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PRICE AND CARBON EMISSION REDUCTION TECHNOLOGY COMPETITION IN THE ELECTRICITY SUPPLY CHAIN BASED ON POWER STRUCTURE

Wei Chen[1,2], Mengyao Cui[1], Matthew Quayson[2] and Heng Du[3,*]

Abstract. This study considers the research on electricity pricing and carbon reduction technology decisions of electricity supply chain enterprises under different power structures. It constructs a two-level electricity supply chain game model composed of two electricity producers and a single electricity retailer. By comparing the equilibrium solution results, the main research results are as follows: (1) in the market structure where electricity producers and electricity retailers make decisions at the same time, electricity producers are more willing to invest in low-carbon technologies and increase carbon emission reduction. The electricity retailer also set the lowest electricity prices at this time, and electricity demand is the highest. (2) In the case of the Stackelberg game for electricity producers, the wholesale electricity price is the highest, and the electricity producers obtain the most profits. In the case of the Stackelberg game for electricity retailers, the electricity price is the highest, and the profit of the electricity retailer is the highest. (3) In the market structure dominated by electricity retailers, the electricity price is the highest, and the electricity producers reduce the investment in carbon emission reduction technology after observation; the carbon emission reduction intensity is the least, and the electricity demand is also the least. (4) With the increase of price competition coefficient, the intensity of carbon emission reduction, electricity demand, electricity producers, and electricity retailer profit increase. However, as the competition coefficient of carbon reduction technology increases, these equilibrium solutions decline. We verify the above conclusions using multi-agent simulation.

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1. Introduction

With the increasingly severe problem of global climate change, the electricity supply chain faces increasing environmental pressure while pursuing economic benefits. Therefore, achieving the balance between price competition and carbon reduction technology competition in the electricity supply chain has become an urgent problem that needs to be solved.

Keywords. Power structure, carbon reduction technology, electricity supply chain, game theory, multi-agent modeling.

[1] College of Management Science, Chengdu University of Technology, Chengdu 610059, P.R. China.

[2] School of Management and Economics, University of Electronic Science and Technology of China, Chengdu 611731, P.R. China.

[3] School of Economics and Management, Nanjing Institute of Technology, Nanjing 211167, P.R. China

*Corresponding author: quange0216@njit.edu.cn

As an essential part of the electricity supply chain, the price competition mechanism of the electricity market is directly related to the allocation efficiency of electricity resources and the economic benefit of electricity enterprises. In the electricity market, different electricity supply chain enterprises compete for market share through price competition, which promotes the prosperity of the electricity market and the optimal allocation of electricity resources to a certain extent. However, price competition in the electricity market also brings problems, such as the waste of resources caused by excessive competition and the impact of price fluctuations on consumers. Therefore, achieving reasonable guidance and regulation of price competition in the electricity market is an essential direction of price competition research in the electricity supply chain.

With the continuous growth of global carbon dioxide emissions, global warming has led to many environmental problems, and the greenhouse gas emission problem dominated by carbon dioxide has become the focus of international concern. For example, due to the environmental crisis caused by fossil fuels, Mondal *et al.* [31] established a sustainable multi-level biofuel and bioenergy supply chain model to study the feasibility of the Indian government's green initiative of blending 20% fuel-grade ethanol with gasoline. Currently, the electricity industry is still the primary source of carbon dioxide emissions, accounting for about 40% of global carbon emissions [1]. To accelerate the reduction of the adverse impact of carbon dioxide emissions on the environment, the upstream and downstream enterprises of the electricity supply chain must scientifically implement carbon emission reduction work and actively assume responsibility for emission reduction. Carbon emission reduction technology is an essential means to achieve this goal, and its development level directly determines the environmental performance and sustainable development ability of the electricity supply chain. However, the research and development and application of carbon reduction technologies require a large amount of capital investment and technical support, which is a huge challenge for enterprises in the electricity supply chain. Therefore, achieving carbon emission reduction technology competition and innovation in the electricity supply chain is a vital issue in the study of carbon emission reduction technology competition in the electricity supply chain.

