

# A Integrated System of The Coal-Fired Unit With CO<sub>2</sub> Capture to Produce Methanol

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**Abstract:** In view of the high energy consumption and subsequent CO<sub>2</sub> utilization in carbon capture power plants, a novel double-reheat thermal system with CO<sub>2</sub> capture and methanol production was designed. Taking a 1000MW unit as a reference, the adaptive particle swarm algorithm was used to optimize the parameters of the proposed system, and the influence of photoelectric hydrogen production cost and other factors on its performances were analyzed. The results show that when the carbon capture rate is 90%, the thermal efficiency of the proposed system is increased by 3.96%, the CO<sub>2</sub> emission intensity is reduced by 5.67g/kWh, and the net benefit reaches 17.9574 billion yuan compared with the coal-fired unit with CO<sub>2</sub> capture. With the decline in the cost of photovoltaic hydrogen production in the future, the net benefit of the integrated system will be significantly improved; When the coal-fired unit, coal-fired unit with CO<sub>2</sub> capture and integrated system reaches 5, 21 and 4 years of service, respectively, they become profitable.

**Key words:** double-reheat coal-fired unit; carbon capture; methanol production; thermal system integration; optimal design

Carbon Capture, Utilization and Storage (CCUS) is an important technical support for the goal of carbon neutrality after carbon peaking. At present, CO<sub>2</sub> has been successfully used in many fields such as medical, food, and chemical industry. Among them, the "liquid sunlight" technology [1] of using intermittent photovoltaics or wind power to produce green hydrogen and convert CO<sub>2</sub> emitted by industry on a large scale to synthesize methanol provides important support for the development of "methanol economy" [2] and has good development prospects. Methanol is an important raw material for the production of other chemical products. The coupling of green hydrogen synthesis methanol process with coal-fired carbon capture unit, combined with energy complementarity and cascade utilization principle for integrated system integration design and parameter optimization, have

important practical significance for solving the problems of subsequent utilization of CO<sub>2</sub> and hydrogen storage and transportation.

CO<sub>2</sub> capture is the forefront of CCUS technology, and when applied in coal-fired power plants, it can be divided into three categories: pre-combustion capture, oxygen-enriched combustion and post-combustion capture according to different carbon capture locations [3]. Among them, the post-combustion capture technology based on chemical absorption method does not require major changes to power plant equipment, and gradually becomes the best technical route for existing coal-fired units to implement carbon capture [4]. However, the traditional chemical absorbent monoethanolamine (MEA) has huge energy consumption for regeneration, up to 3.8GJ/tCO<sub>2</sub>, which can generally reduce the overall

net efficiency of carbon capture power plants by 9%~13% [5]. In order to weaken the adverse effects of carbon capture on the thermal economy of coal-fired power plants, researchers have done a lot of research mainly from the aspects of new absorbent development and thermal system integration optimization. Aliyon K[6] et al. compared MEA and piperazine as chemical solvents for CO<sub>2</sub> absorption, and simulated experiments showed that the reboiler energy required by the chemical absorption method using piperazine as solvent was about 3.4GJ/tCO<sub>2</sub>. ZHOU[7] et al. added 2-amino-2-methyl-1-methanol to pentamethyldiethylenetriamine (PMDETA)/diethylenetriamine (DETA), and the measured regeneration energy consumption could be reduced to 1.8GJ/tCO<sub>2</sub> after optimizing the ratio. Xu[8] et al. proposed a design scheme to increase the small back pressure machine and steam ejector for the integration of carbon capture system and coal-fired unit, which increased the efficiency of carbon capture unit by 4.15%. Fu[9] et al. designed a carbon capture system integration scheme with large carbon capture steam turbine for secondary reheat unit, which can reduce the standard coal consumption rate by 12.64g/kWh compared with conventional carbon capture unit after parameter optimization.

In the study of CO<sub>2</sub> resource utilization, Mustafa A[10] et al. believe that the mode of combining CO<sub>2</sub> and hydrogen into liquid methanol has good prospects for reducing the cost of hydrogen storage and transportation. Bellotti D[11] et al. proposed a new plant for converting methanol from CO<sub>2</sub> and hydrogen emitted from coal-fired power plants, in which hydrogen is produced by electrolysis of water from renewable energy, discussed the feasibility of this

scheme, and analyzed the impact of factors such as methanol price and equipment cost on the profitability of the plant. Kotowicz J[12] et al. designed an integrated system for producing green hydrogen from wind farms and CO<sub>2</sub> from coal-fired power plants to synthesize methanol, and calculated that the efficiency of the entire methanol preparation system could reach 45.5% to 52.9%. Yang N[13] et al. took a 600MW coal-fired unit as an example to propose a CCU system integration scheme to convert captured CO<sub>2</sub> into methanol, in which the heat in the CO<sub>2</sub> conversion reaction was used to supply MEA absorbent regeneration, which reduced the reboiler load by 41.84%.

