{COE}	cost of electricity ($/MWh)
c_F	unit price of standard coal ($/t)
c_{TAX}	unit emission tax of SO_2/NO_x ($/t)
C_{AI}	annual investment cost (M$/y)
C_F	annual cost of fuel (M$/y)
C_I	total investment cost (M$)
C_{OM}	annual cost of O&M (M$/y)
C_S	revenue from product sale (M$/y)
C_T	total annual cost (M$/y)
C_{TAX}	taxation for pollutant emission (M$/y)
D	operation days in a year (d)
f	capital recovery factor (–)
H	annual hours of operation (h)
H_i	net calorific power of fuel (kJ/kg)
H_n	net calorific power of standard coal (kJ/kg)
i	interest rate (–)
k	amortization period (y)
m	unit CO_2 emission amount (t /MWh)
M_C	annual CO_2 emission (t/y)
M_F	rate of fuel consumption (t/d)
P	construction period (y)
r	rate of inflation (–)
r_C	CO_2 capture rate (–)
r_e	ratio of the boiler efficiency of the conventional plant to the Oxy-combustion plant (–)
r_{FG}	energy consumption ratio of the flue gas treatment system to the gross electricity output (–)
r_{OM}	ratio of the cost of O&M to the total investment cost (–)
T_C	unit tax of CO_2 emission ($/t)
v_O	unit theoretic volume of O_2 needed for 1 kg fuel burning (Nm^3/kg)
v_{ASU}	O_2 production rate of ASU unit (NMm^3/h)
V	actual amount of O_2 supplied for fuel burning (NMm^3/h)
w_{ASU}	unit energy consumption of air separation unit (MW)
W_{FGD}/W_{SCR}	energy consumption of wet-FDG/SCR device (MW)
W_g	gross electricity output (MW)
W_{net}	net electricity output (MW)

Greek letters

α	excess air coefficient
β	coefficient
φ	maintenance factor
ξ	amortization factor
η_B	boiler efficiency
η	efficiency of power generation

Subscripts

ar	as-received basis
oxy	Oxy-combustion plant
air	conventional plant

of ASU, CO_2 compression and liquefaction systems, the thermal efficiency decreased from 35% to 23% [2].

There is no full-scale Oxy-combustion plant in operation in China yet. As a matter of fact, Chinese data have never been used in techno-economic evaluation of Oxy-combustion technique. The economic feasibility of Oxy-combustion plant is deeply associated with the commercial environment such as the price of high purity CO_2 and political environment such as carbon tax, and is thus region-dependent. In this study, a detailed economic feasibility evaluation of retrofitted Oxy-combustion plants compared with existing coal-fired plants in China is carried out and the results are presented.

2. Economic evaluation

2.1. The total cost of a power plant

In order to obtain data on the investment and operation costs, an investigation was conducted on the parameters of ASU, subcritical and supercritical pulverized coal-fired power plants in China. A large number of pulverized coal-fired power stations are found in China, and in our study, we considered a 2 × 300 MWe subcritical plant, and a 2 × 600 MWe supercritical plant. These conventional plants usually adopt the $CaCO_3$-gypsum (wet-FGD) method to remove SO_x with the efficiency of over 90%, which results in high investment and operation costs, typically 3 ¥/kg SO_x ('¥' is the Chinese currency, 7.5¥ ≈ 1$ in 2007) in China. And the selective catalytic reduction (SCR) unit is usually used to remove NO_x. There is as yet no special device for the removal of trace metals such as mercury in China at present. On the other hand, the emission tax of pollutants is comparatively low. For example, the SO_2/NO_x emission tax is 0.6 ¥/0.95 kg. Therefore, there may be some conventional plants which are not equipped with de-SO_x and de-NO_x devices. The primary economic data of the two base plants with different equipments are summarized in Table 1.

As for retrofitted Oxy-combustion plants, the de-NO_x device is not considered here since the concentration of NO_x is generally lower than that in its base plants. Moreover, the higher-concentration of SO_x in Oxy-combustion plants due to the recycle of flue gas

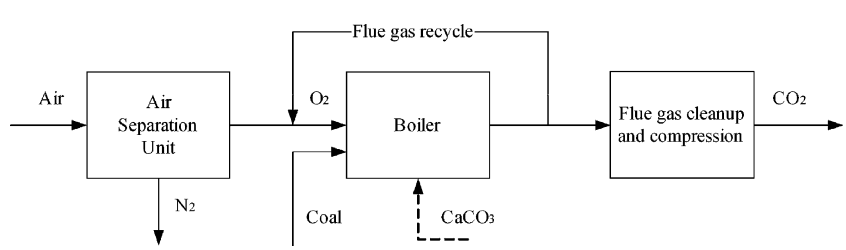

Fig. 1. Schematic diagram of Oxy-combustion.

Table 1
Primary characteristics of the base plants.

