Research on Coordinated Trading of Electricity and Carbon in Clean Energy Under the Background of Carbon Neutralization

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Abstract. Under the "dual carbon" target, China's new energy explosive growth and large-scale grid-connected has become the general trend. For new energy and thermal power enterprises, with the further coupling of power market and carbon market, the traditional fossil energy power system is transforming to a high proportion of new energy power system. Based on the study of the coordination between the electricity market and the carbon market, this paper further divides the trading mode of clean energy electricity and carbon into four forms: pure power, power plus carbon quota, power plus renewable energy quota and power plus carbon quota plus renewable energy quota. On the basis of studying the cost of thermal power and new energy, three typical scenarios of coordinated electricity and carbon trading are analyzed. Finally, reasonable suggestions are put forward for the connection between the construction of the national carbon market and the quota system and Green Certificate Trading Mechanism in the future. Firstly, the carbon market offset mechanism involving renewable energy power generation enterprises should be further explored. Second, it is necessary to fully consider the impact of the carbon market on the adjustment of power supply structure and reasonably determine the renewable energy power quota index.

Keywords: Clean Energy · Carbon Trading · Power Trading · Scenario Analysis

1 Introduction

The coupling of carbon market, green power certificate market and power market focuses on the design of renewable energy consumption responsibility weight and carbon quota mechanism. The weight of renewable energy consumption responsibility connects the electricity market and the green certificate market. In order to meet the requirements of the weight of consumption responsibility, users need to purchase green electricity from the electricity market or green certificate market, thereby affecting market trading volume of renewable energy units. Carbon quota connects the electricity market and the carbon market. Under the constraint of carbon emission quota, generating units need to measure the cost-benefit of electricity purchase and sale and carbon emission rights, thereby affecting the transaction results of conventional thermal power and green power. Under the background of coordinated electricity and carbon trading, this paper studies

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the trading mode of electricity and carbon trading, and then analyzes the typical scenario of electricity-carbon' coordinated trading according to the different clearing prices of the carbon market. Finally, based on the above mechanism, it is proposed to form a close coupling between the future carbon market, the green card market and the power market.

2 Background of Coordinated Trading in Electrical Exploration

With the establishment of China's carbon emissions trading market, in order to achieve the goal of carbon emission reduction in China, the power industry has become an important market subject. How the power industry conducts carbon trading and how grid enterprises participate in the carbon market have become important issues to be solved [4]. The power industry's participation in carbon emissions trading has the following three meanings:

First, with China's economic and social development and the improvement of people's living standards, the current and future electricity demand will continue to grow for a long time. Setting reasonable carbon emissions control objectives in carbon trading can encourage and encourage power enterprises to save energy and reduce emissions, achieve the intended emission reduction targets as soon as possible, and maintain sustained power growth [5].

Second, in the early stage of the carbon trading market, the carbon emission indicators allocated to regions or enterprises dominated by coal-fired power generation ensure their sustainable development ability, and can also promote the development of clean energy in China, which is conducive to the optimization of resource layout [9].

Third, carbon trading in power industry can be coordinated with electricity market and electricity price reform. Under the existing system and mechanism, the allocation of carbon emission indicators can be combined with the electricity index, and the sales price can be linked with the carbon market price, which helps to pass the carbon cost to customers, so as to promote customers' active energy saving and emission reduction. In addition, China's electricity market reform is gradually advancing, and the development of carbon trading market can be linked to the process of electricity market [2].

In recent years, with the increasing demand for environmental protection, government departments at all levels have clearly put forward emission reduction plans. For example, Shanghai environmental protection and ecological construction '12th Five-Year' plan proposed that by the end of the '12th Five-Year', the total emissions of pollutants in Shanghai will be further reduced. By strengthening the control of air pollution in key industries, the operation efficiency of desulfurization facilities in power plants will be improved [8]. On the basis of the comprehensive promotion of low nitrogen combustion technology transformation of coal-fired units in the city's power plants, flue gas denitrification will be implemented to complete the national emission reduction binding indicators of sulfur dioxide, nitrogen oxides and other pollutants. However, for carbon dioxide emissions, only statistical calculations and recommendations for binding indicators are currently available and effective mitigation measures cannot be implemented.