Previous research work has shown that the production mode of using CO<sub>2</sub> captured by coal-fired power plants and green hydrogen to synthesize methanol is conducive to solving the problems of unstable renewable energy consumption and high-cost hydrogen storage and transportation, and at the same time, it can also make full use of the energy interaction between the CO<sub>2</sub> capture process and the methanol synthesis process, and effectively improve the thermal efficiency of the overall system through reasonable system integration design and parameter optimization. To this end, taking a secondary reheat unit as an example, the author designs an integrated system of "coal-carbon capture-methanol production", which integrates the hydrogen and CO<sub>2</sub> synthesis methanol process with the coal-fired carbon capture unit, heats the condensate of the coal-fired unit with the energy release in the methanol preparation process, and uses by-product steam as the heat source of the reboiler. The parameters of the proposed system were optimized, and compared with the reference coal-fired unit and the coal-fired carbon capture unit,

and then the influence of methanol selling price and unit service time on the system performance was analyzed.

### 1 System description

#### 1.1 Carbon capture system

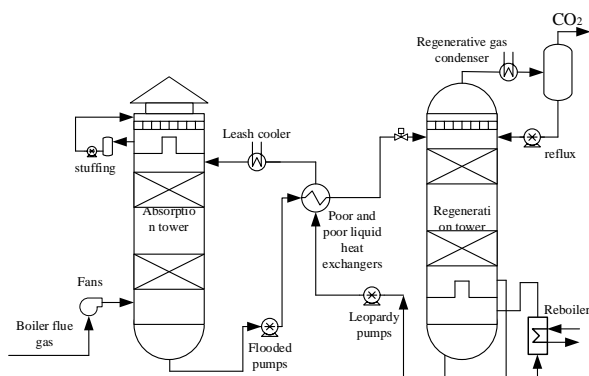


Fig.1 Process flow diagram of carbon capture system

The process flow of carbon capture technology after combustion based on chemical absorption method is shown in Figure 1. Chemical absorbents need to consume a large amount of heat in the regeneration tower to complete the regeneration, and this heat is usually supplied by the steam turbine in the coal-fired unit through the reboiler. In this paper, PMDETA/DETA-2-amino-2-methyl-1-methanol described in literature [7] is used as a chemical absorbent, and its working conditions are basically the same as MEA, and the regeneration temperature is about 122 °C.

#### 1.2 The coal-fired unit with CO<sub>2</sub> capture

The key to the integration of coal-fired units and carbon capture systems lies in the selection of the reboiler steam source. When CO<sub>2</sub> is captured on a large scale, a huge amount of steam flow is required. Under normal circumstances, in order to meet the needs of the regeneration parameters of the absorbent, the medium pressure cylinder exhaust steam is mostly supplied to the reboiler after temperature and pressure reduction [14-15], but this integration method will cause greater energy loss. Therefore, this paper adopts the carbon

capture turbine integration method proposed in the literature [9], and its connection system is shown in Figure 2, which effectively solves the energy supply matching problem of the reboiler in the carbon capture system.

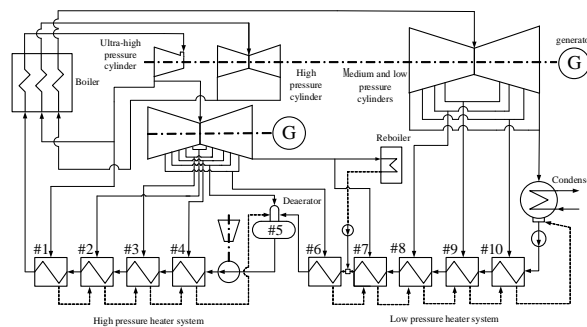


Fig.2 Steam-water flow diagram of a double-reheat coal-fired unit with CO<sub>2</sub> capture

#### 1.3 Methanol preparation system

There are three main reversible chemical reactions in the synthesis of methanol from carbon dioxide and hydrogen, which are shown in Equation (1) ~ Equation (3), and the general process flow chart is shown in Figure 3.