Devices	Parameters	2 × 300 MW subcritical plant	2 × 600 MW supercritical plant
Base plant (no de-SO_x and de-NO_x devices)	Cost of boiler $C_{I\text{-}B}$(M\$)	40	80
	Efficiency of boiler η_B	92%	94%
	Total investment cost C_I (M\$)	320	576
	Net electrical output W_{net} (MW)	595	1192
	Efficiency of power generation η	38%	41%
De-SO_x device (Wet-FGD)	Investment cost (M\$)	21	27
	Energy consumption W_{FGD}(MW)	3–5	5–7
	Added cost of electricity $c_{COE\text{-}add}$ (\$/MWh) [19]	2.3–3.2	1.6–2.5
De-NO_x device (SCR, pure NH_3)	Investment cost (M\$)	35	53
	Energy consumption W_{SCR}(MW)	1	2
	Added cost of electricity $c_{COE\text{-}add}$ (\$/MWh) [20]	1.8	1.4

allows some de-SO_x techniques, with comparatively low efficiency but low cost, to be applied. The technique of limestone injection into the furnace and the activation of unreacted calcium (LIFAC) [8], which has de-SO_x efficiency of typically 50% and reduction cost of typically 1 ¥/kg, is a good alternative to reduce the SO_x in the Oxy-combustion. The costs and energy consumptions of the added equipments in retrofitted Oxy-combustion plants are summarized in Table 2. It should be clarified that some data [6,9] from other countries were used as reference to calculate the costs of boiler upgrades and CO_2 treatment devices due to the lack of these experimental data in China. The sale of N_2 produced in ASU is not considered in this paper.

The cost of operation & maintenance (O&M), C_{OM}, is 4% of the total investment cost (C_I) in this paper [10]; and the annual investment cost, C_{AI}, which is also named amortization cost, is expressed as [11]

$$C_{AI} = \varphi \cdot f \cdot C_I = \xi \cdot C_I \tag{1}$$

here φ is the maintenance factor (φ = 1.06 in this paper); ξ is the amortization factor; f is the annual capital recovery factor, which is obtained from [12]

$$f = \left[\frac{q^{(k+P)}-1}{(q-1)q^{(k+P)}} - \frac{q^P-1}{(q-1)q^P}\right]^{-1} \tag{2}$$

$$q = (1+i)(1+r) \tag{3}$$

in which P is the construction period (P = 1 year in this paper); k is the amortization period (k = 20 years in this paper); i is the interest rate (i = 8% in this paper); r is the rate of inflation; and the prescribed value of r in this paper is 1.13%, the average value of the last 10 years in China (1998–2007, −0.8, −1.4, 0.4, 0.7, −0.8, 1.2, 3.9, 1.8, 1.5, 4.8, respectively). Based on the above equations and values, ξ is estimated to be 12.88%.

In this paper, two kinds of coal with obvious differences in sulphur contents are chosen as fuels, the elementary analysis and industrial analysis of which are all listed in Table 3. In which M_{ar}, A_{ar}, C_{ar}, H_{ar}, O_{ar}, N_{ar}, and S_{ar} mean as-received basis of the moisture, ash, element carbon, hydrogen, oxygen, nitrogen and sulphur in the coal, respectively; H_i is the net calorific power of the raw coal.

The theoretic volume of oxygen (v_O) needed for 1 kg as-received basis fuel burning can be calculated as follows:

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

The actual amount of O_2 (V) supplied for coal burning can be calculated as

$$V = M_F v_O \alpha/24 \tag{5}$$

in which M_F means the rate of raw coal consumption (t/d); the excess air coefficient α is set as 1.15 in this paper. This formula is used to calculate the number of the air separation units. The greatest O_2 supply velocity of ASU is 60,000 Nm^3/h in China.

Then, the annual cost of fuel (C_F) is obtained by

$$C_F = c_F D M_F (H_i/H_n) \tag{6}$$

where c_F is the unit price of standard coal, and the raw coal consumption (M_F) should be converted to the standard coal consumption; H_n is the net calorific power of standard coal, H_n = 29,270 kJ/kg; D is the number of operation days, D = 300 in this paper. The variables in Eqs. 4–6 are listed in Table 4.

It is assumed that boiler efficiency is enhanced by 2% in Oxy-combustion process. In this case, the rate of raw coal consumption will decrease accordingly for the same gross electricity output. A linear transform is chosen to calculate the rate of raw coal consumption in Oxy-combustion plants.

The annual amount of CO_2 generated by the combustion of coal in base plants can be obtained from the annual raw coal consump-

Table 2
Oxy-combustion added equipment costs and energy consumptions.

Case	Investment cost (M\$)	Energy consumption (MW)	References
ASU (unit, 60,000 Nm^3O_2/h)	24	25	–
Boiler upgrades	7% of cost of base boiler	–	[9]
Flue gas treatment	2.5% of total investment cost of base plant	8% of gross electrical output	[6]

Table 3
Elementary analysis and industrial analysis of coal.

Order	Type	M_{ar} (%)	A_{ar} (%)	C_{ar} (%)	H_{ar} (%)	O_{ar} (%)	N_{ar} (%)	S_{ar} (%)	H_i (kJ/kg)
#1	ShenHua coal	13.8	11	60.51	3.62	9.94	0.7	0.43	22,768
#2	HuangShi coal	6	26.18	59.21	2.56	2.12	0.82	3.11	22,310

The subscript of 'ar' indicates the as-received basis.