The linkage mechanism between the electricity market and the carbon market should be established, and the existing electricity market and the carbon market management

agencies, participants, trading products, market mechanisms and other factors should be deeply integrated [3]. The multi-subject bidding system, the incentive mechanism related to emission reduction and income, the transaction mode of "unified market and unified operation", and the price system of organic integration of electricity price and carbon price should be established [6].

3 Research on Transaction Mode of Clean Energy Electricity and Carbon

Taking electricity as tying goods, carbon quota and renewable energy quota as tying goods for bundled transactions, four forms of packages are formed: pure electricity, electricity plus carbon quota, electricity plus renewable energy quota and electricity plus carbon quota plus renewable energy quota.

3.1 Pure Electricity Trading

Pure power refers to the price of electricity sold by power generation enterprises only includes the electricity sold, and does not include carbon quotas and renewable energy quotas. Users can independently choose to purchase electricity commodities with only electricity energy or carbon quota or renewable energy quota.

3.2 'Electricity + Carbon Quota' Trading

Power + carbon quota refers to the carbon quota generated by the purchase of electric energy by users at the same time, so as to guide users to use low carbon energy through electricity price. In the future, thermal power enterprises are expected to transfer some carbon emission costs to the terminal, which will be borne by power consumers; carbon prices will be coupled with power generation costs to promote the transformation of China's energy structure. New energy operators as the main provider of carbon dioxide emission reduction and new energy power, through the sale of carbon quota distribution, so as to realize the price reduction, which makes the new energy operators will increase income become the main beneficiary.

3.3 'Electricity + Renewable Energy Consumption Responsibility Weight' Trading

Power + Renewable Energy Accommodation Responsibility Weight refers to the responsibility weight of purchasing power and renewable energy at the same time. Users can purchase green electricity directly from new energy manufacturers and obtain green certificates. Green consumption is realized in one transaction. It can also buy thermal power from thermal power plants, and then buy the corresponding proportion of green certificates to realize the purchase package of power and renewable energy consumption responsibility weight.

3.4 'Electricity + Carbon Quota + Renewable Energy Accommodation Responsibility Weight' Trading

The power + carbon quota + renewable energy consumption responsibility weight refers to the user's simultaneous purchase of power plus carbon quota and renewable energy consumption responsibility weight. When purchasing, users can choose to buy green and carbon quotas from new energy power producers, or choose to buy electricity from thermal power producers, and then go to extra carbon quotas and renewable energy consumption responsibility weights.

4 Mathematical Model of Clean Energy Carbon Quota Cost

At present, the initial carbon allocation in the world mainly includes free allocation, auction allocation, free allocation and auction mixed allocation. China mainly adopts free distribution. In the case of government free allocation of certain carbon emission quotas to enterprises, when the actual output of the enterprise is greater than the given quota, it is necessary to purchase carbon emission quotas in the market; on the contrary, carbon emission quotas can be sold in the market to obtain profits [1].

After considering the carbon trading and green card trading system, due to the differences in power generation costs, carbon trading and green card transaction costs between thermal power and renewable energy generators, the net income functions of different types of generators are not the same, among them:

(1) The profit function of thermal power generators.
The net income of thermal power generator i mainly includes three parts: the first part is the net income of power generation, minus the cost of power generation; the second part is the cost that thermal power producers should pay for buying carbon quotas in the carbon market or the income from selling carbon quotas; the third part is the fees that thermal power producers need to pay for purchasing the green certificate with the proportion specified by the regulatory agencies in the green certificate market. Then, the net income function of thermal power producer i can be expressed as:

$$\pi_{h,i}(q_{h,i}) = p_e q_{h,i} - C_{h,i}(q_{h,i}) - q_{h,i}^{co_2} p_{co_2} - \lambda q_{h,i} \rho$$

