Research on low-carbon power planning with gas turbine units based on carbon transactions

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Abstract. In the context of low carbon economy, introducing carbon trading and developing low-carbon energy generation is an important means to realize low-carbon development of the power system. Because gas power generation has the advantages of high efficiency, low carbon emission and strong peak load capability, the gas generator unit is added to the planning plan and a low carbon power planning model based on carbon trading is established. The goal of the model is to minimize the cost of the system integration. The cost includes investment operation cost and carbon transaction cost. And the natural gas supply constraints and carbon trading constraints are increased in the constraint condition. Finally, the discrete bacterial colony chemotaxis algorithm is adopted to solve this model. Through the model comparison and sensitivity analysis, it is concluded that the addition of gas turbine unit and carbon trading mechanism can optimize the power supply structure, promote the construction of low carbon unit. and realize the conclusion of low carbon emission reduction of power system. And the results verify the effectiveness of the proposed power planning model.

1 Introduction

Experts and scholars at home and abroad have conducted various studies on low-carbon power planning, clean energy power generation, and carbon trading mechanisms. Literature [1] studies the impact of wind power, photovoltaic and other clean energy generation on power planning. Literature [2] analyzes the carbon emission intensity of various forms of power generation such as wind, light, water, and fire, and establishes a power planning model with the goal of minimizing carbon emission costs. Literature [3] considers the introduction of environmental cost and demand-side management projects in power planning, which provides new ideas for realizing carbon emission reduction in the process of power planning. Natural gas power generation has received extensive attention due to its abundant reserves, high efficiency, rapid start and stop, and environmental protection [4]. The literature [5-6] respectively introduced in detail the coordinated and optimized operation of natural gas and power systems in Britain and the United States. Literature [7] introduces the operation law of the regional integrated energy system based on power and natural gas systems, and builds a power-natural gas regional integrated energy system model. Literature [8] introduces in detail the research framework of electricity-gas interconnection system under the background of integrated energy system. Literature [9] studies the joint operation mode of power system and natural gas system under the background of energy Internet, while in literature [10],

natural gas system and power system are connected by gas generating units, and a joint planning model of natural gas network and power network is established. Although all the above-mentioned documents have conducted more research on low-carbon power supply planning and electricity-gas interconnection systems, none of the models built takes natural gas power generation into consideration in power planning research.

As an effective carbon emission reduction mechanism, carbon trading mechanism is widely used in the research of power system. Literature [11] introduced two market incentive policies, green certificate trading mechanism and carbon trading mechanism, and added them to the power planning model. Literature [12] applies the carbon trading system to the optimal dispatch of the power system and establishes an economic and environmentally friendly low-carbon dispatch model. Literature [13] applied the carbon trading mechanism to the model of the China Southern Power Grid's power transmission from west to east, providing new ideas for the practical application of the carbon trading mechanism. This article introduces gas generators into the power planning model, and establishes a low-carbon power planning model with the goal of minimizing the overall cost during the planning period based on the carbon trading mechanism.

2 Modeling ideas

2.1 Natural gas power generation output model

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With the construction of integrated energy systems, natural gas power generation has received more and more attention. Compared with coal-fired units, gas-fired units have low carbon emissions and no emissions of sulfur dioxide and dust. Compared with other low-carbon energy sources, such as wind power and photovoltaics, gas-fired units have the performance advantages of high conversion efficiency, rapid start and stop, and flexible operation. Therefore, proper development of gas power generation instead of coal-fired power generation for peak shaving can become electric power. An important measure for the industry to fulfill its carbon emission reduction commitments. The natural gas system and the power system have a variety of joint operation methods, such as energy centers, combined cycle machines, and electricity-to-gas, etc. This article mainly considers connecting the natural gas system and the power system through gas generators, that is, the natural gas system is used as the input party to deliver natural gas to the gas generators for power generation. The power system transfers and absorbs the electric energy generated by the gas generating unit. The joint operation relationship in this process can be expressed as:

$$g(P_{GT,j}) = \alpha_2 P_{GT,j}^2 + \alpha_1 P_{GT,j} + \alpha_0 \quad (1)$$

In the formula, $g(P_{GT,j})$ -natural electricity consumed by gas engine j for power generation, Mm^3 ; $P_{GT,j}$ -active output of gas engine j , MW; $\alpha_2, \alpha_1, \alpha_0$ -the consumption coefficient of natural gas consumed by gas engine j for power generation.