Table 4
Data of the cost of fuel and oxygen supply.

	#1 Coal		#2 Coal	
	2 × 300 MW	2 × 600 MW	2 × 300 MW	2 × 600 MW
c_F (\$/t)	70	70	60	60
M_F (t/d)	5300	9800	5400	10,000
v_O (Nm^3/kg)	1.2659	1.2659	1.2557	1.2557
V (NMm^3/h)	0.3215	0.5944	0.3249	0.6017
C_F (M\$/y)	86.576	160.084	74.087	137.198

tions and the elementary analysis of coal. It is assumed that the carbon element in coal is fully converted to CO_2 and 80% of the CO_2 is captured in the Oxy-combustion process. The high purity CO_2 obtained from flue gas in Oxy-combustion after several steps can be utilized to produce urea, methanol, drink, dry ice and Enhance Oil/Gas/Coal-bed-Methane Recovery (CO_2–EOR/EGR/ECMR) [13,14]. Thus, CO_2 sale is also considered here. As a matter of fact, it should be noted that the revenue from CO_2 sale, $C_{S\text{-}CO2}$, counteracts part of the total cost and therefore decreases the unit electricity cost of Oxy-combustion power plant. In China, a market price of 15–25 \$/t of industrially produced CO_2 for EOR is acceptable [14,15].

The $C_{S\text{-}CO2}$ can be described as

$$C_{S\text{-}CO2} = r_C M_{C\text{-air}} c_C = 44 r_C c_C D M_F C_{ar}/12 \tag{7}$$

where r_C means the rate of CO_2 capture (80% in Section 2.2) and ranges from 64% to 96% in Section 3 according to references [2,10]; M_C means the annual amount of CO_2 emission; the subscript 'air' means the conventional plant; c_C means the unit price of CO_2 sale.

Another factor influencing the total annual cost of power plants is the local tax policy of pollutants. The tax of pollutants can help enhance the efficiency of power plants or the technical improvement of clear combustion technique to a certain extent. However, as mentioned above, there are only few coal-fired power plants with SCR and FGD to control the NO_x and SO_2 emissions in China, because the emission taxes of NO_x and SO_2 are still low. In addition, there is no policy of CO_2 taxation in China, although the CO_2 tax has been studied for many years in other countries (Norway, Danish, Sweden, Holand, Italy, Switzerland, etc.) [16–18]. In this study, the taxes of pollutants including CO_2, SO_x and NO_x ($C_{TAX\text{-}CO2}$, $C_{TAX\text{-}SOx}$ and $C_{TAX\text{-}NOx}$) are considered.

Overall, in the evaluation of the total cost of a plant, it is necessary to calculate the annual investment cost of each plant device (C_{AI}), the annual cost of O&M (C_{OM}), fuel cost (C_F), as well as the taxation for pollutant emission (C_{TAX}) and the revenue from product sale (C_S; the product is CO_2 in this paper). So the total annual cost of a plant, C_T, can be calculated by

$$C_T = C_F + C_{AI} + C_{OM} + C_{TAX} - C_S \tag{8}$$

Using the model of C_T that takes various factors into account, the economic feasibility of Oxy-combustion plants compared with conventional plants is evaluated in details, where the cost of electricity (c_{COE}) and the CO_2 avoidance cost (c_{CAC}) are chosen as reference for economic evaluation.

2.2. The cost of electricity

The cost of electricity, c_{COE} with dimension of \$/MWh, is calculated by

$$c_{COE} = C_T/(W_{net} \times H) \tag{9}$$

here W_{net} is the net electricity output (MW); H is the annual hours of operation (7200 in this paper).

Four general cases are considered here: (1) conventional plant without any pollutant-removal devices, where NO_x and SO_2 emission taxes are invoked; (2) conventional plant with SCR and wet-FGD devices; (3) Oxy-combustion plant without CO_2 sale and (4) Oxy-combustion plant with CO_2 sale. In Oxy-combustion plants, no de-NO_x device is applied, and the LIFAC technique is used to remove SO_x. In this section, CO_2 emission tax is not considered.

The c_{COE} of each case can be obtained by the following general models:

Case 1. Conventional plant without de-NO_x and de-SO_x devices and with NO_x and SO_2 emission tax:

$$\begin{aligned} c_{COE1} &= (C_{F1} + C_{AI1} + C_{OM1} + C_{TAX1\text{-}SO2} + C_{TAX1\text{-}NO})/(W_{net1}H) \\ C_{TAX1\text{-}SO2} &= 2DM_F S_{ar} c_{TAX\text{-}SO2} \\ C_{TAX1\text{-}NO} &= 30DM_F N_{ar} c_{TAX\text{-}NO}/14 \end{aligned} \tag{10}$$

where the emission taxes of SO_2 and NO_x are considered. They have the same unit emission tax value in this paper (c_{TAX}, 85 \$/t). NO_x is considered to be NO since there is almost 90% concentration of NO in NO_x.

