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Coupling Mechanism and Synergic Development of Carbon Market and Electricity Market in the Region of Beijing–Tianjin–Hebei

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Abstract: The national carbon emission trading mechanism is an important policy tool for the Chinese government to control and reduce greenhouse gas emissions by using the market mechanism. The Beijing–Tianjin–Hebei power market is the focus of energy conservation and consumption reduction in China. Problems have already existed in the synergic development of the Beijing–Tianjin–Hebei power market and carbon trading market. In this article, the development status of the Beijing–Tianjin–Hebei power market is analyzed and the coupling mechanism between the carbon market and power market is combed out to build a synergism model of the carbon market and the Beijing–Tianjin–Hebei power market based on the system dynamics. From the research results, firstly, the Beijing–Tianjin–Hebei power market comes with a high energy consumption intensity and a high proportion of carbon emissions. The coupling of carbon market and power market forces the power industry to reduce carbon emissions through the effective transmission of carbon costs to power prices. Secondly, carbon price shows an upward trend in the context of the current policy scenario, which can give play to the role of price signal in the future. The revenue of thermal power plants, which are the carbon emission right sellers, with new technologies, has increased significantly, while the revenue of carbon emission right buyers, which are the manufacturers of undeveloped units, has increased less. Finally, the technical progress of thermal power plants, the introduction of auction mechanism, the increase in initial carbon price settings and the direct transmission of carbon costs are all factors that promote the effectiveness of carbon trading policy tools in the Beijing–Tianjin–Hebei power market. This study provides theoretical guidance for the synergic development of the "power-carbon" market.

Keywords: carbon emission trading; system dynamics; synergic development; energy saving and emission reduction

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1. Introduction

In response to global warming, the international community has adopted a series of mitigation policies for climate change. Carbon emission trading is one of the core policies and one of the effective emission reduction policy tools [1]. In order to improve the degree of Intended Nationally Determined Contributions, China promised to the international community that China would reach carbon peaking by 2030 and carbon neutrality by 2060. In this context, the national carbon emission trading market was put into operation on 16 July 2021. At present, the national carbon market only covers the power generation industry, with 2162 key emission units included, covering about 4.5 billion tons of carbon dioxide, and it is the largest carbon market in the world [2]. China's power industry is the main sector of fossil energy consumption and carbon emissions. During the "13th Five Year Plan" period, more than 80% of the carbon emission increment came from the power sector, and carbon emissions accounted for more than 40% of the total social emissions in 2021 [3,4].

Using carbon trading policy tools to fully explore the emission reduction potential of the power industry is one of the important means to achieve the goal of carbon reduction.

The synergic development of the Beijing–Tianjin–Hebei region is one of China's three national strategies. The core of the strategy is to relieve Beijing's noncapital functions orderly and adjust the economic structure and spatial structure [5]. The power industry plays an important role in the synergic development process of the Beijing–Tianjin–Hebei region. Power affects the energy security and economic development of the Beijing–Tianjin–Hebei region, and then relates to the development of various industries. The Beijing–Tianjin–Hebei region is China's high-tech and heavy industry base, with large carbon emissions and huge pressure on emission reduction [6]. It is urgent to realize the synergic development of the carbon emission trading market and the Beijing–Tianjin–Hebei power market. Therefore, the coupling mechanism between the carbon market and the Beijing–Tianjin–Hebei power market should be analyzed in depth, the development status of the Beijing–Tianjin–Hebei power market should be grasped, and the path of the synergic development of the carbon trading market and the Beijing–Tianjin–Hebei power market should be explored because these are not only a realistic guide to the effectiveness of the carbon trading market, but also can provide decision-making support for the realization of the carbon reduction goal of the Beijing–Tianjin–Hebei power market.

2. Literature Review

At present, the research on the synergy between the power market and carbon market generally starts from the perspective of power, considers carbon trading and related policies, such as carbon neutral and carbon peak target, and analyzes the related issues of the power market, such as market trading strategy [7–9] and scheduling strategy [10,11] and trading mechanism optimization. For example, in order to adjust the power supply structure and reduce consumption and emissions, Ziheng Wang et al. [12] proposed an optimization model of power generation rights trading including a new energy system based on carbon trading gains and grid loss costs. Haoyu Hou et al. [13] proposed a multi-virtual power plant alliance game optimization mode because of carbon trading to improve the comprehensive operation efficiency of distributed resources. They focused on the power system, with carbon trading and carbon market as its influencing factors. Different from the traditional "power-based" system, Chongqing Kang et al. [14] put forward the new "carbon-based" power system, with low carbon as the goal and the new power system as the carrier, and they established a cutting-edge research framework involving multi-disciplinary integration. Xiaoli Du et al. [15] started from carbon trading to design a carbon emission reduction reward and punishment and carbon trading matching model for the power industry based on blockchain technology. The research on the coupling of power market and carbon market generally is to explore the coupling mechanism and interaction mechanism between the two markets overall and is often closely related to green certificate trading and green power trading. Ge W et al. [16] elaborated the coupling relationship between China's carbon trading market, green certificate trading and power market and verified the advantages and effects of market coupling. Nan Shang et al. [17] summarized the correlation and coupling mechanism of domestic and foreign carbon markets, power markets, green certificate markets and other markets and put forward suggestions for market coupling and synergic development based on China's current situation. Tiantian F et al. [18] established and simulated the coupling model between China's green certificates, carbon trading and power market, as well as the policy synergy model between carbon trading and green certificate trading, proposed the key points of coupling and synergy between different policies and different markets, and provided optimization suggestions for the joint implementation of carbon trading, green certificate trading and various carbon emission reduction policies. Yunfeng Shuai et al. [19] studied the coupling mechanism between the carbon market and power market in the United States by taking the Regional Greenhouse Gas Initiative (RGGI) with years of development experience as an example and provided suggestions for the construction of China's carbon market and power market. Liu HX [20] et al. have studied the coupling mechanism between electricity, wind power and hydrogen markets. By introducing Power-to-Hydrogen (P2H) mode into the microgrid, the power generated by distributed wind energy is converted into hydrogen energy for storage, and the diagonalization algorithm is used to solve the multi-market equilibrium problem, which effectively solves the problem of the uncertainty and volatility of wind power. Sayed AR [21] et al. focused on the optimal energy management problem arisen by the stronger interactions between power and gas systems. A distributional robust optimization (DRO)-based decision-making framework is derived and the nested column and constraint generation algorithm were used to solve the problem. Azin B [22] et al. have worked out a charging facility plan for the fast-growing electrified automation, which considers the coupling of the transport market and power market. An integrated demand coverage optimization model over a coupled power-transportation (CPT) network is developed to determine the best locations of charging stations. Ding YY [23] et al. have developed a new business model for shared electric vehicles (SEV) that provide transport and energy services, considering the transport and power market. A Stackelberg competition model and a Nash competition model were introduced to study the decisions and interactions of the participants in the market models. The transportation electrification issue was also researched by Qian T et al. [24], where a multi-agent deep reinforcement learning (MA-DRL) method was proposed by them to model the pricing game for urban EV charging stations and determine the optimal charging prices for a single station. Data from two cities in China were used as real-world cases to verify the effectiveness and scalability of the approach. The coupling of natural gas and electricity markets is in progress because of the growing reliance on gas for electricity generation. Wang L and Xing YP [25] have identified the risk factors through a thorough analysis of the evolution mechanism with real-world illustrative examples. A system dynamics model was constructed considering a coupled natural-gas–electricity market to depict the evolutionary behavior of coupled markets and compare the risk response strategies. Dominant risk factors and the aggregated effects of multiple risks were revealed, suggesting the need to comprehensively monitor dynamic risks.

The existing research methods on synergic development for different markets or entities are mainly realized by building different models based on the synergism theory. Yuan Li et al. [26] established a mathematical model based on energy use right trading with the carbon market and conducted an example analysis of two typical high-energy-consuming industries, aiming to study the synergistic effect of two market-based emission reduction mechanisms and emission reduction strategies of high-energy-consuming industries; Yijian Ge et al. [27] incorporated the two energy policies into the CGE model and assessed the impact of renewable energy and energy efficiency policies on the economy, energy and environment from the macroeconomic and micro sector levels; Guiyuan Xue et al. [28] put forward the synergic development mechanism of the national carbon market and power market and took Jiangsu Province as an example to build a market multi-agent behavior decision-making model. Based on the synergism theory and complex system theory, Ling Liu et al. [29] conducted a functional analysis of carbon market from the perspective of system subsystems, divided the pan carbon market system into core carbon market systems including demand, supply and trading subsystems, as well as support subsystems, and built a model of China's carbon market system. Li P et al. [30] have noticed that strong coupling between electric power and heat supply highly restricts the electric power generation range of combined heat and power (CHP) units, hindering the synergic development for the heat and power market. In order to solve the problem, a combined heat and power dispatch model is formulated considering both the pipelines' dynamic thermal performance (PDTP) and the buildings' thermal inertia (BTI) to enhance the co-ordinating operation between the electric power and district heating systems. Zhang BD et al. [31] focused on the plug-in hybrid electric vehicle (PHEV) market development and its combining process with power markets in China and the United States, conducting a comparative analysis of technical route and market development for light-duty PHEV between China and the

US. An evaluation method has been proposed for comparative analysis and qualitative evaluation. The result was helpful to grasp the internal law of the global PHEV market and technology situation. Liu JC et al. [32] studied the synergic development for different renewable energy markets and introduced an optimal sizing model considering uncertainty of photovoltaic (PV), load and price for Hydro-PV-Pumped Storage integrated generation system. The effectiveness of the model was verified by a case study, which provided more suggestions for the co-ordination development for the power market and the renewable market. Schnuelle C et al. [33] established and simulated an agent-based modeling approach for the economic uptake of Power-to-Fuel (P2F) technology to find the solution to the electrification and decarbonization problem in Germany. The synergic development of the renewable power market, power grid and multiple fuel markets was studied to analyze the best implementation path of the P2F technology for the German energy system.

