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Research on operation decision of thermal power units with both electricity spot trading and carbon emissions trading

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Abstract—Low carbon operation is one of the goals of the energy revolution, and the thermal power units are required to achieve more carbon emission reduction for achieving the carbon peaking and carbon neutrality goals. To help thermal power units participating in both electricity spot trading and carbon trading to optimize their operational decisions, a cost-benefit model for thermal power units that take into account both electricity spot trading and carbon trading is built from two perspectives: low-carbon technology and low-carbon policy, combining low-carbon instruments with market mechanisms. The objective is to maximize the profitability of the unit, and the effectiveness of the proposed model is proved by simulation using actual measurement data. The results proves that the proposed model can balance low carbon target and economic aspects, and is also useful for thermal power units to optimize their operational decisions under different scenarios.

1.Introduction

In order to achieve the carbon peaking and carbon neutrality goals, thermal power units, which account for a high proportion of China's total power generation, are under greater pressure to reduce carbon emissions. At present, under the pressure of environmental protection, thermal power units passively respond to the mandatory policy requirements put forward by the state, the scope of environmental cost control is narrow, and post-processing is the main, lack of overall consideration.

The electricity industry has been involved in the carbon trading market ever since. Most scholars believe that considering carbon trading can effectively promote the power system including thermal power units to reduce carbon emissions and operation costs. At the same time, the introduction of carbon capture technology in traditional thermal power units can be transformed into carbon capture power plants.

On the basis of the above studies, this paper focuses on the economic benefits and CO_2 emission reduction of thermal power units, constructs a cost-benefit model of thermal power units that takes into account both power spot trading and carbon trading, comprehensively considers the impact of adding carbon capture devices on the model, and analyzes the operation strategies of the units under different scenarios. In order to provide theoretical guidance and countermeasures for the implementation of carbon trading mechanism for existing thermal power units.

2.Analysis of carbon emission market and current situation of thermal power

2.1 Carbon emission market

Through the establishment of a carbon emission trading market, energy conservation and emission reduction targets can be achieved. By the end of 2022, about 230 million tons of emission allowances had been traded in China's carbon market, with a cumulative transaction value of about 10.4 billion yuan. The daily closing price fluctuated slightly between 55 yuan/ton and 62 yuan/ton throughout the year, and the annual average transaction price was 55.30 tons. More than 2,000 power enterprises have been included in the national carbon emission trading market.

2.2 Current situation of thermal power

The thermal power industry is moving towards a green, clean and efficient direction, while also constantly adapting to policy and market changes to achieve sustainable development. In 2022, the total power production reached 8.4 trillion kilowatt-hours, of which thermal power production accounted for 69.56 percent, or about 5.8 trillion kilowatt-hours, up 1.41 percent year on year. By the end of December 2022, China's installed power generating capacity was about 2.56 billion kW, up 7.87 percent year on year, and the installed thermal power capacity was about 1.33 billion kW, up 2.75 percent year on year. The proportion of installed thermal power capacity continues to decline, reaching 51.96 percent in 2022, down about 4.6 percent year on year.

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3. Cost-benefit model of thermal power units taking into account spot power trading and carbon trading

3.1 Objective function

$$\text{Max } F = \text{Max }(R_c + R_s + R_{CO2} - C_{fuel} - C_k - C_s - C_{CO2} - C_d - C_l) \tag{1}$$

In the formula: F is unit profit; R_c is the income from the unit power sale contract; R_s is the electricity sales income of the unit participating in spot trading, and only the positive value is considered. R_{CO2} is the income obtained by unit participating in carbon trading and selling carbon quota, and only positive values are considered. C_{fuel} is the total coal consumption cost of the unit; C_k is the total cost of unit startup and shutdown; C_s is the power purchase cost of unit participating in spot trading, and only the positive value is considered. C_{CO2} is the cost of purchasing carbon quota for unit participating in carbon trading, and only the positive value is considered. C_d is the depreciation cost of carbon capture equipment; C_l is the cost of solution loss in solution storage.