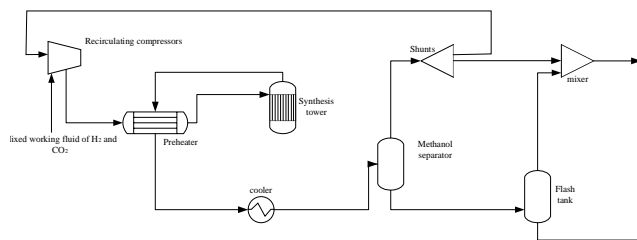
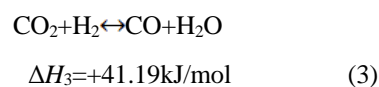
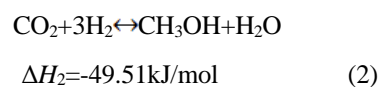
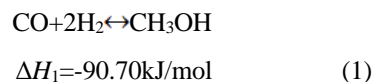


Fig.3 Process flow diagram of methanol production

The mixed fresh gas and circulating gas of H<sub>2</sub> and CO<sub>2</sub> are boosted by the circulating compressor and enter the synthesis tower through the preheater; After the outlet gas is released by the preheater and cooler, it

is sent to the methanol separator for subsequent separation treatment.

#### 1.4 Integrated system

The methanol synthesis reaction is an exothermic process, during which the methanol synthesis tower and working fluid need to release a large amount of heat to a certain temperature when flowing through the cooler. In order to match the reboiler parameter requirements of the carbon capture system, the methanol cooler is split into two stages, and the energy release of the primary cooler and the reaction heat of the synthesis tower are used in the system. The integration mode of the methanol preparation system and the coal-fired carbon capture unit is shown in Figure 4, the condensate in the figure is depressurized by the throttle valve and absorbs the heat released by the first-stage methanol cooler and the synthesis tower, and the steam generated can meet the heat source parameter requirements of the reboiler for use by the carbon capture system, and the reboiler return water is returned to the pipeline between the No. 7 and No. 8 heaters.

This integration method essentially absorbs the heat in the methanol preparation process and the heat from the reboiler return of the carbon capture system by the condensate of the coal-fired unit, which is in line with the principle of energy complementarity and cascade utilization.

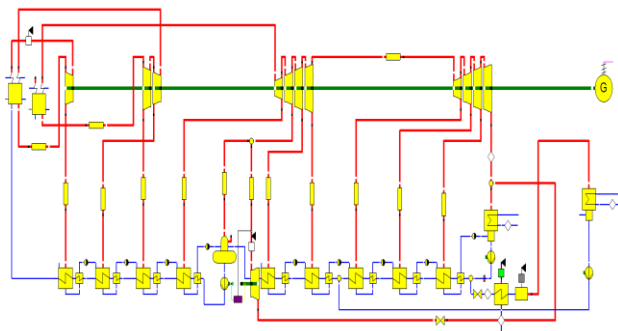


Fig.4 Flow diagram of the double-reheat coal-fired unit

with CO<sub>2</sub> capture and methanol production

## 2 Thermal economy calculation and optimization model

### 2.1 Steam distribution equation

The general steam-water distribution matrix equation for the thermal system of coal-fired units can generally be expressed by equation (4) [16]:

$$A\alpha + q_f = \tau \tag{4}$$

formula:  $A$  is the structural coefficient matrix of the thermal system;  $\alpha$  is the share matrix of each pumping flow;  $q_f$  is the auxiliary energy flow matrix;  $\tau$  is enthalpy lift matrix for heater feed. The steam-water distribution equation of the coal-fired unit with CO<sub>2</sub> capture shown in Figure 2 can be expanded as follows:  $g_i = h_{d,i} - h_{d_i}$ , is hydrophobic heat release for Class I heater units;  $t_i = h_{w_i} - h_{w,i+1}$ , is Class I heater unit feed water to absorb heat;  $q_i = h_i - h_{d_i}$ , is Class I heaters are used to extract steam and discharge heat;  $h_{d_i}$  is the hydrophobic enthalpy of the Class I heater;  $h_{w_i}$  is Water enthalpy at the outlet of the Class I heater;  $t_p$  is enthalpy lift for feed pump;  $q_{id}$  is ental Pilift Forfeld Pamp;  $a_{tc}$  is the share of steam extraction for the reboiler;  $r$  is the total number of steam extracted by ultra-high pressure cylinders and carbon capture steam turbines ihe total number of steam extracted by ultra-high pressure cylinders and carbon capture steam turbines;  $z$  is the total number of vapors extracted;  $k$  is the deaerator serial number.