Case 2. Conventional plants with SCR and wet-FGD devices:

$$\begin{aligned} c_{COE2} &= (C_{F2} + C_{AI2} + C_{OM2})/(W_{net2}H) + c_{COE\text{-}add2} \\ W_{net2} &= W_{net1} - W_{FGD} - W_{SCR} \end{aligned} \tag{11}$$

where W_{FGD}/W_{SCR} means the energy consumption of wet-FDG/SCR device; $c_{COE\text{-}add2}$ is the added cost of electricity due to the addition of SCR and wet-FGD devices. For different coal, the value of $c_{COE\text{-}add2}$ has a slight difference (shown in Table 1).

Case 3. Oxy-combustion plant without CO_2 sale. Two different plant configurations are considered here according to the de-SO_x technique.

Case 3A. Oxy-combustion plant with SO_x emission tax but without LIFAC:

$$\begin{aligned} c_{COE3A} &= (C_{F3} + C_{AI3} + C_{OM3} + C_{TAX3\text{-}S})/(W_{net3}H) \\ &= \frac{(r_e C_{F1} + C_{I3}\xi + C_{I3} r_{OM} + C_{TAX3\text{-}S})}{(W_{net1} - r_e V w_{ASU}/v_{ASU} - r_{FG} \times W_g)H} \end{aligned} \tag{12}$$

where $C_{I3} = C_{I1} + C_{I\text{-}ASU} + C_{I\text{-}B} + C_{I\text{-}FG}$, $C_{I3}\xi = C_{AI3} = C_{AI1} + C_{AI\text{-}ASU} + C_{AI\text{-}B} + C_{AI\text{-}FG}$. $C_{I\text{-}ASU}$ is the investment cost of ASU; $C_{I\text{-}B}$ is the investment cost of boiler upgrading; $C_{I\text{-}FG}$ is the investment cost of flue gas treatment system; $C_{TAX3\text{-}S}$ means the emission tax of the element S (170 \$/t S in this paper); w_{ASU} means the unit energy consumption of ASU; $r_e = \eta_{B\text{-}air}/(\eta_{B\text{-}air} + 2\%)$ in this paper means the ratio of the boiler efficiency of the conventional plant (η_B) to the Oxy-combustion plant. As mentioned above, a linear transform is used to calculate the C_F of Oxy-combustion plant due to a 2% increase of the boiler efficiency; r_{OM} means the ratio of the cost of O&M to the total investment cost (4% in this paper); v_{ASU} means the O_2 production rate of unit ASU (60,000 Nm^3/h in this paper); r_{FG} means the energy consumption ratio (8% in this paper) of the flue gas treatment system to the gross electricity output (W_g).

Case 3B. Oxy-combustion plant with LIFAC but without SO_x emission tax:

$$c_{COE3B} = (C_{F3} + C_{AI3} + C_{OM3})/(W_{net3}H) + c_{COE\text{-}add3B} \tag{13}$$

where $c_{COE\text{-}add3B}$ means the added cost of electricity due to the addition of LIFAC device and the value of 1 \$/MWh is chosen for this low sulphur coal (1.5 \$/MWh for #2 coal with high sulphur).

Case 4. Oxy-combustion plant with CO_2 sale:

$$c_{COE4} = c_{COE3} - C_{S\text{-}CO2}/(W_{net3}H) \tag{14}$$

The obtained costs of electricity and the associated variables in Cases 1-3 are illustrated in Table 5. As for Case 4, the c_{COE} depends on the price of CO_2 sale. Fig. 2 presents the linear decrease of c_{COE} in Case 4 where the unit price of CO_2 increases from 0 to 25 \$/t. It should be emphasized that there are two different relations between the c_{COE} and c_C in Case 4 due to the two different values of c_{COE3} (Cases 3A and 3B).

The results in Table 5 show that: (1) the COE of conventional combustion plant is increased by 6–11% due to the addition of de-SO_x and de-NO_x devices; (2) if the CO_2 sale is not taken into account, the COE

Table 5
The values of different costs in the calculation of c_{COE}.

Cases	c_{COE}	$c_{COE\text{-add}}$	C_F	C_{AI}	$C_{AI\text{-ASU}}$	$C_{AI\text{-B}}$	$C_{AI\text{-FG}}$	C_{OM}	C_{TAX}	W_{net}
	($/MWh)		(M$/y)							(MW)
2 × 300 MW plant fueled with the #1 coal										
Case 1	33.564	0	86.576	41.216	0	0	0	12.8	3.19	595
Case 2	37.142	1.8 + 2.3	86.576	41.216	0	0	0	12.8	0	591
Case 3A	54.422	0	84.734	58.828	16.213	0.361	1.031	18.266	1.138	416
Case 3B	55.042	1	84.734	58.828	16.213	0.361	1.031	18.266	0	416
2 × 600 MW plant fueled with the #1 coal										
Case 1	30.67	0	160.084	74.203	0	0	0	23.04	5.898	1192
Case 2	33.16	1.4 + 1.6	160.084	74.203	0	0	0	23.04	0	1185
Case 3A	48.621	0	156.749	106.772	29.993	0.721	1.855	33.153	2.103	853
Case 3B	49.278	1	156.749	106.772	29.993	0.721	1.855	33.153	0	853
2 × 300 MW plant fueled with the #2 coal										
Case 1	32.469	0	74.087	41.216	0	0	0	12.8	10.984	595
Case 2	35.209	1.8 + 3.2	74.087	41.216	0	0	0	12.8	0	589
Case 3A	53.015	0	72.511	59.002	16.387	0.361	1.031	18.32	8.383	414
Case 3B	51.706	1.5	72.511	59.002	16.387	0.361	1.031	18.32	0	414
2 × 600 MW plant fueled with the #2 coal										
Case 1	29.687	0	137.198	74.203	0	0	0	23.04	20.342	1192
Case 2	31.424	1.4 + 2.5	137.198	74.203	0	0	0	23.04	0	1183
Case 3A	47.402	0	134.34	107.139	30.36	0.721	1.855	33.267	15.524	850
Case 3B	46.366	1.5	134.34	107.139	30.36	0.721	1.855	33.267	0	850