The relevant research on the coupling and synergism of the power market and carbon market mainly focused on the power system. In that research, various mathematical models were built based on carbon trading and carbon emission reduction policies to solve power-related problems, and the effectiveness of the model was verified by using simulation, or the interaction and coupling mechanism among the power market, carbon trading market, green certificate market and green power market were described. However, previous studies generally only focused on carbon quota trading and rarely on the characteristics of CCER trading and renewable energy power generation. Secondly, there is less research on the coupling and synergism of the Beijing–Tianjin–Hebei power–carbon market.

To summarize, the main innovation points of this article are as follows: firstly, the study of the national carbon market does not only focus on carbon quota trading and renewable energy power generation, but also introduces CCER trading to comprehensively study the national carbon trading market. Secondly, the Beijing–Tianjin–Hebei power market is affected by multiple factors and, in this article, a synergism model between the national carbon trading market and the Beijing–Tianjin–Hebei power market is constructed, the interaction between the carbon market and power market is simulated, and measures are found to achieve the synergic development of the two markets.

3. Analysis of the Coupling Mechanism between Carbon Market and the Beijing–Tianjin–Hebei Power Market

3.1. The Development Status of the Beijing–Tianjin–Hebei Power Market

As an important economic circle and urban agglomeration in China, the Beijing–Tianjin–Hebei region is an important driving force for the development of China's power industry and a pilot area for a new round of power market reform [34]. In February 2020, the National Development and Reform Commission and the National Energy Administration issued the Implementation Opinions on Promoting the Independent Standardized Operation of Power Trading Institutions [35], which proposed that "by the end of 2022, all regions should further standardize and improve the market framework, trading rules, trading varieties, etc. based on the actual situation. And the trading institutions in the Beijing-Tianjin-Hebei region, Yangtze River Delta region, Pearl River Delta region and other regions should integrate with each other, to preliminarily form a power market that meets the requirements of regional economic integration". The Beijing–Tianjin–Hebei power market has a relatively standardized system for the medium- and long-term power market and auxiliary service market, but the construction scheme of the spot power market is still being explored.

In terms of power supply and demand in the Beijing–Tianjin–Hebei region, regional power has generally shown an upward trend [36]. In terms of supply, the installed capacity of thermal power in the Beijing–Tianjin–Hebei region accounted for 67.60% and the power generation accounted for 84.48%. As shown in Figure 1, thermal power generation was the main type of power generation from 2016 to 2021, reaching 388.32 billion kW·h by the end of 2021, accounting for more than 90% of the total power generation. Due to the adjustment of the energy structure in the Beijing–Tianjin–Hebei region and the implementation of the policy of "coal to gas", the proportion of regional clean energy power generation continues to increase, but it is still low and needs to be further improved. In terms of demand, the Beijing–Tianjin–Hebei power consumption is still dominated by coal. According to the latest statistical yearbook data, the social power consumption in the Beijing–Tianjin–Hebei region increased from 2016 to 2021 year by year, as shown in Figure 2. Among them, observing the trend line in the chart, from 2016 to 2021, the growth trend of power consumption in Beijing and Tianjin have been slowed down and the growth rate of energy consumption in Hebei is relatively high. Hebei Province will be the main region of regional energy consumption. Under the dual constraints of the integrated development of the Beijing–Tianjin–Hebei region and the "dual carbon" goal, there is little room for the improvement of ultra-low emission transformation of thermal power units. Under the background of the continuous improvement of installed capacity of clean energy and the growth rate of power generation, it is urgent to solve the problem in the regional energy structure of how to further play the role of thermal power as a basic power guarantee, while rapidly improving the power generation and consumption capacity of clean energy.

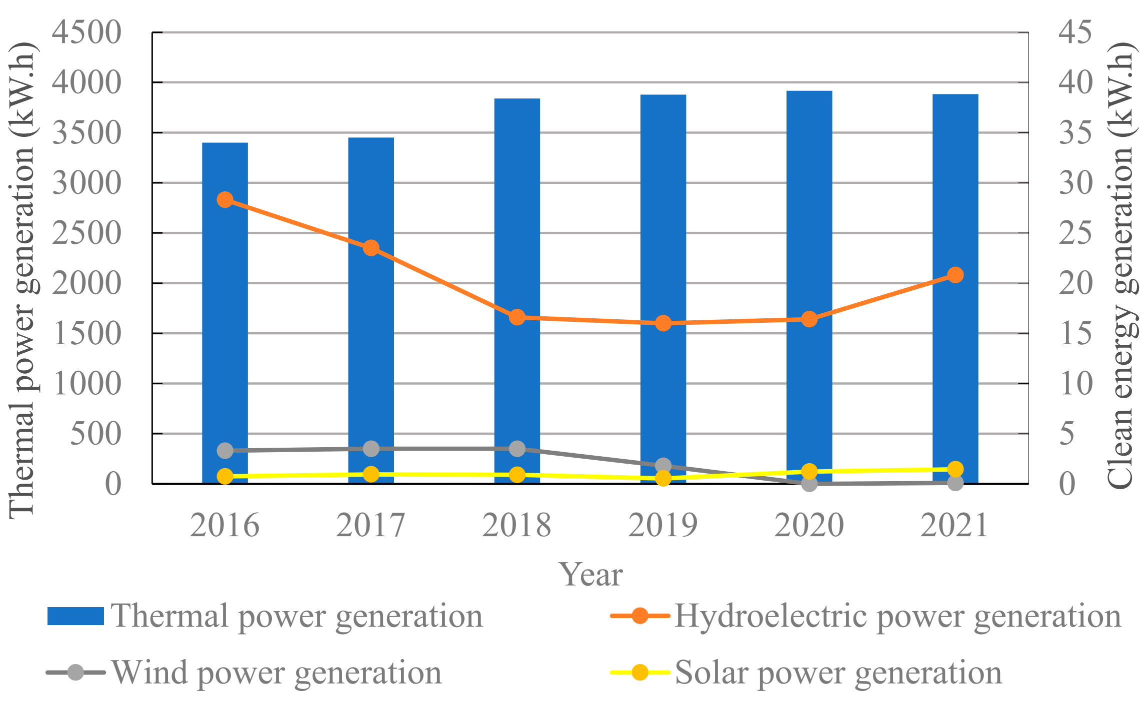


Figure 1. Power generation in the Beijing–Tianjin–Hebei region from 2016 to 2021.

3.2. Coupling Mechanism between Carbon Market and Power Market

As of 15 July 2022, the cumulative trading volume of carbon emission quotas in the national carbon market has reached 194 million tons and the cumulative turnover has reached CNY 8.492 billion [37]. According to the development status and future trend of the national carbon market, a coupling mechanism between the carbon market and power market has been established, as shown in Figure 3. The carbon market is generally divided into primary carbon market and secondary carbon market. In the primary carbon market, the initial allocation of carbon quotas is conducted according to government policies, and the allocation modes include free allocation and auction. The secondary carbon market is mainly a market where enterprises and users conduct carbon quota market trading. With the start of trading in the national carbon market, the national China Certified Emission Reduction (CCER) market is expected to restart to provide an effective supplement to the carbon market.