$$\begin{bmatrix} q_1 \\ \gamma_2 & q_2 \\ \gamma_3 & \gamma_3 & q_3 \\ \vdots & \vdots & \ddots & \ddots \\ \gamma_k & \gamma_k & \cdots & \gamma_k & q_k \\ \tau_{k+1} & \tau_{k+1} & \cdots & \cdots & \tau_{k+1} & q_{k+1} \\ \tau_{k+2} & \tau_{k+2} & \cdots & \cdots & \tau_{k+2} & \gamma_{k+2} & q_{k+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ \tau_r & \tau_r & \cdots & \cdots & \tau_r & \gamma_r & \cdots & \gamma_r & q_r \\ \tau_{r+1} & \tau_{r+1} & \cdots & \cdots & \tau_{r+1} & \gamma_{r+1} & \cdots & \cdots & \gamma_{r+1} & q_{r+1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ \tau_z & \tau_z & \cdots & \cdots & \tau_z & \gamma_z & \cdots & \cdots & \cdots & \gamma_z & q_z \end{bmatrix}_{z \times z} + \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \vdots \\ \alpha_k \\ \alpha_{k+1} \\ \alpha_{k+2} \\ \vdots \\ \alpha_r \\ \alpha_{r+1} \\ \vdots \\ \alpha_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \tau_p \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ \vdots \\ q_{td} \\ \tau_{r+1} \\ \vdots \\ \tau_z \end{bmatrix} [\alpha_{tc}] = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \vdots \\ \tau_k \\ \tau_{k+1} \\ \tau_{k+2} \\ \vdots \\ \tau_r \\ \tau_{r+1} \\ \vdots \\ \tau_z \end{bmatrix} \quad (5)$$

2.2 Thermal economy calculation and optimization model

The thermal economy of coal-fired unit with CO<sub>2</sub> capture and the integrated systems can be evaluated by circulating thermal efficiency, and for the coal-fired unit with CO<sub>2</sub> capture, the circulating thermal efficiency is shown in Equation (6):

$$\begin{cases} w_1 = h_0 + (1 - \sum_{j=1}^r \alpha_j - \alpha_{tc})(q_{rh1} + q_{rh2}) - \alpha_{tc} h_{tc} - \sum_{j=1}^z \alpha_j h_j - \alpha_p h_p - (1 - \sum_{j=1}^z \alpha_j - \alpha_{tc} - \alpha_p) h_c \\ q_1 = h_0 - h_{fw} + (1 - \sum_{j=1}^r \alpha_j - \alpha_{tc})(q_{rh1} + q_{rh2}) \\ \eta_1 = \frac{w_1}{q_1} \end{cases} \quad (6)$$

formula:  $w_1$  is the cyclic work done per unit working fluid;  $q_1$  is The circulating heat absorption of the unit working fluid;  $h_0$  is new steam enthalpy;  $h_c$  is exhaust enthalpy;  $h_{fw}$  is boiler feed enthalpy;  $q_{rh1}$  is one and then another enthalpy;  $q_{rh2}$  is secondary reheat enthalpy;  $h_j$  is Class J heater extracts enthalpy;  $h_{tc}$  is the reboiler inlet enthalpy;  $\alpha_p$  is Feed pump turbine flow share;  $h_p$  is Feed water pump turbine inlet enthalpy.

Taking equation (5) to substitute the steam extraction share into the equation (6), and combining it with the turbine expansion process line, the circulating thermal efficiency of the system  $\eta$  can be expressed as a function of the steam extraction pressure and reheat pressure at all levels [17], namely:

$$\eta = f(p_1, p_2, \dots, p_z, p_{rh1}, p_{rh2}) \quad (7)$$

Then, taking the circulating thermal efficiency of the thermal system as the optimization goal, it can be determined that the coal-fired unit with CO<sub>2</sub> capture optimization model shown in Figure 2 is shown in Equation (8):

$$\begin{cases} \max \eta_1 = f(p_1, p_2, \dots, p_z, p_{rh1}, p_{rh2}) \\ \text{s.t. } p_{tc} < p_i < p_0 \quad (i = 1, 2, \dots, r) \\ p_c < p_j < p_{tc} \quad (j = r + 1, r + 2, \dots, z) \\ p_c < p_{rh2} < p_{rh1} \end{cases} \quad (8)$$

formula:  $p_0$  and  $p_c$  the inlet pressure and exhaust pressure of the secondary reheat turbine are respectively;  $p_{tc}$  is the exhaust pressure of the carbon capture steam turbine;  $p_{rh1}$  and  $p_{rh2}$  Primary and secondary reheat section pressures, respectively.

Similarly, for the integrated system shown in Figure 4, the cyclic thermal efficiency is only related to the 10-stage extraction pressure and the 2-stage reheat pressure.