of Oxy-combustion plant is much greater than (1.5–1.7 times) that of conventional combustion plant. However, if the unit price of CO_2 sale is considered as 17–22 $/t (different cases), the COE of Oxy-combustion plant nearly equals to that of the conventional combustion plant; (3) Compared to the conventional plant, the power generation in Oxy-combustion plant decreases nearly by 30%; (4) an addition of LIFAC to the Oxy-combustion plant fueled with high sulphur coal is more economical than paying the tax of SO_x emission, whereas paying the tax of SO_x emission is more economical than the Oxy-combustion plant fueled with the low sulphur coal.

2.3. The CO_2 avoidance cost

The CO_2 avoidance cost (CAC) is an economic indicator that is widely used in the field of techno-economic evaluation of CO_2 emission control systems. It expresses the cost to avoid the CO_2

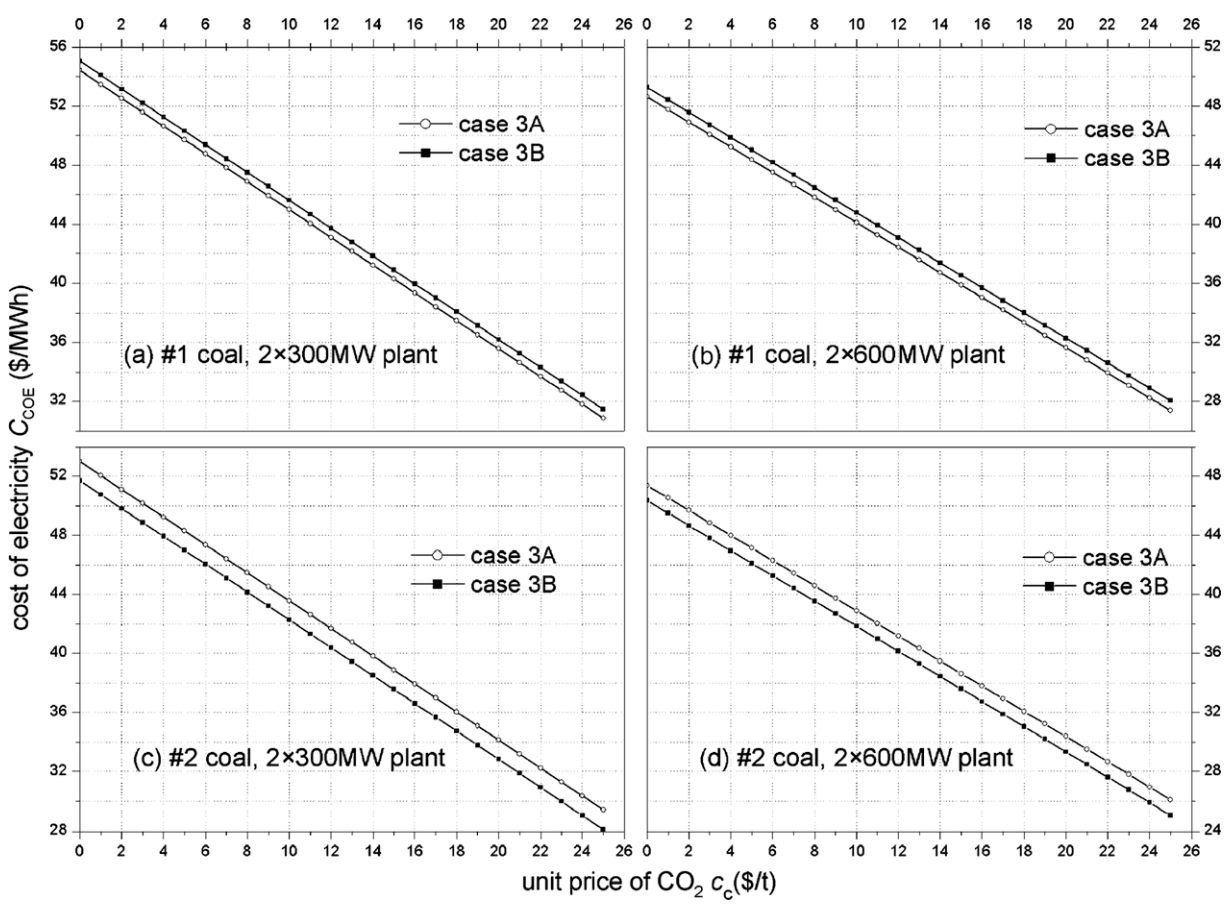

Fig. 2. The relation between c_{COE} and c_C.