$$\begin{cases} R_c = p_c \cdot Q_{c,t} \\ R_s = I_t \cdot Q_t \\ Q_t = P_{Gi,t} - P_{Di,t} - Q_{c,t} \\ R_{CO2} = K_{CO2} \cdot (E_q - E_A) \\ E_q = \alpha \cdot E \\ E_A = \sum_{i=1}^{N} \sigma_i \cdot P_{Gi,t} \\ C_{fuel} = \sum_{i=1}^{N} U_{i,t}\left(a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i\right) \\ C_k = \sum_{i=1}^{N}\left[U_{i,t}(1-U_{i,t-1}) + U_{i,t-1}(1-U_{i,t})\right] \cdot C_{ki} \\ C_s = I_t \cdot Q_t' \\ Q_t' = Q_{c,t} - (P_{Gi,t} - P_{Di,t}) \\ C_{CO2} = K_{CO2} \cdot (E_A - E_q) \\ C_d = C_{FL}\frac{(1+r)^{N_{ZJ}} \cdot r}{365 \cdot 24 \cdot \left[(1+r)^{N_{ZJ}} - 1\right]} + R_{RY}V_{RY}\frac{(1+r)^{N_{RY}} \cdot r}{365 \cdot 24 \cdot \left[(1+r)^{N_{RY}} - 1\right]} \\ C_l = \sum_{i=1}^{N} K_s \cdot \varphi \cdot E_{CO2,it} \end{cases} \tag{2}$$

The unit completes the corresponding generating capacity according to the signed contract. Multiply the contracted electricity quantity by the agreed price and get the income from the electricity sale contract. When the thermal power unit meets the existing contract capacity on the basis of increasing output. The increase of this part of output multiplied by the real-time electricity price of the spot market of electricity in this period of time is the income of participating in the spot market of electricity; otherwise, it is the cost of participating in the spot trade of electricity. The unit will sell the surplus carbon quota in the carbon market to obtain a certain income, on the contrary, the purchase of carbon quota will produce the corresponding cost. The first part of the depreciation cost of carbon capture equipment is the depreciation cost of shunt carbon capture equipment, and the second part is the depreciation cost of solution storage, which is calculated through the corresponding equipment cost, a certain depreciation period and a certain discount rate. The solution loss cost can be obtained by multiplying the mass of carbon dioxide captured by the carbon capture equipment by the solvent cost coefficient of ethanolamine and then by the solvent operating loss coefficient.

In the calculation of profit, this model does not consider other costs except the above costs, such as labor costs, etc., and this model is only used for theoretical calculation.

3.2 Constraints

(1) Constraints on unit power balance

$$\begin{cases} \sum_{i=1}^{N} U_{i,t} P_{Gi,t} + Q_t' = Q_{c,t} + Q_t + \sum_{i=1}^{N} P_{Di,t} + \sum_{i=1}^{N} P_{Bi,t} \\ P_{Bi,t} = \lambda \cdot E_{CO2,it} \end{cases} \tag{3}$$

The total output of the thermal power unit in a certain period of time plus the purchased electricity of the unit in the electricity spot market during the period of time shall be the contracted electricity of the unit in the period of time plus the sold electricity of the unit in the electricity spot market plus the fixed energy consumption of the unit and carbon capture equipment.

(2) Constraints on unit output

$$\begin{cases} P_{min} \le P_{Gi,t} \le P_{max}, \quad U_{i,t} = 1 \\ P_{Gi,t} = 0, \quad U_{i,t} = 0 \end{cases} \tag{4}$$

Since the upper and lower limits of output of different thermal power units are different after starting up, corresponding processing constraints should be set to ensure that the thermal power units can generate electricity within the permissible range.

(3) Unit climbing constraints

$$-R_{down,i} \le P_{Gi,t} - P_{Gi,t-1} \le R_{up,i} \tag{5}$$

As there is a certain constraint on the maximum output that can be increased or decreased in a certain period of time for thermal power units, and the situation of different units is different, the corresponding climbing constraint for thermal power units should be set.

(4) Unit start-stop constraints

$$\begin{cases} \sum_{k=t}^{T_{OFF}+t-1}(1 - U_{i,k}) \ge T_{OFF}(U_{i,t-1} - U_{i,t}) \\ \sum_{k=t}^{T_{ON}+t-1} U_{i,k} \ge T_{ON}(U_{i,t} - U_{i,t-1}) \end{cases} \tag{6}$$

Since different thermal power units have corresponding minimum shutdown time and minimum startup time, the corresponding start-stop constraint should be set to ensure the normal startup and shutdown behavior of thermal power units.