### 2.3 Dynamic adaptive particle swarm algorithm

Compared with other optimization algorithms, dynamic adaptive particle swarm optimization (DAPSO) is used for parameter optimization, because dynamic adaptive particle swarm optimization shows relatively excellent convergence and solution accuracy in thermal system parameter optimization [17]. Its expression can be expressed as shown in Equation (9) and Equation (10):

$$v_i^{t+1} = \omega_i^t v_i^t + c_1 r_1 (P_i^t - x_i^t) + c_2 r_2 (G_i^t - x_i^t) \tag{9}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1}, i = 1, 2, \dots, n \tag{10}$$

formula:  $x_i^t$  is the position of the  $i$ -th particle at the  $t$  iteration;  $c_1$  and  $c_2$  is acceleration factor, generally take  $c_1 = c_2 = 2$ ;  $P_i^t$  is the best position searched for by the  $i$ th particle in  $t$  iterations;  $G_i^t$  is the best position searched for by the whole population in  $t$  iterations;  $r_1$  and  $r_2$  is a random number that varies in the range  $[0,1]$ ;  $\omega_i^t$  is the inertia weight of the  $i$ th particle at  $t$  iterations, Its value varies with the number of particles and their iterations. Its defining equation is shown in equation (11):

$$\omega_i^t = \begin{cases} \beta s_2 & (s_2 > a, \text{ and } s_1 < b) \\ 1 - \alpha h_i^t + \beta s_1 & (\text{other}) \end{cases} \tag{11}$$

Where:  $\alpha$ 、 $\beta$  select within  $[0,1]$ , take  $\alpha = \beta = 0.5$ ;  $a$ 、 $b$  is the control threshold of the aggregation factor, take  $a = 0.9$ ,  $b = 0.5$ ;  $h_i^t$  is the evolutionary speed factor, calculated by equation (12);  $s_1$  and  $s_2$  is the aggregation factor, calculated by equation (13) and equation (14):

$$h_i^t = 1 - \frac{|\min(F(P_i^{t-1}), F(P_i^t))|}{|\max(F(P_i^{t-1}), F(P_i^t))|} \tag{12}$$

$$s_1 = \frac{|\min(F_t, \bar{F}_t)|}{|\max(F_t, \bar{F}_t)|} \tag{13}$$

$$s_2 = 1 - \frac{1}{NL} \sum_{i=1}^N \sqrt{\sum_{d=1}^D (P_{id} - \bar{P}_d)^2} \tag{14}$$

Where:  $F_t$  is the best adaptation value in the  $t$ th

iteration;  $\bar{F}_t$  is the average adaptation value in the  $t$ th iteration;  $N$  is the population size;  $L$  is the longest radius of the search space;  $D$  is the dimension of the solution space;  $P_{id}$  is the  $d$ th dimensional coordinate of the  $i$ -th particle;  $\bar{P}_d$  is the average of the  $d$ th dimensional coordinates of all particles.

### 2.4 Economic evaluation method

The economic efficiency of the system can be examined through economic analysis, and the economic expenditure of the system  $CO$  can be calculated by equation (15)[18]:

$$CO = C_{ic} + \sum_{n=1}^r \frac{C_n}{(1 + \alpha)^n} \tag{15}$$

Where:  $C_{ic}$  is the initial construction cost;  $C_n$  is the operating cost in the  $n$ th year;  $\alpha$  is the discount rate;  $r$  is the life cycle of the unit;  $C_{ic}$  and  $C_n$  can be calculated from equation (16) and equation (17), respectively[19]:

$$C_{ic} = (c_{ic,p} + c_{ic,ccs}) \times W_e + c_{ic,m} \tag{16}$$

$$C_n = (c_{cp,OM} + c_{ccs,OM}) \times W_e + c_{m,OM} + M_c P_c + M_H P_H \tag{17}$$

Where:  $W_e$  is the installed capacity of the unit;  $c_{ic,p}$  and  $c_{ic,ccs}$  respectively Initial investment cost per unit of electricity for coal-fired units and carbon capture systems;  $c_{ic,m}$  is the initial investment cost of methanol preparation system;  $c_{cp,OM}$  and  $c_{ccs,OM}$  are the O&M unit power costs for coal-fired units and carbon capture systems, respectively;  $c_{m,OM}$  is the O&M cost of the methanol preparation system, take  $c_{m,OM}$  for  $c_{ic,m}$  of 4%;  $M_c$  and  $M_H$  are the mass of coal and the mass of hydrogen consumed annually, respectively,  $P_c$  and  $P_H$  are the cost of coal and the cost of photovoltaic hydrogen production, respectively.

For  $c_{ic,m}$ , can be calculated from equation (18)[19]:

$$c_{ic,m} = \theta \times c_{ic,m,ref} \times \left(\frac{S_j}{S_{j,ref}}\right)^m \quad (18)$$

Where:  $\theta$  is the domestic production index, generally taken 0.65;  $c_{ic,m,ref}$  is the initial investment cost of the reference methanol production plant,  $S_j$  and  $S_{j,ref}$  are the syngas feed volumes of the integrated system and the reference methanol production plant proposed in this paper, respectively;  $m$  is the size factor, generally taken 0.67.