Table 6
Data of CO_2 capture and CO_2 sale.

	#1 Coal		#2 Coal	
	2 × 300 MW	2 × 600 MW	2 × 300 MW	2 × 600 MW
$m_{C,air}$ (t/MWh)	0.824	0.76	0.821	0.759
$m_{C,oxy}$ (t/MWh)	0.236	0.212	0.236	0.213
$\triangle m_C$ (t/MWh)	0.588	0.548	0.585	0.546
β	0.624	0.645	0.621	0.642
Oxy-plant A, c_{CAC} (\$/t)	35.481	32.772	35.105	32.436
Oxy-plant B, c_{CAC} (\$/t)	30.45	29.427	28.186	27.357
Oxy-plant A, critical c_C (\$/t)	22.131	21.138	21.793	20.82
Oxy-plant B, critical c_C (\$/t)	18.993	18.98	17.498	17.56

emission of one unit amount (\$/t). The CO_2 avoidance costs range from 26 to 42 \$/t according to references [6,10]. It can be calculated as

$$c_{CAC} = \frac{c_{COE\text{-}oxy} - c_{COE\text{-}air}}{m_{C\text{-}air} - m_{C\text{-}oxy}} = \left(c_{COE\text{-}oxy} - c_{COE\text{-}air}\right) \Big/ \left(\frac{M_{C\text{-}air}}{W_{net\text{-}air}H} - \frac{M_{C\text{-}oxy}}{W_{net\text{-}oxy}H}\right) \quad (15)$$

m means the unit CO_2 emission amount (t CO_2/MWh); the subscript 'oxy' and 'air' means the Oxy-combustion plant and conventional plant, respectively.

Two general Oxy-combustion plants are considered here to calculate the CAC:

(A) Oxy-combustion plant without LIFAC device, named Oxy-plant A, whose reference plant is the conventional plant with NO_x and SO_2 emission tax.
(B) Oxy-combustion plant with LIFAC device, named Oxy-plant B, which corresponds to the conventional plant with SCR and wet-FGD devices. The values of variables in the Eq. (15) for the two plants are listed in Table 6. The CO_2 avoidance costs of the Oxy-combustion plants, that fuel different coals and equip different de-SO_x devices, range from 27.357 to 35.481 \$/t, which is consistent with the results from other researchers [6,7,9,10].

2.4. The CO_2 tax

It should be emphasized that the CO_2 taxation and CO_2 sale are not considered in the calculation of c_{CAC} above. The value of c_{CAC} will differ a lot if the CO_2 taxation and CO_2 sale are considered, which is shown as follows:

$$\begin{aligned} c'_{CAC} &= c_{CAC} + \left(\frac{C_{TAX\text{-}oxy} - C_{S\text{-}oxy}}{W_{net\text{-}oxy}H} - \frac{C_{TAX\text{-}air}}{W_{net\text{-}air}H}\right) \Big/ \left(\frac{M_{C\text{-}air}}{W_{net\text{-}air}H} - \frac{M_{C\text{-}oxy}}{W_{net\text{-}oxy}H}\right) \\ &= c_{CAC} + \left(\frac{(1-r_C)M_{C\text{-}air}T_C - r_C M_{C\text{-}air}c_C}{W_{net\text{-}oxy}} - \frac{M_{C\text{-}air}T_C}{W_{net\text{-}air}}\right) \Big/ \left(\frac{M_{C\text{-}air}}{W_{net\text{-}air}} - \frac{(1-r_C)M_{C\text{-}air}}{W_{net\text{-}oxy}}\right) = c_{CAC} - T_C - c_C/\beta \end{aligned} \quad (16)$$

in which $\beta = \frac{W_{net\text{-}oxy}}{W_{net\text{-}air}r_C} - \frac{1-r_C}{r_C}$.

here c'_{CAC} means the c_{CAC} when the CO_2 taxation and the CO_2 sale are taken into account. In most cases, the value of β is smaller than 1.

When the electricity cost of the reference plant equals to that of the corresponding Oxy-combustion plant, viz. the value of c'_{CAC} equals to zero. The resulting relation between the unit tax of CO_2 emission (T_C) and the c_C is obtained and presented in the following equations:

$$T_C = c_{CAC} - c_C/\beta \quad (17)$$

The values of β, the critical values of c_C ($T_C = 0$) in different cases are also shown in Table 6. There are eight different c_{CAC} and four different β in Table 6, so eight different lines of Eq. (17) can be obtained and drawn in Fig. 3.