2.2 Carbon trading mechanism

2.2.1 Introduction of carbon trading mechanism

The carbon trading mechanism is an effective mechanism for promoting carbon emission reduction through trading carbon emission rights. Relevant departments allocate carbon emission allowances to power generation companies. Through the carbon trading mechanism, power generation companies can actively adopt more low-carbon power generation energy and low-carbon power generation technologies, reduce carbon emissions and obtain carbon trading benefits by selling carbon emission rights. The carbon trading mechanism model contains the following two elements:

1) Carbon emission allowances

Carbon emission allowances are free allocation of carbon emission rights, which are distributed to all companies participating in the carbon trading market. There are many ways to allocate carbon emission allowances. The carbon emission allowance allocation model used in this article is shown in formula (2):

$$D_G = \sum_{i \in \Omega_G} \lambda P_i \quad (2)$$

In the formula, D_G -the carbon emission allowance of the generator set, t; P_i -the power generation of a single

unit, MW; λ -the allocation rate of carbon emission allowance per unit active output of the generator set, λ is 0.798; Ω_G -The collection of all units.

2) Carbon trading price

The carbon trading price is the trading price of carbon emission allowances in the carbon trading market. According to the global carbon trading market, the current carbon trading price is between 120 and 280 yuan [12], and the carbon trading price is 130 yuan under the benchmark scheme in this paper.

2.2.2 The impact of carbon trading

Low-carbon energy power generation is cleaner and lower-carbon than traditional coal-fired power generation. However, due to the higher operating costs of gas-fired units, the intermittent and uncertain wind power output has resulted in low-carbon energy generation that does not have a competitive advantage in terms of economics. In the context of low-carbon power market, the low-carbon nature of power generation energy and economy have contradicted, and the introduction of carbon trading mechanism increases the carbon emission cost of coal-fired power plants, highlights the low-carbon emission advantages of low-carbon energy power generation, and promotes low carbon emission. The development of carbon energy power generation. From the perspective of power supply planning, the introduction of carbon trading mechanisms and the economic benefits and carbon emission reduction benefits in the process of comprehensive power planning can optimize the power supply structure.

3 Mathematical model

3.1 Objective function

In the power planning plan, the pre-commissioned units during the planning period include coal-fired units, gas-fired units and wind turbines. Establish a low-carbon power planning model based on carbon trading with the goal of minimizing comprehensive costs. The comprehensive cost includes the investment and operating costs of the system during the planning period and carbon trading costs. The objective function is:

$$C = \min(C_{SYS} + C_{CO2}) \quad (3)$$

In the formula, C_{SYS} -system investment cost and operating cost, yuan; C_{CO2} -carbon transaction cost, yuan..

3.1.1 Investment and operating costs during system planning

The sum of power investment cost and operating cost during the system planning period can be expressed as:

$$C_{SYS} = C_{INV} + C_{OPE} \quad (4)$$

1) Investment cost

C_{INV} in formula (4) is the power investment cost during the system planning period, and is the fixed cost related to the capacity of the unit being built:

$$C_{INV} = \sum_{y=1}^{N_y} \sum_{g \in \Omega_G} (1+r)^{-y} I_g^y d_{yg} \frac{r(1+r)^{N_g}}{(1+r)^{N_g} - 1} \quad (5)$$

In the formula, N_y -planning period, a ; r -discount rate, taking $r=0.05$; I_g^y -fixed investment cost of unit g in the y th year during the planning period, 100 million yuan/unit; d_{yg} -0-1 variable, used to indicate whether unit g is put into construction in the y th year, if it is put into construction, $d_{yg}=1$, if it is not put into construction, $d_{yg}=0$; N_g -the put into construction period of unit g , a.