The economic income  $CI$  of the system can be calculated by equation (19):

$$CI = \sum_{n=1}^r \frac{(W_{e,net} \times c_e + P_m \times c_m) \times T}{(1 + \alpha)^n} \quad (19)$$

Where:  $W_{e,net}$  is the net generation capacity of the unit;  $c_e$  is the price of electricity;  $P_m$  is methanol production;  $c_m$  is the price of methanol;  $T$  is the annual system utilization hours.

Then the net benefit NPV of the system can be expressed by equation (20):

$$NPV = CI - CO \quad (20)$$

Assuming that the annual utilization hours of the system is 5000, the price of coal is RMB 800/t, the cost of photovoltaic power generation is RMB 0.2/kWh, 50 degrees of electricity is needed to produce 1kg of hydrogen by electrolysis of water, the price of electricity is RMB 0.5/kWh, the price of methanol is RMB 2500/t, and other parameters are taken as shown in Table 1.

Tab.1 Economic parameters and sources

Parameters	Numerical value	Data source
$c_{ic,p}/(\text{yuan} \cdot \text{kW}^{-1})$	3986	[18]
$c_{ic,ccs}/(\text{yuan} \cdot \text{kW}^{-1})$	4395.77	[18]
$c_{ic,m,ref}/\text{yuan}$	124200000	[20]
$S_{j,ref}/(\text{mol} \cdot \text{s}^{-1})$	10810	[20]

$$c_{cp,OM}/(\text{yuan} \cdot \text{kW}^{-1}) \quad 133 \quad [18]$$

$$c_{ccs,OM}/(\text{yuan} \cdot \text{kW}^{-1}) \quad 120.71 \quad [19]$$

$$r/\text{year} \quad 25 \quad [21]$$

$$\alpha/\% \quad 8 \quad [18]$$

### 3 Example calculation

In this paper, a domestic 1000MW ultra-supercritical secondary reheat coal-fired unit is used as a reference unit, and its reheat system includes "four high, five low and one de-oxygenation" with a total of 10 heater stages.

Tab.2 Rated parameters of a 1000MW double-reheat unit

Parameters	Numerical value
Unit power /MW	1000
Main steam flow /( $\text{kg} \cdot \text{s}^{-1}$ )	706.24
Main steam pressure /MPa	30
Main steam temperature / $^{\circ}\text{C}$	600
Primary reheat temperature / $^{\circ}\text{C}$	620
Secondary reheat temperature / $^{\circ}\text{C}$	620
Vapor discharge pressure /MPa	0.005

The main parameters of the carbon capture system and the methanol production process are shown in Table 3.

Tab.3 The main parameters of carbon capture system and methanol production process

Parameters	Numerical value
Steam temperature at the exothermic end of the reboiler / $^{\circ}\text{C}$	132
Steam pressure at the exothermic	0.287

end of the reboiler /MPa		$p_6$ /MPa	0.729	0.608
CO <sub>2</sub> removal rate from flue gas/%	90	$p_7$ /MPa	0.287	0.335
Energy consumption for regeneration of absorbent	1.8	$p_8$ /MPa	0.148	0.152
/(GJ·tCO <sub>2</sub> <sup>-1</sup> )		$p_9$ /MPa	0.063	0.063
Carbon capture turbine isentropic efficiency /%	90	$p_{th1}$ /MPa	9.967	9.967
Fresh gas CO <sub>2</sub> molar share /%	26	$p_{th2}$ /MPa	2.346	2.903
Synthesis tower reaction temperature /°C	215	Thermal efficiency/%	46.08	50.04
Diversion ratio	0.98	The comparison indexes of coal-fired unit, coal-carbon-capture unit and integrated system are shown in Table 5.		
Synthesis tower reaction pressure /MPa	8			
First stage cooler process outlet temperature/°C	115			
Second stage cooler process outlet temperature /°C	35	Tab. 5 Index comparison of different units		

The comparison indexes of coal-fired unit, coal-carbon-capture unit and integrated system are shown in Table 5.

Comparative indicators	Coal-fired		
	Coal-fired unit	unit with CO <sub>2</sub> capture	Integrated system
CO <sub>2</sub> Emission Intensity			
/(g·kWh <sup>-1</sup> )	695.57	71.67	66.00
Standard coal consumption for electricity supply rate			
/(g·kWh <sup>-1</sup> )	259.04	283.96	261.50
Net benefit/billion	7.9333	0.5788	17.9574

Referring to the above coal-fired unit, the main steam flow rate was kept constant, and the system parameters were redesigned based on the coal-fired unit with CO<sub>2</sub> capture shown in Figure 2 and the integrated system shown in Figure 4, provided that the feedwater temperature remained unchanged.