The crossing points between the lines formulated by Eq. (17) and the longitudinal axis, that is, the T_C values when $c_C = 0$, represent CO_2 mitigation cost, which can be seen as another annotation of the CO_2 avoidance cost. The crossing points of these lines and the abscissa axis, in other words, the c_C values when $T_C = 0$, are the critical values of the unit prices of CO_2 sale as listed in Table 6. For instance, the corresponding line of Oxy-plant A of 2 × 300 MW which is fueled by #1 coal characterizes the critical economic feasibility of Oxy-plant A. Above the line (Region A), the COE of the Oxy-combustion plant is smaller than that of the reference plant, viz. the value of c'_{CAC} is smaller than zero, while below the line (Region B), the value of c'_{CAC} is bigger than zero. For example, if the unit price of CO_2 sale is 20 \$/t and the local CO_2 tax is 5 \$/t, the economic feasibility of the plant can be quantified by the point 'C' in Fig. 3a. In this situation, the Oxy-plant is more economical with respect to the conventional plant. However, where c_C is 5 \$/t and T_C is 20 \$/t (the point 'D' in Fig. 3a), the Oxy-combustion technique, economically speaking, cannot compete with the conventional technique.

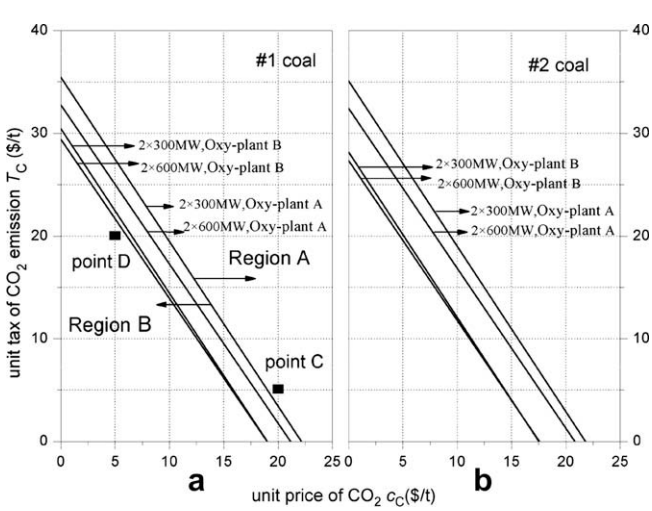

Fig. 3. The relation between T_C and c_C when $c_{COE\text{-}air}$ equals to $c_{COE\text{-}oxy}$.

3. Sensitivity analysis

Sensitivity analysis has been carried out in order to study the influences of some typical variables on the economic characteristics of conventional and Oxy-combustion systems. The cost of electricity (c_{COE}), the CO_2 avoidance cost (c_{CAC}) and the critical price of CO_2 sale (c_C) are calculated. For simplification, the 2 × 300 MW plant fueled with #1 coal is considered as the base case. The variables considered here include the unit price of standard coal (c_F), the unit price of ASU (c_{ASU}), the unit energy consumption of ASU (w_{ASU}), the rate of inflation (r), the rate of CO_2 capture (r_C) and the unit emission tax of SO_2/ NO_x (c_{TAX}). Two kinds of coal are considered in the sensitivity analysis of the variable c_{TAX}.

The sensitivity analysis results of these six variables are shown in Fig. 4. It should be clarified that the results of those variables, which do not influence the c_{COE}, c_{CAC} or $c_{C,}$ are not included in Fig. 4.

Fig. 4a–d show that: (1) in each case, c_{COE} is most correlated with c_F and is almost not influenced by r; (2) c_{COE} of the Oxy-combustion plant are strongly correlated with c_{ASU} and w_{ASU}; (3) the influence of c_{TAX} on the c_{COE} of the plant fueled with low sulphur coal is very low, whereas for the plant fueled with high sulphur coal, the influence is much bigger. Therefore, at the point where the change rate of the c_{TAX} is nearly +90%, the c_{COE} of the plant fueled with #2 high sulphur coal surpasses that of the plant fueled with #1 low sulphur coal.

Fig. 4e–h show that: (1) in each case, c_C and c_{CAC} are most correlated with r_C and are strongly correlated with w_{ASU}, c_F and c_{ASU}; (2) c_C and c_{CAC} are weakly influenced by r and c_{TAX}; (3) c_C and c_{CAC} are negatively correlated with r_C, viz. c_C and c_{CAC} decrease when r_C increases.

It can be observed from Fig. 4 that a conventional plant or an Oxy-combustion plant fueled with high sulphur coal is more economical than one which is fueled with a low sulphur coal in a low c_{TAX} situation. In contrast, in a high c_{TAX} situation, the low sulphur coal is preferred. Therefore, taxation is an effective and advisable choice to control the pollutants emission.