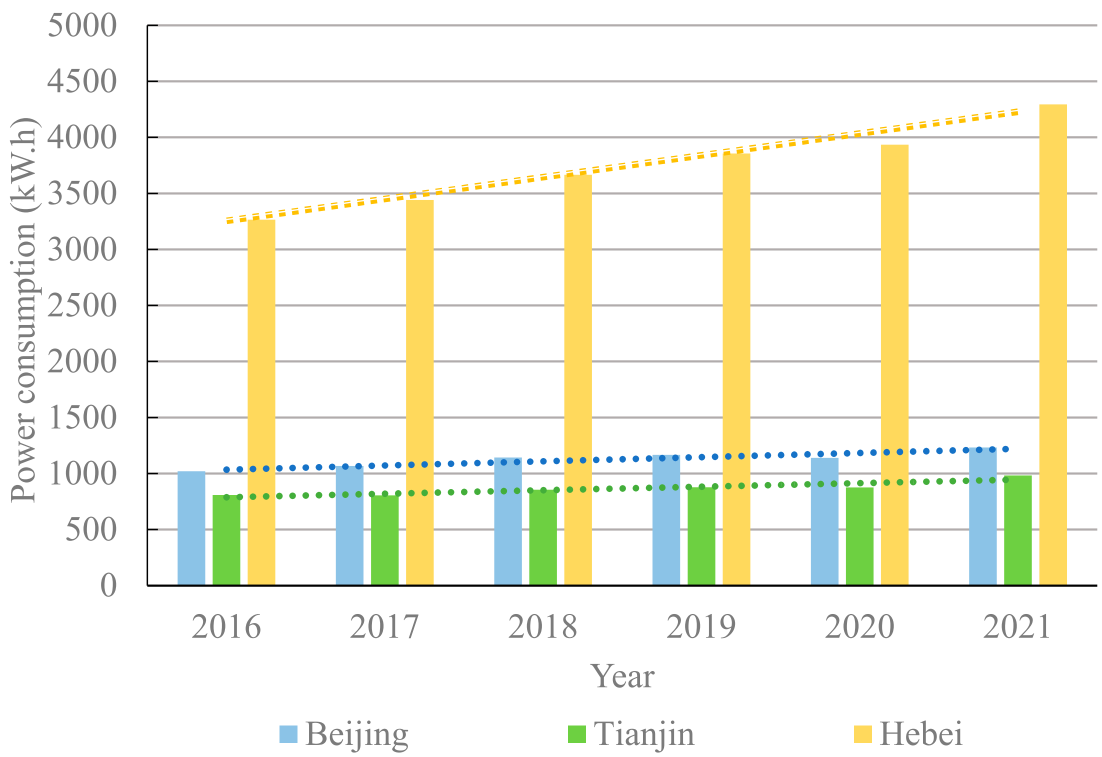


Figure 2. Power consumption in the Beijing–Tianjin–Hebei region from 2016 to 2021.

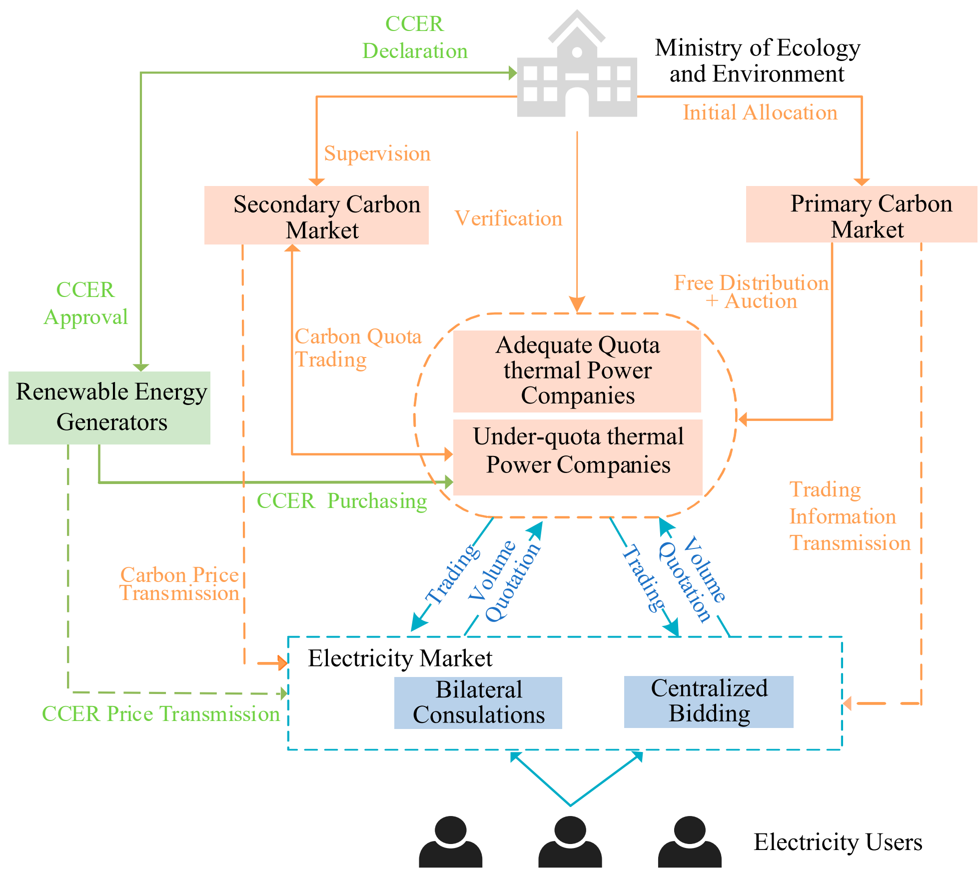


Figure 3. Coupling mechanism of power–carbon market.

The coupling effect of the carbon market and power market is mainly reflected in three aspects. The first one is the close relationship between the two markets' information. The power market and carbon market are highly consistent on the trading participants, which leads to the mutual circulation of information between the two markets and mutual reference for trading decisions. The closer the power–carbon market is connected, the more frequent and deeper the business data interaction between the two markets [38]. The second is the price coupling of carbon price and power price. Carbon trading internalizes the external cost of carbon dioxide generated by power generation enterprises in an economic way to solve the problem of environmental pollution [39]. In the short term, the cost transmission of carbon price will affect the clearing price in the spot market [40], the contract price in the medium- and long-term markets, and the power trading price in the auxiliary service market. In the long run, the price signal will improve the installed power structure and increase the installed capacity of renewable energy [41]. The third is the design interaction between the two-market mechanism. Boqiang Lin indicated that, with the improvement of quota design, allocation and trading methods of the carbon market, the operation of the carbon market will further promote the reform of the power market mechanism [42]. The operation of the new power market mechanism can effectively alleviate the pressure on emission reduction but, at the same time, it can inhibit the activity of the carbon market [39] and reversely promotes the reform of the carbon market mechanism.

4. Construction of Synergism Model between Carbon Market and the Beijing–Tianjin–Hebei Power Market

In the article, based on clarifying the interaction between the carbon market and power market, the system dynamics theory is used to build a system dynamic model of the interaction between the carbon market and the Beijing–Tianjin–Hebei power market. The model is composed of an open system and a closed system. The closed system is the interaction of factors within the system and the factors in the open system are exogenous variables. However, the closed system is the focus of the study, so the analysis in the text focuses on the closed-loop system. The development of the Beijing–Tianjin–Hebei power market is studied under the synergism of the carbon market and the Beijing–Tianjin–Hebei power market, and simulation is carried out according to the actual situation of the Beijing–Tianjin–Hebei region.

4.1. System Boundary and Assumptions

In the model, the factors within the system boundary are analyzed as a complete system, while the factors outside the boundary are ignored.

① Carbon market. In order to study the mechanism of carbon trading, Beijing–Tianjin–Hebei thermal power generators are divided into thermal power generators in the national carbon market and other thermal power generators, and the thermal power generation capacity in the Beijing–Tianjin–Hebei region in the national carbon market is divided into thermal power generators of carbon emission rights buyer and that of carbon emission rights seller (hereinafter referred to as buyer thermal power generators and seller thermal power generators). Among them, the seller thermal power generators improve technology through investment, with a higher carbon emission reduction rate. When compliance is completed, excess carbon quotas are generated and the excess carbon quotas are sold in the national carbon market to earn profits. The buyer thermal power generators do not improve technology and complete compliance by purchasing carbon quota in the national carbon market.

② Beijing–Tianjin–Hebei power market. On the power supply side, only the overall situation of thermal power generation companies is considered and renewable energy power generation companies are not considered temporarily.

Assumptions of this model are as follows: ① This project only focuses on carbon trading between power generation enterprises, without focusing on carbon trading with other industries. The carbon emission reduction rate of the seller thermal power generators is higher than that of the buyer thermal power generators. ② The initial value of the carbon price is weighted and averaged according to the situation since the operation of the national carbon market. The upper limit of the carbon price is set as CNY 600/ton and the lower limit is set as CNY 10/ton. ③ When buyer thermal power generators purchase carbon emission rights, it will give priority to purchase CCER and can complete the expected purchase in the national market. ④ The carbon quotas expected to be purchased or sold by thermal power generators of the Beijing–Tianjin–Hebei buyers and sellers can be purchased or sold in the national carbon market. ⑤ The installed capacity, annual utilization hours and final power generation capacity of thermal power generators of the Beijing–Tianjin–Hebei buyers and sellers are the same, so the total carbon quota allocated by the government to the buyers and the sellers is the same. ⑥ The new installation period of thermal power units is 6 months.