(5) Carbon quota balance constraint

$$\begin{cases} E = \sum E_q \\ \sum \alpha = 1 \end{cases} \tag{7}$$

The government grants free carbon allowances to units participating in the carbon market, which are calculated on an annual basis. Therefore, in the process of solving the model, the total amount of carbon quota in each period of a year should be equal to the annual quota allocated by the government.

(6) Carbon capture equipment constraints

$$\begin{cases} 0 \le E_{CO2,it} \le \eta \cdot \beta \cdot \sigma_i \cdot P_{Gi,max} \\ E_{CO2,it} = E_{Wi,t} + \beta \cdot \delta_{i,t} E_{Ai,t} \\ E_{Wi,t} = \theta \cdot V_{Ni,t} \cdot c_R \cdot \rho_R \cdot \frac{M_{CO2}}{M_{MEA}} \\ E_{Ai,t} = \sigma_i \cdot P_{Gi,t} \end{cases} \tag{8}$$

Carbon dioxide exists in solution as a compound, so it is necessary to consider the relationship between the mass of carbon dioxide and the volume of ethanolamine solution.

(7) Constraints on the amount of liquid stored in solution memory

$$\begin{cases} V_{CFYi,t} = V_{CFYi,t-1} - V_{Ni,t} + V_{Mi,t} \\ V_{CPYi,t} = V_{CPYi,t-1} + V_{Ni,t} - V_{Mi,t} \\ 0 \le V_{CFYi,t} \le V_{CRi} \\ 0 \le V_{CPYi,t} \le V_{CRi} \end{cases} \tag{9}$$

Because the capacity of solution storage in the carbon capture equipment installed by the unit is fixed, and the solution circulates in the rich liquid storage and the lean liquid storage with the operation of the equipment, a certain constraint of solution storage liquid should be satisfied.

3.3 Example analysis

This paper adopted a thermal power unit with a minimum output of 200MW and a maximum output of 455MW. At the same time, according to the collected real data of market demand, a group of market demand conditions were randomly sampled, and gurobi was called in Matlab to optimize and solve the model.

Firstly, carbon emission trading results of units in the model are obtained, as shown in the figure below.

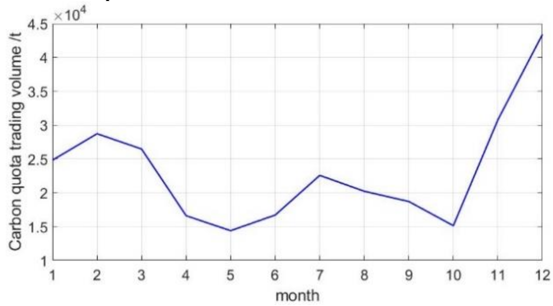

Fig 1. Curve of trading volume of carbon emission permits in Model 3

It can be seen that there are large fluctuations in the carbon quota trading volume curve. In fact, the carbon quota of thermal power units is relatively high at present, and the carbon quota to be traded only accounts for about 10% of the total carbon dioxide emissions of the units.

In addition, the model is solved by hour. The solution results show that thermal power units sell carbon emission rights in a small amount, but in most cases they buy carbon emission rights in order to increase output to meet the demand of the power market and obtain better profits. This is because at present, the carbon quota of the unit is high and the carbon price in the carbon market is low. The thermal power unit can obtain better economic profits by increasing output in response to the demand of the power market. As a result, the carbon dioxide emissions of the unit are greater than the carbon quota, which is reflected in the purchase of carbon emission rights in the carbon market.

At the same time, for comparison, based on the established model, relevant Settings of carbon capture equipment were cancelled in this paper, and the solution was re-optimized. The obtained results were compared with the initial operation results of the model, and the optimal decisions of thermal power units without carbon capture equipment and with carbon capture equipment were obtained. The results are shown in Table 1.

Table 1 Influence of carbon capture equipment on thermal power units

	Generated energy /MW•h	Income from electricity sales /10,000 yuan	Cost of buying carbon permits /10,000 yuan	Profit /10,000 yuan	Carbon emission /t
No carbon capture equipment	3183258	18360	5042	52910	2864932
Carbon capture equipment was set up	3496609	18360	1615	52560	2028033

As can be seen from the above table, when the demand of power spot market remains unchanged, the electricity sold by thermal power units remains unchanged, thus resulting in the income from electricity sales remains unchanged. However, the power generation with carbon capture equipment is still 313,351MWh higher than that without carbon capture equipment. This is because carbon capture equipment has a certain energy consumption in operation, and the energy consumption of this part is larger, and the corresponding increased coal consumption cost is also larger, so that the unit's profit decreases instead of rising when the power generation increases. However, also affected by carbon capture equipment, carbon emissions of the unit decreased significantly by 836,899 tons, resulting in the cost of purchasing carbon emission rights of the unit decreased by 68%.