In the above formula, $q_{h,i}$ is the power generation of thermal power suppliers, $q_{h,i}^{co_2}$ indicates that the actual number of carbon quotas purchased or sold by thermal power suppliers i can be positive or negative. ρ is the green stock trading price, and satisfies the following functional relationship:

$$\rho = \xi - \tau \left[(1-\lambda) \sum_{j=1}^{n} q_{r,j} - \lambda \sum_{i=1}^{m} q_{h,i} \right]$$

In the above formula, ξ and τ are constants greater than zero; λ is the proportion of renewable energy generation that each power producer needs to fulfill its

obligations. Due to the non-renewable energy power issued by the thermal power generator i, the thermal power generator i needs to purchase the green certificate with the number of $\lambda q_{h,i}$ to meet the requirements of the government quota assessment, and the renewable energy generator j sends all the renewable energy power, so the generator j can sell the green certificate with the number of $(1-\lambda)q_{r,j}$ in the green certificate market.

(2) Renewable energy generator revenue function

Compared with thermal power generation, the power generated by renewable energy generators is all clean power with zero carbon emissions, and they do not need to participate in carbon market transactions. Therefore, in addition to obtaining a part of the power generation income in the electricity market, renewable energy generator j can also sell a part of the green certificate to obtain income in the green certificate market. Then, the net income objective function of renewable energy generator j can be expressed as:

$$\pi_{r,j}(q_{r,j}) = p_e q_{r,j} - C_{r,j}(q_{r,j}) + q_{r,j}^{TGC}\rho$$

In the above formula, $q_{r,j}$ is the power generation of renewable energy producers, $q_{r,j}^{TGC}$ represents the actual number of green certificates sold by renewable energy producers.

5 Typical Scenario Analysis of 'Electricity - Carbon' Coordinated Trading

Under the influence of carbon trading, the thermal power subjects in the electricity market will participate in the three market transactions of the electricity market, the electricity generation right trading market and the carbon emission right trading market at the same time, so as to maximize their own profits. This section will use the scenario analysis method to analyze the potential market behavior of each subject in the electricity market in these three typical scenarios, referring to the three typical scenarios of low, growth and excessive carbon emission right clearing price, and then obtain the coordinated trading mode of electricity and carbon emission right.

Scenario 1: Carbon Market Clearing Price is Low

When the initial carbon emission policy is relatively loose, the number of carbon allowances in the market is large, the clearing price of carbon emission rights is low, and the cost of purchasing the required carbon emission rights for small thermal power units is not high. At this time, thermal power entities in the power market participate in market competition. The competitiveness of the unit still mainly depends on the power generation cost competition of the unit itself. This paper assumes that the on-grid electricity price of different thermal power plants is the same, and the unit average profit of the power generation subject is used to reflect the core competitiveness of the power generation subject. Due to the low clearing price of carbon emission rights at this time, the competition between high-efficiency thermal power and small thermal power still mainly depends on the level of competition between fixed costs and variable costs, as shown in Fig. 1.

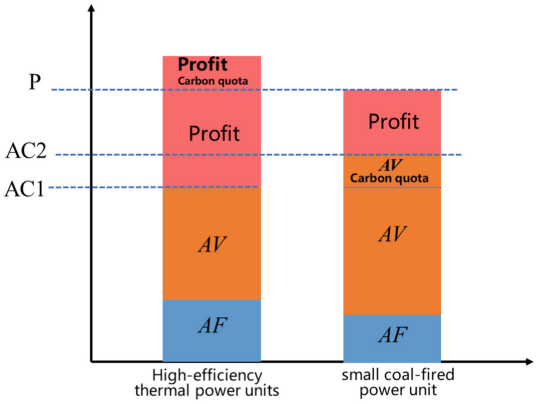

Fig. 1. Comparison of production cost and profit between high-efficiency units and small thermal power units

Due to the low coal consumption of power generation, the variable cost of high-efficiency thermal power units is more competitive than that of small thermal power units. However, most of the high-efficiency thermal power units are newly built thermal power units, facing multiple financial pressures such as repayment of loans and fixed assets. Therefore, in the competition for small and medium-sized thermal power units, it may be more advantageous in the fixed cost. Considering the two factors comprehensively, the high-efficiency units and small thermal power units should have little difference.