4.2. Causality Analysis

First, a causal cycle diagram of the carbon market is built, as shown in Figure 4. The causal diagram includes a negative feedback loop and a positive feedback loop. For the negative feedback loop, with the increase in the power generation capacity of the thermal power generation enterprises, the demand for carbon emission quotas increases, resulting in the excess demand for carbon quotas. According to the principle of supply and demand balance, with the rise in the carbon price, thermal power cost rises. According to the principle of supply and demand balance, with the rise in the carbon price, thermal power cost rises. Accordingly, thermal power generation will reduce the installed capacity and reduce the thermal power generation capacity. Thus, the balance of power supply and demand is reached. For the positive feedback loop, when the power generation capacity of thermal power generation enterprises increases, the demand for carbon emission rights increases. Relatively speaking, thermal power generation companies hold less carbon quotas to result in carbon quotas and CCER purchase expectations. As the excess demand for carbon quotas increases, the carbon price increases, the cost of thermal power generation companies increases, the installed capacity of thermal power decreases, the thermal power generation capacity decreases and the demand for carbon quotas decreases, so that the carbon market is balanced.

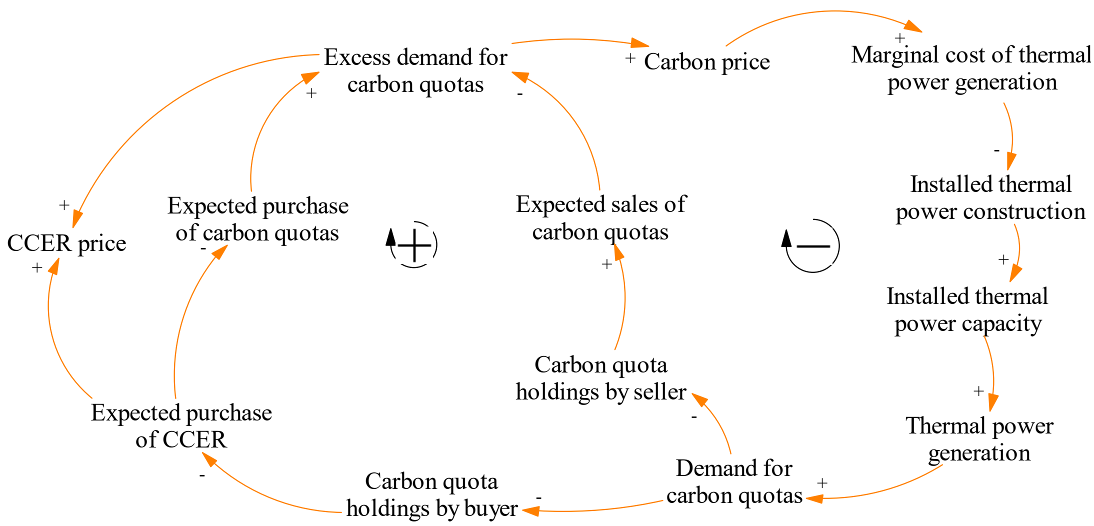


Figure 4. Causal cycle diagram of carbon trading market.

Secondly, a causal cycle diagram of the power market is built, as shown in Figure 5, which includes three negative feedback loops. For the small negative feedback loop in the middle, the power demand increases and the thermal power price increases. When the price of thermal power rises too high, the demand for power decreases. For the negative feedback loop on the right side, the buyer thermal power generators generate more power, the power supply increases, and the thermal power price decreases. Accordingly, it reduces the profit of the buyer thermal power generators, the installed capacity and the amount of thermal power generated by the buyer thermal power generators. The causal cycle process of the seller thermal power generators is like that of the buyer thermal power generators.

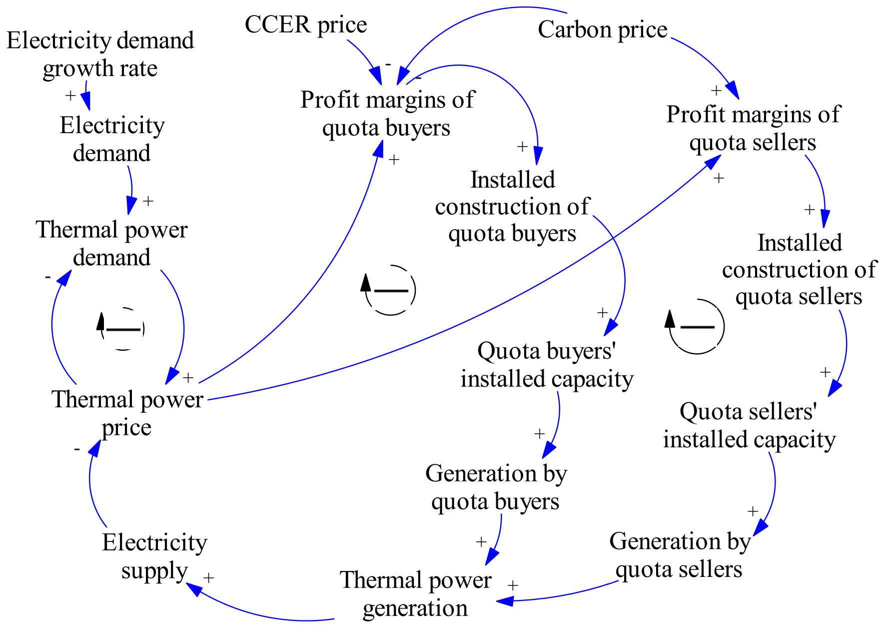


Figure 5. Causal cycle diagram of power market.

Finally, based on the above feedback mechanism, a causal cycle diagram of the interaction between the carbon trading market and power market is constructed, as shown in Figure 6. It includes three negative feedback loops and one positive feedback loop, which is the mutual coupling relationship between the carbon trading market and power market. The power market and carbon trading market generate causality through carbon price, carbon quota demand and CCER price.

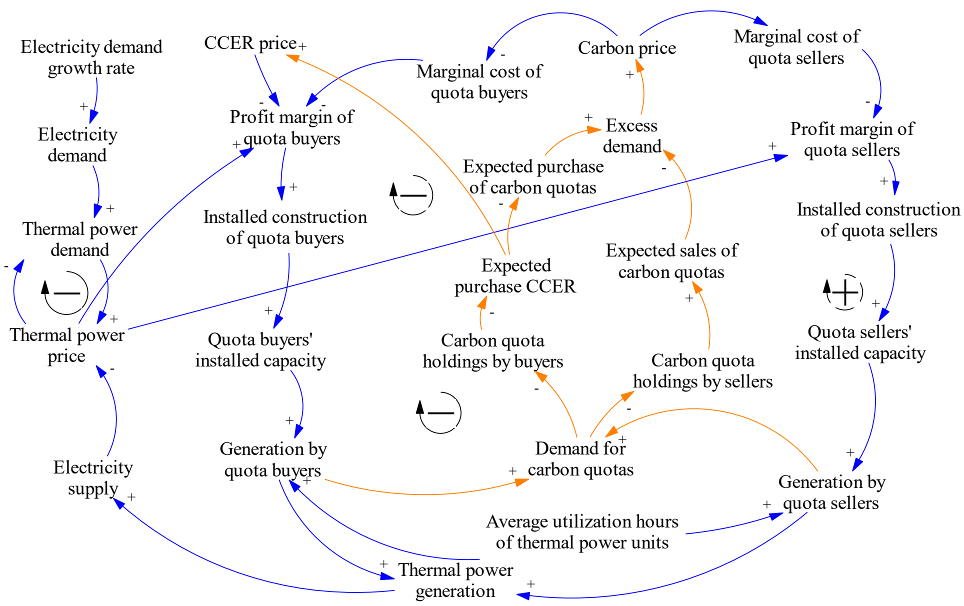


Figure 6. Interaction causal cycle diagram of carbon trading market and power market.

4.3. Construction of System Dynamics Model

Because of the above causality diagram, the stock flow diagram of the interaction between the carbon market and power market is further drawn, as shown in Figure 7. By using different symbols to represent different types of variables, different types of arrows represent different functional relationships. In addition, it is important to emphasize that "BTH" means "Beijing–Tianjin–Hebei" in the figure. The variables of the electricity market are connected by the blue arrow and the variables of the carbon market are connected by the orange arrow. In the dotted box is the interaction of variables in the carbon trading market and outside the dotted box is the interaction of variables in the electricity market. Variables in the model are divided into four categories of state variables, rate variables, auxiliary variables and constants.