2) Operating cost

C_{OPE} in formula (4) is the unit operating cost during the system planning period:

$$C_{OPE} = \sum_{y=1}^{N_y} (1+r)^{-y} c_{OPE} \quad (6)$$

In the formula, c_{OPE} -the annual operating cost during the planning period, expressed by the unit's active output:

$$c_{OPE} = \sum_{n \in \Omega_{GF}} \alpha_n (a_n P_{GF,n}^2 + b_n P_{GF,n} + c_n) + \sum_{j \in \Omega_{GT}} \beta_j g_{GT,j} + \sum_{z \in \Omega_{GW}} \varepsilon_z P_{GW,z} \quad (7)$$

In the formula, $\Omega_{GF}, \Omega_{GT}, \Omega_{GW}$ -coal-fired unit collection, gas turbine unit collection, wind power unit collection; $P_{GF,n}$ 、 $P_{GW,z}$ -coal-fired unit n , wind power unit z active power output, MW; $g_{GT,j}$ -Gas turbine j power generation consumes natural gas, Mm^3 ; a_n, b_n, c_n -consumption characteristic curve parameters of coal-fired unit n ; α_n -coal-fired unit n power generation cost coefficient, 10,000 yuan/MW; β_j -gas turbine j power generation Cost coefficient, ten thousand yuan/ Mm^3 ; ε_z -cost coefficient of wind power generation, ten thousand yuan/MW.

3.1.2 Carbon transaction cost

Carbon emissions will be generated during the construction and operation of power plants. This article only considers the carbon emissions during the operation of generator sets. The relationship between carbon emissions and the effective output of a generator set is:

$$E_G = \sum_{n \in \Omega_{GF}} \delta_n P_{GF,n} + \sum_{j \in \Omega_{GT}} \xi_j P_{GT,j} \quad (8)$$

In the formula, E_G -carbon emission of generator set, t ; δ_n -coal-fired generating set n unit active output carbon emission intensity coefficient, ξ_j -gas turbine j unit active output carbon emission intensity coefficient, t/MW .

According to the carbon trading price M_{CO_2} , the carbon trading cost can be calculated:

$$C_{CO_2} = M_{CO_2} (E_G - D_G) \quad (9)$$

According to the carbon trading mechanism, when $E_G > D_G$, there is $C_{CO_2} > 0$, and the system needs to purchase carbon emission rights to incur carbon emission costs; when $E_G < D_G$, there is $C_{CO_2} < 0$, and the system has excess carbon emission allowances that can be sold to obtain carbon emissions benefits. When the carbon emissions E_G of the power generation system is small enough and the carbon trading price is relatively high, the carbon trading revenue that power generation companies can obtain through the sale of carbon emission rights will increase, which will promote the use of clean energy for power generation and realize the optimization and adjustment of the energy structure.

3.2 Restrictions

3.2.1 Electricity constraints

The total installed capacity of the system should meet the maximum load of the system:

$$\sum_{i \in \Omega_G} P_{Gi} \geq P_{Max} \quad (10)$$

In the formula, P_{Gi}, P_{Max} -the rated capacity of generator set n and the maximum load of the system, MW.

3.2.2 Power constraint

The power generation of all units of the system in year N should not be less than the power demand of the load in that year:

$$\sum_{i \in \Omega_G} W_{Gi} \geq W_N \quad (11)$$

In the formula, W_{Gi}, W_N -generating capacity of unit n , annual load power demand, MWh.

3.2.3 Output constraint of generator set n

$$P_{G \min,i} \leq P_{G,i} \leq P_{G \max,i} \quad (12)$$

In the formula, $P_{G \max,i}, P_{G \min,i}$ -the upper and lower limits of active power output of generator set n , MW.

3.2.4 Natural gas supply constraints

$$g_{\min,i} \leq g_i \leq g_{\max,i} \quad (13)$$

In the formula, $g_{\max,i}, g_{\min,i}$ -the upper and lower limits of gas source natural gas supply, Mm^3 .