Scenario 2: Carbon Market Clearing Growth

When the initial carbon emission policy is gradually tightened, the clearing price of carbon emission rights is gradually increasing, and the cost for small thermal power units to purchase carbon emission rights is also gradually increasing. At this time, the competitiveness of thermal power subjects in the electricity market to participate in market competition needs to consider the market price of carbon emission rights in addition to the cost advantage caused by the low coal consumption rate of units. At the same time, small thermal power units will face the following choices. One way is to complete the power generation task by purchasing carbon quotas, and the other way is to sell power generation rights to other generating units to replace power generation to complete the power generation task.

(1) Scenario 2-1 Purchasing carbon emission rights to complete the power generation task Since the clearing price of carbon emission rights is low at this time, the competition between high-efficiency thermal power and small thermal power depends not only on the level of fixed and variable costs, but also on transactions in the carbon trading market. Situation, as shown in Fig. 2.

With the tightening of carbon emission rights policy, the relationship between supply and demand in the market will gradually evolve into a scenario of supply less than demand. At this time, the price of carbon emission rights will gradually increase, and the cost of small thermal power units will gradually increase. If the electricity price remains unchanged, the profit of small thermal power units will

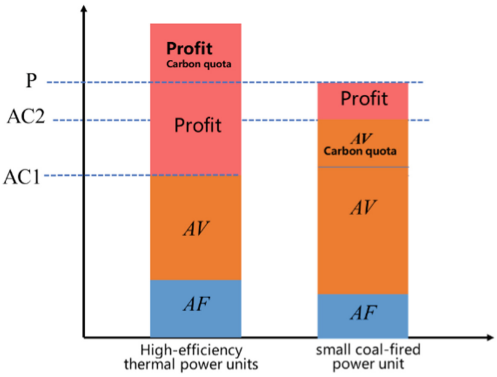

Fig. 2. Comparison of production cost and profit between high-efficiency thermal power units and small thermal power units II

be further compressed. In comparison, the extra carbon emission rights of high efficiency thermal power units will gradually increase, and the total profit of high efficiency thermal power units will increase under the original electricity price. In this scenario, the competitiveness of small thermal power units is obviously inferior to that of high efficiency thermal power units.

(2) Scenario 2-2 sells power generation rights to complete power generation tasks in this case, small thermal power units will face new choices. Small thermal power units can replace high-efficiency thermal power units to complete power generation tasks through the power generation rights trading market, and obtain power generation rights trading benefits. In this scenario, small thermal power units will sell generation rights only if the PGR of generation rights trading price is higher than this benchmark, if the income obtained by purchasing carbon emission rights to generate their own power generation plans is the benchmark. By participating in power generation right trading, small thermal power units can be replaced by large ones. By means of market-oriented trading, comprehensive carbon emissions of power production are reduced, resource utilization efficiency is improved, and a win-win outcome of power generation right trading subjects is realized.

Scenario 3: Excessive Carbon Market Clearing

When there is an extreme scenario, that is, the carbon emission policy is too strict and the price of carbon emission rights is too high, the power generation cost of small thermal power units increases sharply after the use of their own carbon quotas, and the profit space is greatly squeezed, resulting in that the profit of small thermal power units from selling power generation rights is much higher than that from purchasing carbon emission rights to complete power generation tasks. In the long run, small thermal power units will rely on the sale of power generation rights to obtain profits, and there may be the following two scenarios.