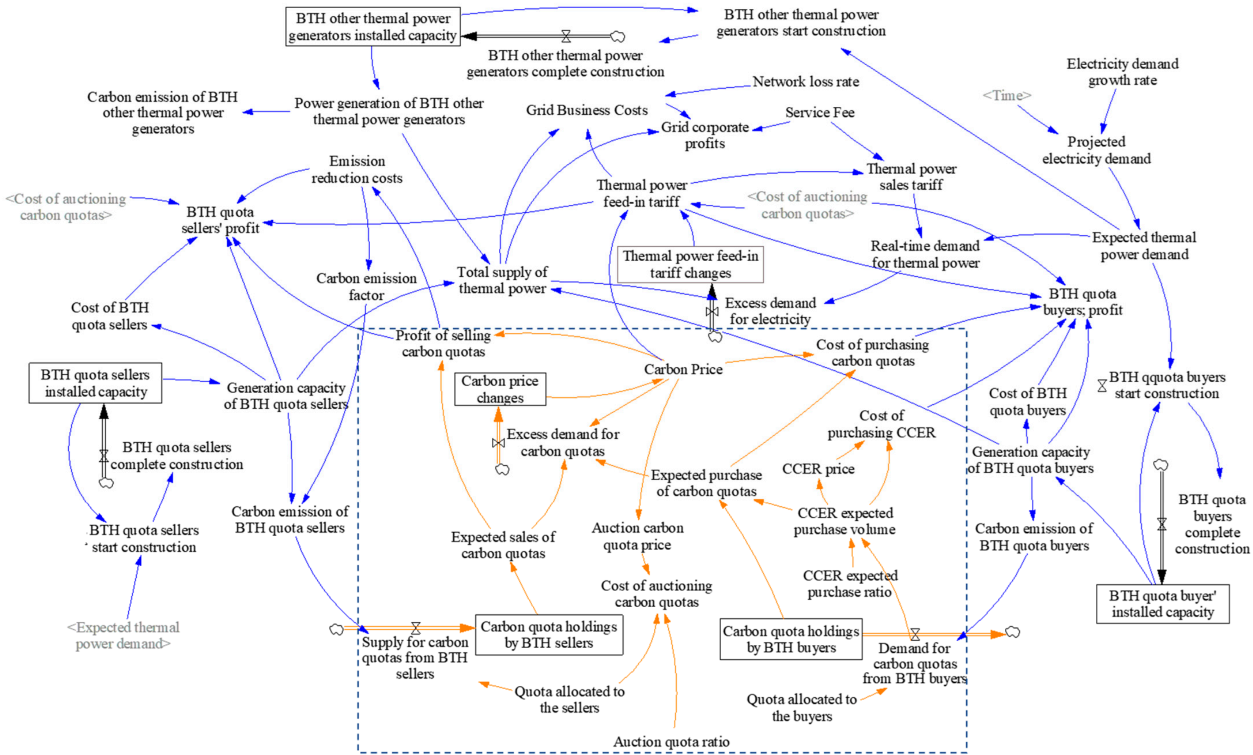


Figure 7. Interactive stock flow of carbon trading market and power market.

State variables: BTH quota buyers installed capacity, BTH quota sellers installed capacity, BTH other thermal power generators installed capacity, carbon quota holdings by BHT sellers, carbon quota holdings by BHT buyers, carbon price change and thermal power grid price change.

Rate variables: BTH quota sellers' complete construction, BTH quota buyers' complete construction, BTH other thermal power generators' complete construction, supply for carbon quotas from BTH sellers, demand for carbon quotas from BTH buyers, the excess demand for carbon quotas and excess demand for electricity.

Auxiliary variables: BTH other thermal power generators' start construction, BTH quota buyers' start construction, BTH quota sellers' start construction, thermal power feed-in tariff, thermal power sales tariff, projected electricity demand, expected thermal power demand, real-time demand for thermal power, profit of selling carbon quotas, cost of purchasing carbon quotas, power generation of BTH other thermal power generation, generation capacity of BTH quota sellers, generation capacity of BTH quota buyers, total supply of thermal power, carbon emissions of BTH other thermal power generators, carbon emissions of BTH quota sellers, carbon emissions of BTH quota buyers, cost of BTH quota sellers, cost of BTH quota buyers, emission reduction cost, carbon emission factor, cost of auctioning carbon quota, auction carbon quota price, expected sales of carbon quota, expected purchase of carbon quota, carbon price, cost of purchasing CCER, CCER expected purchase volume, CCER price, grid business costs and grid corporate profits.

Constants: power demand growth rate, service fee, CCER expected purchase ratio and network loss rate.

5. Analysis of Simulation Results

5.1. Scenario Setting

The scenario settings are shown in Table 1. The initialization parameters required by the model are shown in Table A1.

Table 1. Basic scenario settings.

Main Parameters	Parameter Assignment
Carbon emission coefficient of the seller thermal power generator (technical progress)	9000~8000 t/100 million kW·h
Proportion of carbon quota auctioned	0%
Total quota of thermal power generators	130 million tons

5.2. Analysis of Basic Scenario Results

Based on the above parameters and scenario settings, the system dynamics model of carbon trading and power market interaction was simulated, and the fluctuation of carbon price, carbon trading and power price under the interactive operation of the carbon trading market and power market, as well as the impact on key enterprises, were analyzed. The following results were obtained.

(1) Carbon price

Figure 8 shows the trend of change in carbon price. The carbon price curve shows a trend of a stable level, followed by a linear increase, with a fluctuation range of CNY 150~220/ton. Possible reasons for this fluctuation trend of carbon price are, in the early stage of carbon market, the carbon quota allocated by the government can basically meet the demand of thermal power plants, so the demand for carbon trading is small, the carbon market is not hot and the trend in the change in carbon price is not obvious. With the increasing level of power demand and the increase in thermal power generation, the demand of thermal power generation enterprises for carbon emission rights has increased. The carbon market is in a seller's market. According to the principle that market supply and demand determine the price, the carbon price shows an upward trend.

(2) Carbon emissions

Figure 9 shows the trend of carbon emissions of the buyer and seller thermal power generators. Overall, the carbon emissions of the buyer thermal power generator are higher than those of the seller thermal power generators in the whole stage, with the fluctuation range of the buyer's carbon emissions ranging from 7.5 to 14 million tons and the seller's carbon emissions ranging from 4.8 to 7.5 million tons. The carbon emissions of the thermal power generators of the buyer and the seller can be divided into three stages: in the first stage, the carbon emissions of both buyer and seller thermal power generators show an upward trend before the 20th month, ranging from 4.8 to 10 million tons; in the second stage, the carbon emissions of the buyer and the seller change smoothly between the 20th and the 45th month, but the difference between the carbon emissions of the buyer and the seller becomes larger than that in the first stage; in the third stage between the 45th and the 60th month, the carbon emissions of the buyer and the seller show a trend of a rising curve, followed by a flat level, and the difference between the carbon emissions of the buyer and the seller is larger than that in the second stage.

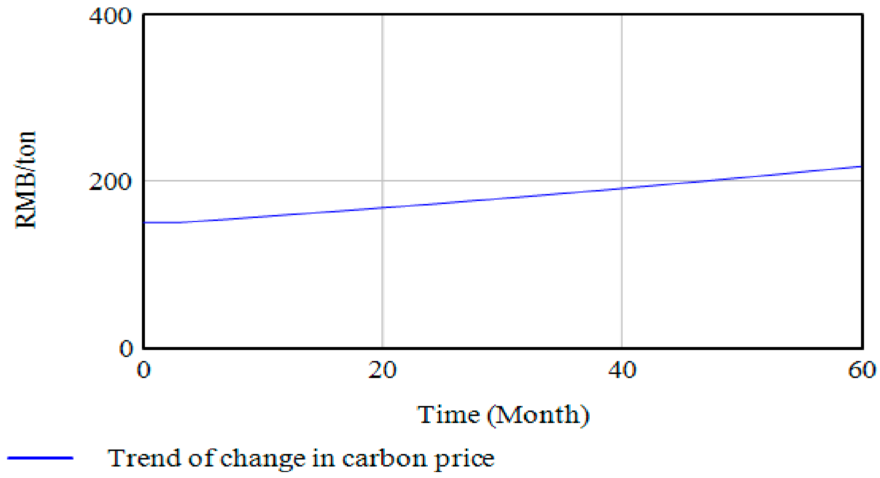


Figure 8. Trend of change in carbon price.

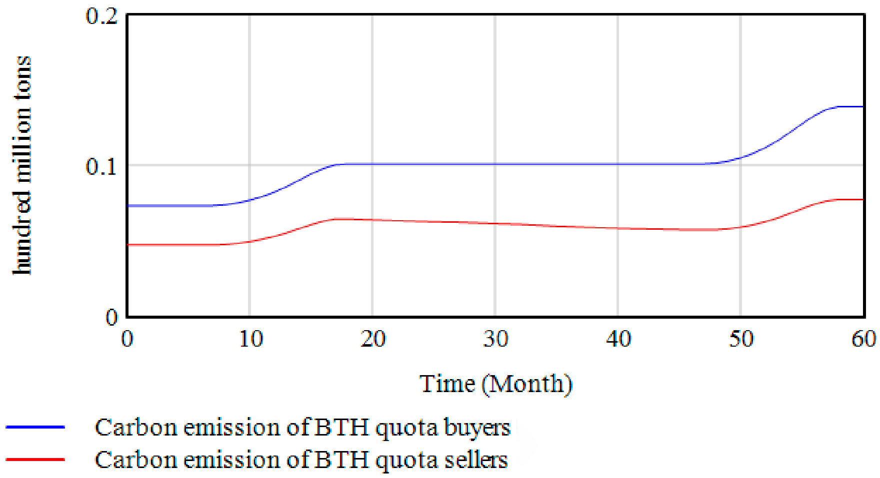


Figure 9. Trend of change in carbon emissions.