3.2.5 Carbon trading volume constraints

When the actual amount of CO₂ emitted by a power generation company exceeds the carbon emission quota, it must purchase the excess carbon emission rights on the market to avoid high fines; when the actual carbon emission is less than the obtained carbon emission quota,

the remaining The allowance is sold on the market to obtain carbon trading income:

$$E_G = D_G + C_b - C_s \quad (14)$$

$$C_s \geq 0 \quad (15)$$

$$C_b \geq 0 \quad (16)$$

In the formula, C_s, C_b -CO₂ emission rights sold and purchased by power generation companies, t.

4 Case analysis

In this paper, krill Herd (KH) algorithm is used for simulation to verify the feasibility and rationality of the low-carbon power planning model established in this paper.

4.1 Data base

According to the low-carbon power supply planning model established in this paper, a power supply structure planning for a certain region in China from 2018 to 2022 is carried out. The annual maximum load and annual electricity consumption forecast data during the planning period^[5] are shown in Table 1. The parameters of the original unit and the unit to be built in the system^[11] are shown in Table 2 and Table 3 respectively. The allocation of carbon emissions per unit of active output is 0.798 t/MWh, and the system reserve capacity is 15%.

Table 1. Annual maximum load and annual electricity consumption forecast data during the planning period.

Year	Annual maximum load/MW	Annual electricity consumption/100 million kWh
2018	3000.0	130.62
2019	3300.0	143.73
2020	3630.0	157.33
2021	3993.0	173.23
2022	4392.3	190.73

4.2 Simulation results

Under the benchmark scheme, the KH algorithm is used to simulate the model established in this paper, and the types and capacities of units to be built in each year during the planning period are shown in Figure 1. It can be seen from Figure 1 that in the early stage of the planning period, under the constraint of carbon emissions, gas-fired units and wind turbines with lower carbon emissions were put into construction first and the number of units to be built was large. In 2018, 3 units of 400 MW gas-fired units and 100 MW were put into construction. 8 wind turbines, 1 gas-fired unit and 2 wind turbines will be built in 2019; 600 MW coal-fired A unit with smaller carbon emissions is better than 300 MW coal-fired B unit and 1 station will be put into construction in 2018.

Table 2. Original unit parameters.

Type	Coal-fired B unit	Coal-fired C unit	Gas unit	Wind turbine	Hydropower unit
Unit capacity / MW	300	100	400	100	100
Quantity	3	4	2	6	3
Annual utilization hours/h	6020	6020	5510	2530	3240
Minimal technical effort	0.5	0.5	0.5	0.0	0.2
Carbon emission intensity/t·MWh ⁻¹	0.728	0.935	0.343	0.000	0.000

Operating cost/t· MWh ⁻¹	279.4	318.4	659.5	100.5	444.3
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Table 3. Unit parameters to be built.

Type	Coal-fired A unit	Coal-fired B unit	Gas unit	Wind turbine
Unit capacity / MW	600	300	400	400
Quantity	4	6	7	10
Operating cost/t· MWh ⁻¹	260.6	285.6	658.4	100.5
Annual utilization hours/h	6000	6000	5000	2500
Minimal technical effort	0.5	0.5	0.5	0.0
Carbon emission intensity/t· MWh ⁻¹	0.681	0.746	0.362	0.000
Investment cost/100 million yuan	22.2	12.9	12.3	8.0

In the middle of the planning period, with the gradual increase in power demand, in order to meet the power demand, the construction of coal-fired units will be put into operation. In 2020, one coal-fired unit A and one coal-fired unit B will be built, and one coal-fired A unit

will be built in 2021. At the end of the planning period, a gas-fired unit that can meet both power demand and carbon emission reduction requirements under carbon emission constraints is superior to coal-fired units. One unit will be put into construction in 2022.

Fig. 1. Type and capacity of units to be built in each year during the planning period.