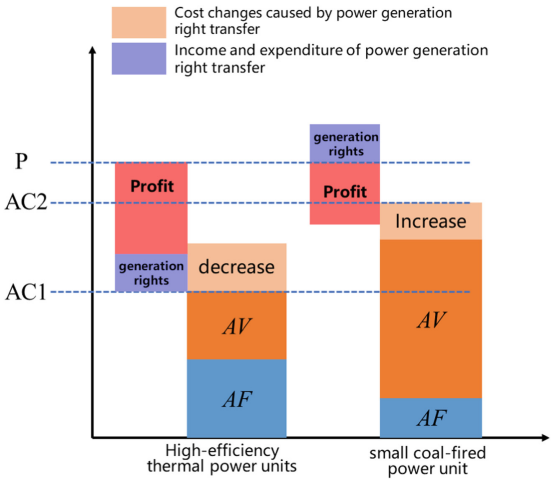

Fig. 3. Unit comparison under power generation right

(1) Scenario 3-1 The surplus power generation capacity of other generating units replaces the power generation of small thermal power units. If the surplus power generation capacity of high-efficiency thermal power units, hydropower units, and new energy units can meet the power generation requirements for the sale of power generation rights for small thermal power units, the Modes such as "replacing small thermal power" and "replacement by wind and fire" can meet the needs of small thermal power generation rights trading power. From a long-term perspective, the phase-out trend of small thermal power units is positively correlated with the strict trend of carbon emission rights and other policies. The income and expenditure comparison is shown in Fig. 3.

(2) Scenario 3-2 Other generators are not able to absorb the power generation share of small thermal power units. If the surplus power generation capacity or power generation willingness of high-efficiency thermal power units, new energy units and other generator sets cannot meet the power generation requirements of small thermal power units to sell power generation rights, it is too strict. The carbon emission right policy will lead to an increase in the comprehensive power generation cost of small thermal power units and a decrease in the willingness to generate electricity. However, there is no surplus power generation capacity outside the small thermal power units, resulting in a mismatch between the supply and demand of the power system, which affects the safe operation of the power system. The income and expenditure comparison is shown in Fig. 4.

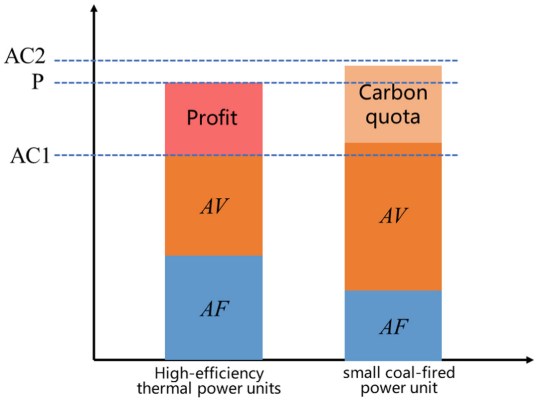

Fig. 4. Unit comparison under high carbon emission cost

6 Conclusion

Based on the consideration of a variety of trading packages, this paper studies the cost of thermal power and new energy, and analyzes three typical scenarios of coordinated trading of electricity and carbon. Under different clearing prices, power producers also face different choices. In the future, the convergence of national carbon market construction with quota system and green card trading mechanism needs to focus on the following two aspects:

The first is to explore the carbon market offset mechanism that renewable energy power generation companies participate in based on green certificates. The offset mechanism is an important part of the carbon emission trading system [7]. By offsetting carbon emissions with nationally certified voluntary emission reductions (CCERs) or other emission reduction indicators generated by voluntary greenhouse gas emission reduction projects, it can effectively reduce the compliance cost of key emission units and promote the reduction of greenhouse gas emissions such as renewable energy power generation. Project development with obvious discharge effect and outstanding ecological and environmental benefits. Green certificate, as the attribute identification of green power generated by renewable energy, is a natural and very accurate measure of carbon dioxide emission reduction, which can form a natural connection with the carbon emission reduction trading system.

Secondly, combined with the progress of national carbon market construction, based on the total carbon emission distribution of power generation enterprises and the adjustment of power supply structure under the distribution mode, the impact on the implementation of renewable energy quota system is analyzed. China's electric power industry carbon emissions accounted for half of the country's carbon emissions, the effectiveness of carbon reduction in the power industry has a significant impact on the realization of carbon neutrality goals. Against the background of total carbon emission control in the power industry, the future carbon emission right will become a scarce resource, the development space of thermal power will gradually tighten, and the carbon price will gradually increase the cost of thermal power, prompting power generation enterprises to

invest in new energy, and the power structure and layout will have significant changes. In the future, it is necessary to fully consider the impact of the carbon market on the adjustment of power supply structure and reasonably determine the renewable energy power quota index.

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