Beijing mainly consumes energy in the tertiary industry, while Tianjin and Hebei mainly consume energy in secondary industry, and Hebei has the highest carbon emissions. In Figure 9, with population growth and economic development, carbon emissions of thermal power generators from both parties are rising. The implementation of carbon trading policy for the "carbon peaking and carbon neutrality" goal limits the carbon emissions of both parties. However, with the development of the carbon market, the power generation capacity of the buyer thermal power generators will increase and no emission reduction measures will be taken, leading to a gradual increase in carbon emission, which will further increase the demand for carbon quotas.

(3) Thermal power feed-in tariff

Figure 10 shows the change trend of feed-in tariff for thermal power, which is consistent with the change trend of carbon price. The overall trend shows an increase, and the fluctuation range is CNY 0.8~1.25/kW·h. During the development of the carbon trading market, the carbon cost for thermal power generators in production and trading are increasing. Due to the communal nature of environmental issues, thermal power generators, in pursuit of maximizing their own interests, reasonably transfer some of the carbon costs through the tariff to the users associated with the electricity consumption chain. Comparing the carbon price with the feed-in tariff for thermal power, it can be found that, in the initial stage of carbon market, the power price is less affected by the carbon price. As the carbon market continues to develop, the power price also rises as carbon price rises. It can be concluded that carbon prices need to be introduced to maintain a good transmission mechanism for carbon costs.

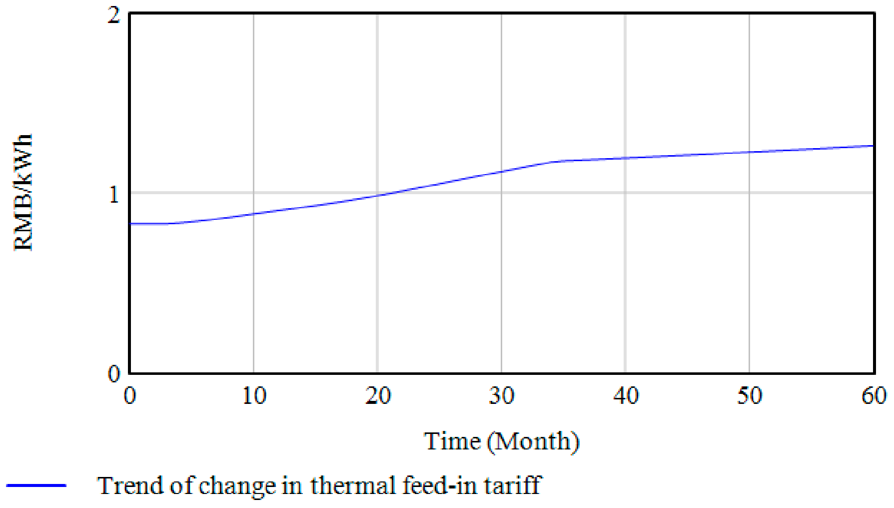


Figure 10. Trend of change in thermal feed-in tariff.

(4) Profits of generators

Figure 11 shows the profit change trend of power generation generators. Overall, the profits of the buyer and the seller thermal power generation generators show a stable and then rising trend, but the profits of the buyer thermal power generation generators decline after reaching a certain height. The fluctuation range of the profits of the buyer and the seller thermal power generation generators is CNY 4.5~12 billion and CNY 4.5~37.5 billion, respectively.

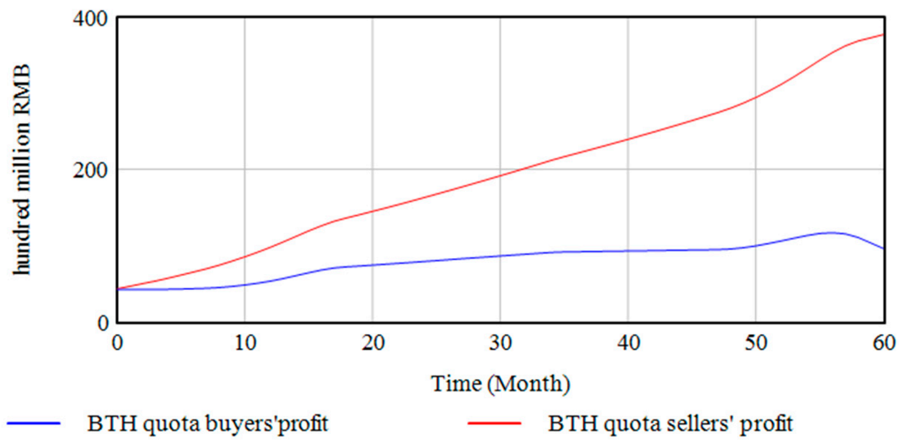


Figure 11. Trend of change in profits of thermal power generators.

At the initial stage of carbon market, thermal power generators are less active in the carbon market and the carbon price is less volatile. The profits of the buyer and the seller are not easily affected by the carbon market, and the profit size of both parties is very close. With the development of the carbon market, the profits of thermal power generators fluctuate with the change in carbon price and carbon trading volume. Compared with the carbon quota buyer, the carbon quota seller has higher profits, which reflects the situation of the sellers' market in the late stage of the carbon market. The possible reason for the decline in the profits of the buyer thermal power generation companies is that, with the increase in carbon price, the cost of purchasing carbon quotas will also increase, resulting in a decrease in profits.

(5) Profits of power grid enterprises

Figure 12 shows the profit change trend of grid corporate profits. Overall, it shows a rising trend initially, followed by a decline and an increase in the last stage, with a fluctuation range of CNY 1.2 billion to CNY 1.55 billion.

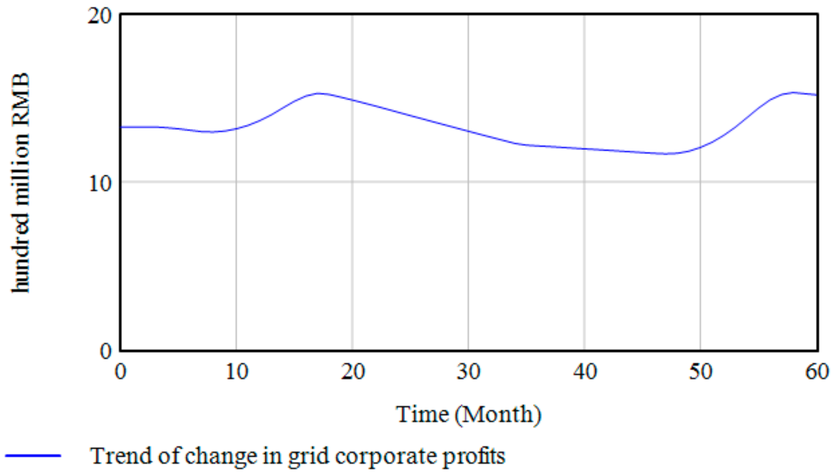


Figure 12. Trend of change in grid corporate profits.

During the operation of the carbon trading market and power trading market, the profits of power grid enterprises will fluctuate due to the transmission of carbon costs to power prices. In the initial stage of carbon market, due to the imperfect carbon cost transmission mechanism, the profits of grid corporate are less affected by it. However, as the carbon market becomes full-fledged, the carbon price is transmitted to the power price, resulting in an increase in the cost of power purchasing of the power grid enterprises. In addition, the profits are further reduced due to the COVID-19 epidemic and the periodic price reduction policy. As the coal price rises, the power price also rises and the power consumption only increases, so the profits of power grid enterprises are rising again. Although grid corporate do not directly participate in the carbon trading market, their production and operation will still be indirectly affected by the carbon market.

5.3. Analysis of Multi-Scenario Results

According to the development of the EU carbon market and the current state of China's carbon market, the development of the national carbon market can be divided into three stages: the initial stage, the middle stage and the late stage of carbon market. Among them, the carbon emission reduction coefficient of the seller thermal power generator is the intensity of carbon dioxide emission by the thermal power enterprise through technology improvement and other ways. It is assumed that, with the development of technology, the emission reduction capacity will increase. Carbon price transmission means that the carbon price will be transferred to the power price to a certain extent and the degree of carbon price transmission will gradually increase. The transmission of cost of carbon quota auction means that the cost of carbon quota auctions of thermal power enterprises will be transferred to the power price to a certain extent and the transmission degree will gradually increase. The specific parameter settings are shown in Table 2, mainly with reference to the corresponding development stage of the EU.