Various costs during the planning period are shown in Table 4. From the data in Table 4, due to the large number of units put into construction, the investment cost in 2018 was relatively high, accounting for 11.3% of the total cost. In 2019, due to the high operating cost of gas generating units, the operating cost of the system increased by 8.3%. At the same time, due to the large-scale investment in gas generating units and wind turbines in the initial planning stage, the carbon

transaction cost of the system was reduced by 12.6%. In the third year of the planning period (2020), with the commissioning of coal-fired units, carbon transaction costs increased by 5.7% compared with the previous year (in 2019). At the later stage of the planning period, due to the re-commissioning of gas-fired units, the last year (in 2022), the operating cost will increase by 1.6% compared with the previous year (2021), and the carbon transaction cost will be reduced by 10.9%. In summary,

compared with coal-fired units, gas-fired and wind turbines can reduce carbon transaction costs. Bring low-carbon benefits; however, due to the intermittent output of wind turbines and the greater uncertainty, and the higher operating costs of gas-fired units, the economical type of coal-fired units is still better than low-carbon units.

4.3 Comparative analysis of different models

This article introduces gas-fired units into the power planning. As gas-fired units have low carbon emissions, carbon emissions decrease and carbon trading benefits

increase. The model built in this paper is compared with the power planning model excluding gas generators. The planning schemes of the two models during the planning period are shown in Figure 2. It can be seen from Figure 2 that compared with the traditional power planning model without gas-fired units, the low-carbon power planning model with gas-fired units constructed in this paper will significantly reduce the number of coal-fired units put into construction and the power generation efficiency is high. Gas-fired units with strong peak regulation capabilities can replace coal-fired units to meet the load demand of the system during the planning period.

Table 4. Various costs during the planning period.

Year	Total cost/100 million yuan	Carbon transaction cost/100 million yuan	Investment cost/100 million yuan	Operating cost/100 million yuan
2018	75.99	-11.07	8.98	78.57
2019	73.97	-12.41	1.98	84.62
2020	77.64	-11.64	2.35	87.33
2021	84.67	-11.88	2.21	94.23
2022	83.46	-13.13	0.67	96.64

Fig. 2. Investment units and capacity of 2 models.

Table 5. Comparison of two model indicators.

Mode	Total cost/100 million yuan	Carbon transaction cost/100 million yuan	Investment cost/100 million yuan	Operating cost/100 million yuan
Low carbon model	396.52	15.38	431.19	-62.87
Conventional model	340.32	16.22	357.02	-42.74

Under the two models shown in Figure 2, all wind turbines with no carbon emissions have been put into construction. Carbon emission quota constraints have

promoted the development and construction of clean energy generators. Table 5 shows the comparison of key indicators of the two models.

From the comparison of the important indicators of the two models in Table 5, it can be seen that due to the higher fuel price of the gas-fired unit, the operating cost of the model proposed in this paper increased by 20.3% compared with the traditional unit, and the investment and construction cost was reduced by 2.2%. It is significantly smaller than that of coal-fired units. The carbon transaction cost of the model proposed in this paper is 1.83 billion yuan lower than that of the traditional model, and the total cost is 16.5% higher than that of the traditional model. Through the comparison of the two models, although the total investment cost of the unit proposed in this paper is higher than that of the traditional model, the benefits of carbon emission reduction are obvious. Under the requirements of the power industry's transition to low-carbon development and the incentives of relevant policies, the model proposed in this article has certain feasibility.

5 Conclusion

This paper comprehensively considers the economy and low-carbon properties of the system and proposes a low-carbon power planning model for gas-fired units based on carbon trading with the goal of minimizing the overall system cost during a planning period. Through

model comparison and sensitivity analysis, the conclusions are as follows:

1) Compared with clean energy power generation technologies such as wind power and photovoltaic power generation, combustion power generation has less uncertainty, can provide a stable power supply with high efficiency and strong peak shaving capacity; compared with traditional coal-fired power generation, gas-fired power generation has lower carbon emissions, and no discharging pollution such as sulfur dioxide and dust. Therefore, it is necessary to consider power planning for gas-fired units.

2) The carbon trading mechanism is an effective incentive mechanism to achieve carbon emission reduction. Under the carbon trading mechanism, although the unit power generation cost of natural gas power generation is higher than that of coal-fired power generation, gas power generation can effectively reduce carbon emissions and enable companies to obtain carbon emissions benefits. When carbon trading prices and natural gas prices are appropriate, carbon trading benefits are significant.

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