4. Conclusion

The economic feasibility of Oxy-combustion technology based on existing coal-fired power plants in China has been studied and evaluated. The CO_2 taxation and CO_2 sale are considered to analyze the cost of electricity (c_{COE}) and CO_2 avoidance cost (c_{CAC})

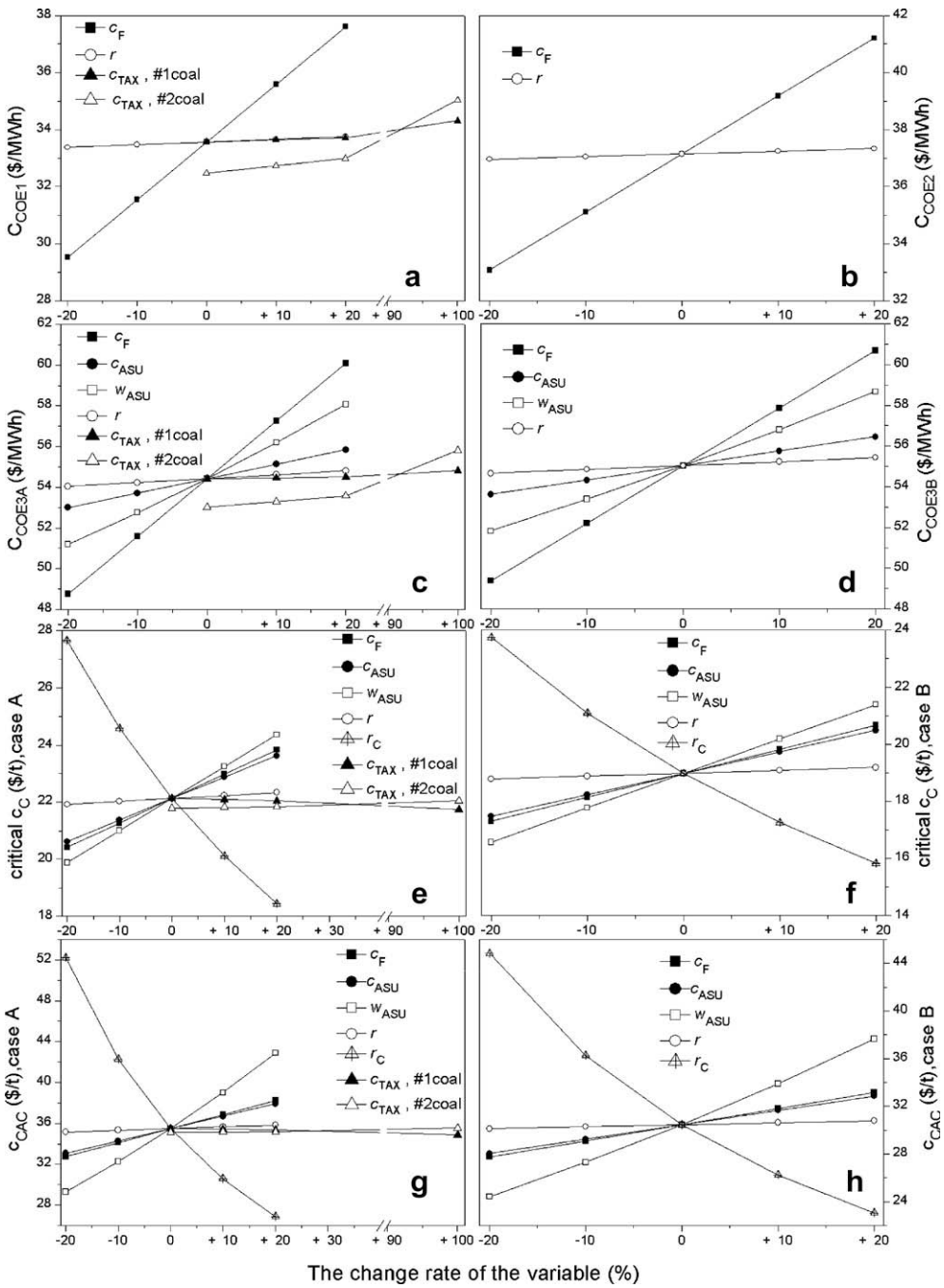

Fig. 4. The results of the sensitivity analysis.

in different cases. A sensitivity analysis on some typical variables has also been performed.

A number of conclusions can be drawn from the work:

(1) The cost of electricity of the Oxy-combustion plant is much greater (1.5–1.7 times) than that of the conventional combustion plant (with NO_x and SO_2 emission tax), even when the De-SO_x (wet-FGD) and de-NO_x (SCR) devices are added to the conventional plant. However, the costs of electricity of the Oxy-combustion plant and the conventional plant are nearly the same if the CO_2 sale price is within 17–22 \$/t (different cases). The retrofit from a conventional plant into an Oxy-combustion plant leads to a reduction of nearly 30% of the power output.
(2) The CO_2 avoidance costs of the retrofitted 2×300 MW Oxy-combustion plants, which range from 28.186 to 35.481 \$/t in different cases, are 1–3 \$/t bigger than those of the retrofitted 2×600 MW Oxy-combustion plants (generally 27–33 \$/t for different cases). Supercritical plants are more economical and more appropriate for Oxy-combustion retrofit.
(3) Based on the definition of the CAC, a new model of calculation of the CAC, where the CO_2 taxation and CO_2 sale are considered, has been carried out. The relation between T_C, c_C and $c_{CAC,}$ which could be used to analyze the economic feasibility of the retrofit of a plant, can be easily obtained by using the new model.
(4) the c_{COE} is most correlated with c_F and the c_{COE} of the Oxy-combustion plant are strongly correlated with c_{ASU} and w_{ASU}; the c_C and the c_{CAC} are most correlated with r_C and strongly correlated with w_{ASU}, c_F and c_{ASU}.

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