(1) Carbon price

As shown in Figure 13, the carbon price curves in all three scenarios show an upward trend. The carbon price in the initial stage of carbon market fluctuates in the range of CNY 50~70/ton, the carbon price in the middle stage in the range of CNY 80~120/ton, and the carbon price in the later stage in the range of CNY 150~217/ton. It can be concluded that the carbon price in the late stage of carbon market is higher than those in the initial and middle stages of carbon market.

Table 2. Multi-scenario settings.

Main Parameters	Initial Stage of Carbon Market	Middle Stage of Carbon Market	Late Stage of Carbon Market
Carbon emission coefficient of the seller thermal power generator (technical progress)	9000~8000 t/100 million kW·h	8000~7000 t/100 million kW·h	7000~6000 t/100 million kW·h
Proportion of carbon quota auctioned	0%	20%	50%
Total quota of buyer/seller thermal power generator	130 million tons	127.79 million tons	124.98 million tons
Initial value of carbon price	CNY 50/ton	CNY 80/ton	CNY 150/ton
Carbon price conduction	CNY 0.00208/kW·h	CNY 0.004/kW·h	CNY 0.006~0.0067/kW·h
Price of carbon quota auctioned	-	Carbon price × 0.6	Carbon price × 0.7
Transmission of cost of carbon quota auction	-	Cost of carbon quota auction × 6%	Cost of carbon quota auction × 7%

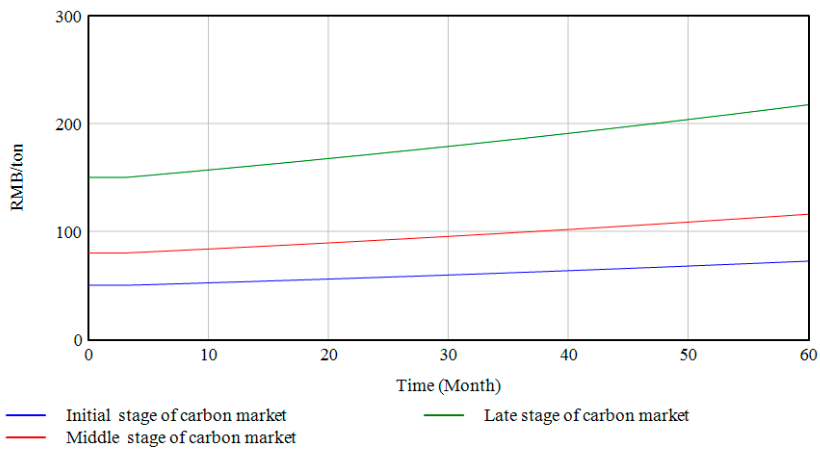


Figure 13. Trend of change in carbon price in three scenarios.

According to the principle of market supply and demand determining price, the increasing level of power demand and the increase in thermal power generation, coupled with the increase in coal price, the carbon price has an upward trend. However, the carbon price at the beginning of the carbon market is lower than the price at the middle and end of the carbon market. This is due to the low demand for carbon quotas and low carbon trading activity in the early stage. In the late stage of carbon market, given the requirements of the "carbon peaking and carbon neutrality" goal, along with the adjustment of carbon quota supply and demand, the gap between its carbon price and the carbon price in the initial and middle stages of carbon market is narrowed.

(2) Carbon emissions

Figure 14 shows the change in carbon emissions of the seller thermal power generators. Overall, the carbon emissions of the seller thermal power generators in the initial, middle and late stages of carbon market vary from 6 to 11 million tons, from 5 to 9 million tons and from 4.6 to 7.7 million tons, respectively. The carbon emissions of the seller thermal power generators in the late stage of carbon market are less than those in the early and middle stages of carbon market.

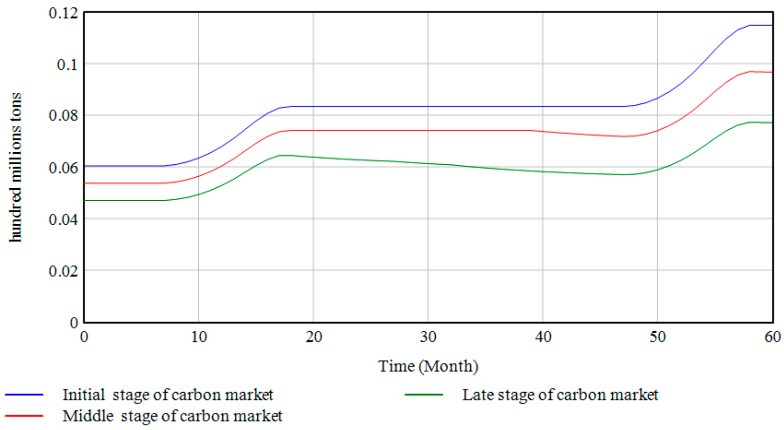


Figure 14. Trend of change in carbon emissions of the seller thermal power generators in the Beijing–Tianjin–Hebei region.

Under the "carbon peaking and carbon neutrality" goal, the implementation of carbon trading policy gradually limits the carbon emissions of the buyer and the seller. In order to sell more carbon quotas, the seller thermal power generator will also reduce its own carbon emissions. In addition, Environment, Social and Governance (ESG) has been introduced as an important part of the enterprise. Since the establishment of the enterprise, low-carbon environmental protection, green transformation and other issues have been taken into consideration. In addition, the above issues are incorporated into the cost model, so that more and more people can participate in carbon sink and carbon trading. Therefore, the carbon emissions of the seller's thermal power generation companies will be reduced and reach a stable state in the later period.

(3) Thermal power feed-in tariff

Figure 15 shows the change trend of the thermal power feed-in tariff. Overall, the thermal power feed-in tariff shows an upward trend. The thermal power feed-in tariff in the late stage of carbon market is higher than those in the initial and middle stages of carbon market. The variation in electricity price in the late carbon market ranges from CNY 0.82/kW·h to CNY 1.25/kW·h, and the variation in electricity price in the initial and middle carbon market ranges from CNY 0.44/kW·h to CNY 0.71/kW·h and CNY 0.50/kW·h to CNY 0.82/kW·h, respectively.

In recent years, China's renewable energy power generation industry has made great progress, but thermal power still provides more than 60% of the power in the Beijing–Tianjin–Hebei region, so the cost of thermal power directly determines the power price. The most important factor affecting the cost of thermal power is the price of coal, which accounts for 60% of the cost of thermal power. However, the pressure of coal supply and demand results in an increase in the coal price and the concomitant rise in the cost of thermal power generation, along with the also rising carbon price, which leads to the rise in power price.

(4) Profits of generators

Figure 16 shows the change trend of the profits of the seller and buyer of thermal power generators in the Beijing–Tianjin–Hebei region under the three scenarios. The trend of seller's profit is shown in Figure 16a and the trend of buyer's profit is shown in Figure 16b. Overall, the profits of the seller thermal power generators show an upward trend, and the profits in the late stage of carbon market are larger than those in the middle and initial stages. In Figure 16a, the variation range of the profits of the seller thermal power generators in the initial, middle and late stages of carbon market is CNY 1.8~12.0 billion, CNY 2.3~17.0 billion and CNY 4.3~37.7 billion, respectively. The profits of the buyer thermal power generation companies show a trend of fluctuating upward, followed by a decline. The profits of the buyer thermal power generation generators in the late carbon market are still larger than those in the middle and initial carbon markets. In Figure 16b, the variation range of the profits of the buyer thermal power generation generators in the initial, middle and late carbon markets is CNY 2.1~6.4 billion, CNY 2.5~7.6 billion and CNY 4.2~11.7 billion, respectively.

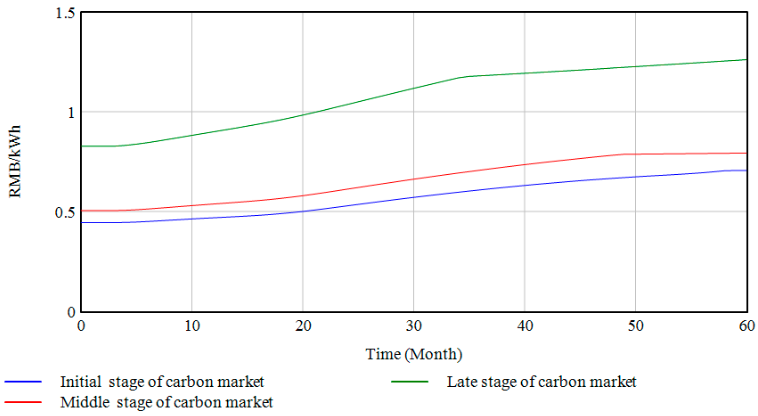
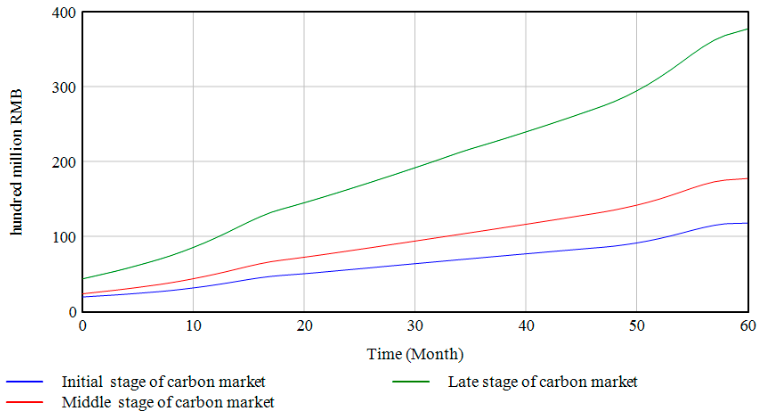


Figure 15. Trend of change in to-grid price of thermal power.