Under the combined action of coal consumption cost and carbon emission right cost, although the profit of thermal power units with carbon capture equipment is still smaller than that without carbon capture equipment, the profit difference is small, with an annual profit difference of 3.5 million yuan, which only accounts for 0.7% of the annual profit of thermal power units with carbon capture equipment.

Specifically, the comparison curve of power generation of thermal power units without carbon capture equipment and with carbon capture equipment is shown in Fig.2, profit comparison curve is shown in Fig.3, and carbon emission comparison curve is shown in Fig.4.

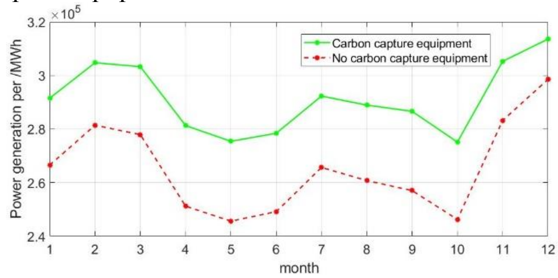

Fig.2 Comparison of power generation of thermal power units

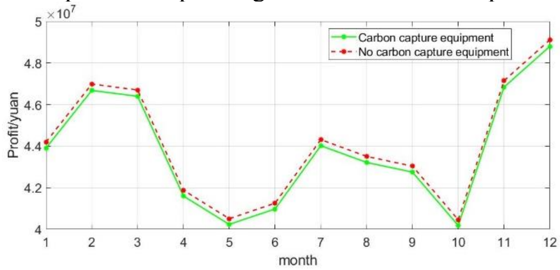

Fig.3 Profit comparison of thermal power units

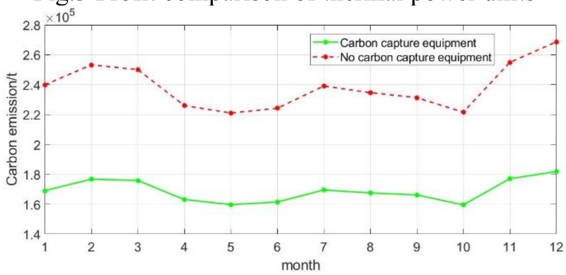

Fig.4 Comparison of carbon emissions of thermal power units

As can be seen from Fig.2, since the real-time demand of power spot market is within a certain range, and the hourly difference in energy consumption of carbon capture equipment is not large, the generation curve of thermal power units with or without carbon capture equipment is still similar to that of conventional thermal power units with medium - and long-term transactions only. Although there is a certain gap per hour, the gap is not obvious after monthly addition. Similarly, combined with the above analysis and program operation results, it can be seen that the profit curve trend of thermal power units with or without carbon capture equipment in Fig.3 is similar to that of conventional thermal power units. In addition, under the influence of various costs and benefits, the profit of thermal power units with carbon capture equipment in Model 3 is lower than that of thermal power units without carbon capture equipment, but the difference is not large. After adding carbon capture equipment, a small reduction in unit profits leads to a substantial reduction in unit carbon emissions as shown in Fig.4.

4 Conclusion

In order to help thermal power units participating in power spot trading and carbon emission trading to optimize operation decision-making, a cost-benefit model is constructed in this paper, and the following conclusions are drawn through simulation examples:

(1) When no carbon capture equipment is set, the carbon emission cost of thermal power units is relatively high, which is the inevitable result of actively responding to national environmental protection policies. The addition of carbon capture equipment increases the power generation of the unit. But the carbon emission of the unit has been significantly improved, resulting in a substantial decrease in the cost of carbon quota purchase of the unit.

(2) In general, the addition of carbon capture equipment can reduce the profit of the unit a little, but the carbon emission is greatly reduced. Therefore, under the current circumstances, it is advantageous to add carbon

capture equipment for the operation of thermal power units that take into account spot power trading and carbon trading.

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