The dynamic adaptive particle swarm optimization algorithm was used, and the population size was 20, the number of iterations was 500, and 50 iterations were performed to select the best optimization results as shown in Table 4.

Tab.4 Optimization results of Particle swarm algorithm

Parameters	Coal-fired unit with CO <sub>2</sub> capture	Integrated system
$p_1$ /MPa	10.717	10.717
$p_2$ /MPa	7.776	5.404
$p_3$ /MPa	5.180	3.121
$p_4$ /MPa	3.223	1.730
$p_5$ /MPa	1.681	1.089

As shown in the above table, the thermal efficiency of the integrated system is improved by 3.96% compared with the coal-fired unit with CO<sub>2</sub> capture, indicating that the introduction of methanol preparation in the coal-fired unit with CO<sub>2</sub> capture can effectively improve the overall system energy consumption level. At the same time, the CO<sub>2</sub> emission intensity and the standard coal consumption

on rate of the integrated system are reduced by 5.67 g/kWh and 22.46 g/kWh, respectively. compared with the reference coal-fired unit, the CO<sub>2</sub> emission intensity of the integrated system is reduced by 629.57 g/kWh, and the net benefit is increased by 10.0241 billion yuan, which has considerable emission reduction potential and economic advantages.

The product revenue and cost expenditure components of the integrated system over its life cycle are analyzed in detail, and the results are shown in Figure 6 and Figure 7. From the figures, it can be seen that due to the huge amount of CO<sub>2</sub> captured, methanol revenue will become the major part of the integrated system revenue, reaching 68.25% of the total system revenue. It also leads to the fact that the cost of photovoltaic hydrogen production takes up a large part of the total system cost, reaching 62.21%. Therefore, in the future, effectively reducing the cost of hydrogen production or increasing the price of methanol sold can significantly increase the net income of the integrated system and thus promote the rapid development of the "methanol economy".

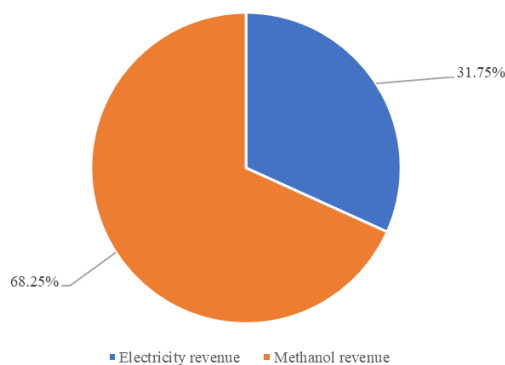


Fig.5 Revenue decomposition of products in the double- reheat coal-fired unit with CO<sub>2</sub> capture and methanol production

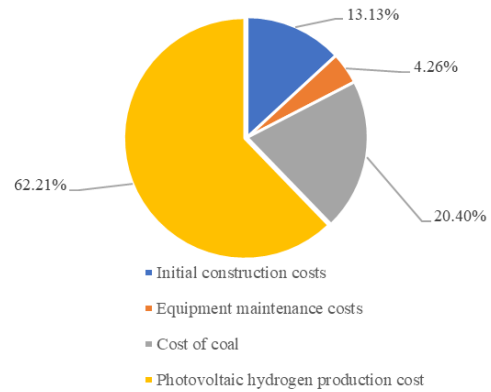


Fig.6 Decomposition of costs and expenditures of the double- reheat coal-fired unit with CO<sub>2</sub> capture and methanol production

#### 4 Analysis of influencing factors

##### 4.1 photovoltaic hydrogen production cost

As can be seen from Figure 7, when the assumed photoelectric hydrogen production cost is 10 yuan/kgH<sub>2</sub>, the hydrogen production cost in the integrated system accounts for 62.21% of its total cost expenditure. It can be seen that the hydrogen production cost is the key factor affecting the good or bad net benefit of the integrated system, taking the variation range of hydrogen production cost from 5 yuan/kg to 15 yuan/kg, and the relationship between the net return of the system and the photoelectric hydrogen production cost when the carbon capture rate is 90% is shown in Figure 9.