(a)



(b)

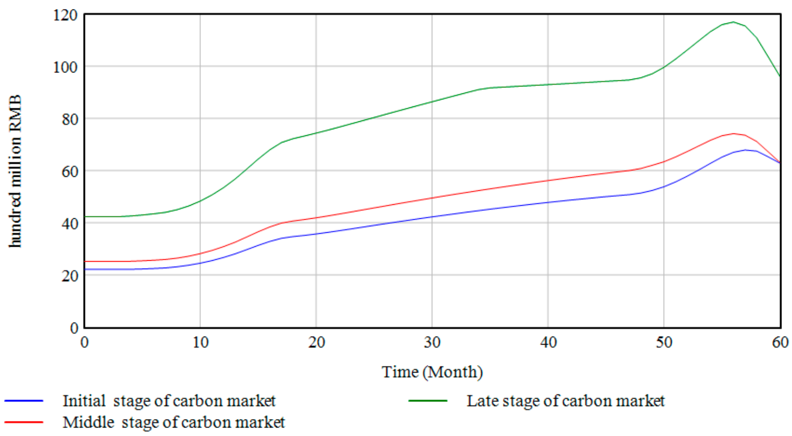


Figure 16. Trend of change in profits of the thermal power generators in the Beijing–Tianjin–Hebei region. (**a**) Change trend of carbon quota sellers' profit; (**b**) Change trend of carbon quota buyers' profit.

With the development of the carbon trading pilot project and the launch of the online trading of the national unified carbon market, the carbon trading market has gradually become well established. The profits of thermal power generators in the later stage of the carbon market are higher than those in the early and middle stages. In addition, the profit of seller thermal power generators is higher than the profit of buyer thermal power generators. This indicates that the carbon market not only achieves carbon emission reduction, but also enables the seller thermal power generators to benefit from the carbon trading market. This will increase the incentive for thermal power generators to reduce emissions.

6. Discussion

In the future, the carbon market will be deeply coupled with the Beijing–Tianjin–Hebei power market, especially the coupling in grid price of thermal power and carbon trading price. With the increase in total carbon emissions, carbon price will become an important factor affecting the economic benefits of thermal power generators. According to the Higher Committee on Carbon Pricing, carbon price will be USD 50~USD 100/ton by 2030 to reduce carbon emissions in a cost-effective manner. Therefore, China's carbon price will play a signal role in the future, and there is still room for carbon price to rise. When the carbon price rises, the transmission of carbon price to power price will increase the cost of thermal power generators, reduce their competitiveness and, therefore, provide development space for renewable energy power generators. The economic efficiency of different power generation technology is influenced by factors such as carbon price and power price via its cost, which will become the focus of future evaluation of economic benefits of different power generation technologies.

With the advancement of the carbon market and the Beijing–Tianjin–Hebei power market, the increase in carbon quota proportion and carbon trading price will encourage enterprises to apply low-carbon and emission reduction technologies and attract funds for low-carbon investment. In addition, new energy can be fully connected to the grid with a fair price. The synergy of carbon market and power market can help adjust the power supply structure and help it transform to a new power system dominated by renewable energy, which will make a significant contribution to reducing carbon emissions and promoting the consumption of renewable energy.

7. Conclusions and Policy Recommendations

Studying the coupling mechanism and synergic development of the carbon market and the Beijing–Tianjin–Hebei power market will help to reform the power market mechanism and achieve the goal of carbon emission reduction. This study analyzes the coupling mechanism between the carbon market and power market, constructs a system dynamics model for the synergy between the carbon market and the Beijing–Tianjin–Hebei power market, and conducts simulation. The results show that: first, the coupling mechanism between the carbon market and the Beijing–Tianjin–Hebei power market is mainly reflected in the carbon price, power price and market mechanism. Second, carbon market and power market are mutually constrained, and the increase in carbon emissions will cause the rise in carbon trading price. While the profits of the quota seller thermal power generator increase, the costs of the buyer thermal power generator will also increase. The profits of power grid enterprises will also rise in the first place, followed by a stable state via the transmission of carbon price onto power price. Third, the carbon price, power price and generator profits in the late stage of carbon market are higher than those in the initial and middle stages, while the opposite is true for carbon emissions.

Based on the above findings, the study proposes the following policy recommendations to promote the synergic development of the carbon trading market and the Beijing–Tianjin–Hebei power market under the "carbon peaking and carbon neutrality" goal.

First, the linkage between the carbon market and power market should be guided by price. The effective transmission of carbon costs is the key to the sustainable development and effectiveness of the carbon market. On the one hand, the power price formation mechanism should be improved and the carbon price should be directly considered in the power price in the form of cost, so that the carbon cost can be transmitted to the user side. On the other hand, the market attribute of power price in the Beijing–Tianjin–Hebei region should be strengthened, the power selling price should be further liberalized based on liberalizing to-grid price of coal, and a linkage mechanism between carbon cost and sales power price should be established.

Second, the correlation between the Beijing–Tianjin–Hebei power and social emission reduction targets should be strengthened. There are many green and low-carbon policies, such as carbon tax, green certificate, energy use right transaction, green power transaction, renewable energy power consumption guarantee mechanism, etc. From the perspective of emission reduction, the Beijing–Tianjin–Hebei power market is suitable to use carbon trading policy tools. However, from the perspective of the nature, function and tool objectives of the policies, multiple policy combinations are conducive to the optimization of the power supply structure of the Beijing–Tianjin–Hebei power market and the construction of a new power market.

Thirdly, a scientific understanding of the development mechanism of carbon quota market, CCER market and the Beijing–Tianjin–Hebei power market should be established. The carbon market promotes the emission reduction from high-carbon-emission resources and CCER helps renewable energy power generation, both of which rely on the power market. Since offset mechanisms can reduce the binding effect of total carbon emissions and dilute the incentive effect of the carbon market, which, in turn, affects the achievement of electricity emission reduction targets, the government needs to control the type of offsets and the percentage of offsets for renewable energy. In addition, the power sector needs to optimize the choice of emission reduction methods. It is necessary to consider both the goal of power emission reduction and the security of power supply.

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Data Availability Statement: The data is available upon request (https://www.ine.cn/index.html, accessed on 2 September 2022).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Parameter assignment.

Parameter	Parameter Assignment	Unit
Initial value of carbon quota holdings for buyers in Beijing–Tianjin–Hebei region	0	100 million tons
Initial value of carbon quota holdings for sellers in Beijing–Tianjin–Hebei region	0.089	100 million tons
Initial value of thermal power generators installed for buyers in Beijing–Tianjin–Hebei region	0.111	100 million kW

Table A1. *Cont.*

Parameter	Parameter Assignment	Unit
Initial value of thermal power generators installed for sellers in Beijing–Tianjin–Hebei region	0.111	100 million kW
Initial value of other thermal power generators installed in Beijing–Tianjin–Hebei region	0.111	100 million kW
Initial value of thermal power feed-in tariff	0.43885	CNY 100 million/100 million kW·h
Initial value of carbon price	50	CNY 100 million/100 million tons
Total thermal power generation in the previous year	2686.6	100 million kW·h
Average annual utilization hours of thermal power units participating in the carbon market	7258	Hour/year
Average annual utilization hours of other thermal power units	4952	Hour/year
Annual electricity demand growth rate	0.8	%
Unit construction cycle	6	Month
Grid tariff change delay time	5	Month
Thermal power feed-in tariff cap	0.3	CNY 100 million/100 million kW·h
Thermal power feed-in tariff floor	0.7	CNY 100 million/100 million kW·h
Carbon price change delay time	3	Month
Carbon price cap	600	CNY 100 million/100 million tons
Carbon price floor	20	CNY 100 million/100 million tons
Thermal power benchmark tariff	0.372	CNY 100 million/100 million kW·h
Transmission and distribution price	0.1224	CNY 100 million/100 million kW·h
Service Fee	0.001	CNY 100 million/100 million kW·h
Network loss rate	6	%
CCER purchase ratio	5	%

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