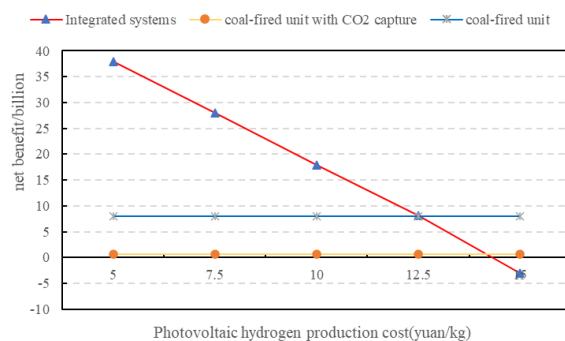


Fig.7 Impact of the cost of photoelectric hydrogen production on the net benefit of system

It can be seen that the net benefit of the system is

linearly decreasing with the increase of photoelectricity hydrogen production cost, and the net benefit of the integrated system decreases about 4.061 billion yuan for each increase of photoelectricity hydrogen production cost of 1 yuan/kg, and the integrated system can be in a profitable state when the hydrogen production cost is lower than 14.4 yuan/kg, and the net benefit of the integrated system is better than Coal-fired unit with CO<sub>2</sub> capture when the hydrogen production cost is lower than 14.2 yuan/kg. When the cost of hydrogen production is below 12.4 yuan/kg, the net benefit of the integrated system is better than that of the coal-fired unit.

#### 4.2 Unit service time

In the previous analysis, we assumed that the service life of the unit is 25 years and all three systems generate profits, more or less, while in fact, the service time of the unit plays a crucial role in the net income of the system, and the unit may face the risk of loss of interest or even collapse if the service time is too short. The following is to analyze the influence law on the net benefit of the system when the service time of the unit varies within 25 years, as shown in Figure 10.

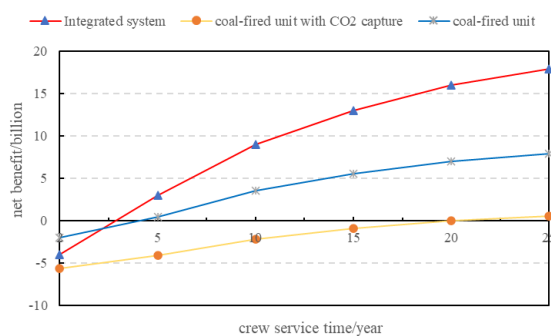


Fig 8 Impact of crew service time on the net benefit of system

From Figure 10, it can be seen that the net benefit of all three systems shows a steady growth trend as the service time of the units increases, and the growth rate gradually slows down and the net benefit gradually

stabilizes. When the service time of the unit is 2 years, all three systems have negative net benefit, which is mainly due to the fact that the product benefit of all three systems is not enough to offset the initial investment and operation and maintenance costs of the system. For the coal-fired unit, it can start to be profitable when their service time reaches 5 years; for the coal-fired unit with CO<sub>2</sub> capture, it can start to be profitable when their service time reaches 21 years; and for the integrated system, it can start to be profitable when their service time reaches 4 years. Therefore, for the coal-fired unit with CO<sub>2</sub> capture and integrated systems, the length of service time of carbon capture devices should be taken into consideration to avoid the loss of revenue of the whole system due to its short service time.

#### 5 Conclusion

(1) Based on the principle of energy step utilization, a integrated system is designed by heating the condensate of coal-fired units with the released energy from the methanol preparation process and using the by-product steam as the reboiler heat source, which shows significant advantages in terms of system thermal efficiency, CO<sub>2</sub> emission intensity and net system revenue when compared with coal-fired units and coal-carbon-capture units.

(2) When the carbon capture rate is 90%, the optimization calculation of each system by particle swarm algorithm shows that the integrated system has considerable carbon emission reduction potential and economic advantages as the CO<sub>2</sub> emission intensity is reduced by 629.57g/kWh and the net benefit is increased by 10.0241 million yuan compared with the coal-fired unit; the thermal efficiency is increased by 3.96% compared with the coal-fired-carbon capture unit, and the CO<sub>2</sub> emission intensity and Compared

with coal-fired-carbon capture units, the thermal efficiency is improved by 3.96%, and the CO<sub>2</sub> emission intensity and standard coal consumption rate of electricity supply are reduced by 5.67g/kWh and 22.46g/kWh, respectively.

(3) The cost of photovoltaic hydrogen production accounts for more than 60% of the total cost of the integrated system, and effective reduction of hydrogen production cost is the key to improve the advantages of the integrated system. When the cost of hydrogen production of the integrated system is lower than 16.2 yuan /kg, it can achieve profitability, when the cost of hydrogen production is lower than 15.8 yuan /kg, the net return is better than that of the coal-fired-carbon capture unit, and when the cost of hydrogen production is lower than 13.9yuan /kg, the net benefit is better than that of the coal-fired unit.

(4) For the coal-fired unit, it can start to be profitable when its service time reaches 5 years; for the coal-fired unit with CO<sub>2</sub> capture, it can start to be profitable when its service time reaches 21 years; for the integrated systems, it can start to be profitable when its service time reaches 4 years. Therefore, for the coal-fired unit with CO<sub>2</sub> capture and the integrated system, the length of service time of carbon capture devices should be taken into consideration to avoid the loss of revenue of the whole system due to their short service time.

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