From the perspective of enterprise practice, electricity producers have done much work on related carbon emission reduction technologies. For example, to develop near-zero emission coal-fired electricity generation technology, China Huaneng Group Co., Ltd. pioneered the "green coal power" plan to develop critical technologies of green coal power[1]. The carbon emission research team of the Electric Power Research Institute of China Huadian Group Co., Ltd. planned to build the first online carbon emission detection experimental platform in the electric power industry, realize the simulation and research of online carbon emission monitoring technology in complex application scenarios of power plants, and provide a scientific basis for the promotion and application of online carbon emission monitoring technology[2]. China Southern Power Grid Corporation established China Southern Power Grid Carbon Asset Management Co., LTD. The company's business scope mainly includes carbon asset investment and management, carbon emission reduction, carbon conversion, carbon capture, carbon storage technology research and development[3]. Huadian Zhejiang Company adheres to scientific and technological innovation to boost high-quality development and shows new achievements in developing electric power equipment and technology application of emerging business projects centering on green and low-carbon technologies[4]. Therefore, theoretically, describing the game model of carbon emission reduction technology competition and price competition is of practical significance.

The main problems studied in this paper are as follows:

(1) Under which power structure is carbon emission reduction intensity the largest?
(2) Under which power structure do the upstream and downstream enterprises of the supply chain gain the most profits?
(3) How do the price competition coefficient and carbon emission reduction technology competition coefficient impact the decision-making of upstream and downstream enterprises in the supply chain?

[1] https://www.chng.com.cn/detail_zdgjjs/-/article/jXCQ2CQLyPh3/v/839195.html
[2] https://www.chd.com.cn/site/2/2021-06-21/dbf576facee149678b74458ad8660656.html
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Given the above research questions, this paper explores the impact of price competition and carbon emission reduction technology competition level on the decision-making of upstream and downstream enterprises in the electricity supply chain under the three-game models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game, respectively. We construct a game model of a two-level electricity supply chain consisting of two producers and a single electricity retailer. Among them, electricity producers choose the input of carbon emission reduction technology, and electricity retailers buy electricity products from electricity producers and decide the electricity price before selling them to the electricity market. This paper obtains the equilibrium solution under the three-channel rights structures through backward induction. Based on this, we discuss the effects of the production cost coefficient, price competition coefficient, carbon emission reduction technology competition coefficient, and carbon emission reduction technology cost coefficient of electricity products on the equilibrium solution, respectively. Then, we compare the carbon emission reduction intensity of electricity products, wholesale electricity price, electricity price, electricity market demand, and the profits of electricity producers and electricity retailers under the three rights structures. Finally, on the one hand, we verify the theoretical conclusion through the multi-agent simulation experiments. On the other hand, we analyzed the influence of each parameter on the equilibrium solution and gave management implications. The novelties and contributions of the study are as follows:

- With the power structure of the electricity supply chain as the background, this paper constructs three power structure models: Stackelberg game of electricity producer, Stackelberg game of electricity retailer, and the vertical Nash game. It discusses the influence of different power structures on wholesale electricity price, electricity price, and carbon emission reduction intensity. On this basis, the theoretical conclusions were verified through multi-agent simulation experiments.
- This paper systematically expounds on the internal mechanism of price competition and carbon emission reduction technology competition. It provides enlightenment for the decision-making and management of upstream and downstream enterprises in the electricity supply chain.
- Based on the existing literature, this paper increases the research on the competition of carbon emission reduction technologies and also combines three different power structures. This enriches the research of the power supply chain.
- In the context of low carbon, this paper points out that when electricity producers and electricity retailers act as leaders, respectively, the profits of electricity producers and electricity retailers are the largest.
- When electricity producers and electricity retailers act as "leaders" at the same time, the carbon emission reduction intensity of the electricity supply chain is the greatest. This means that in order to achieve maximum carbon reduction, electricity producers and electricity retailers should make decisions at the same time.
- This paper provides theoretical support for the upstream and downstream enterprises of the electricity supply chain to sort out the mode choice and provides a basis for the government to formulate relevant policies.

2. Literature review

The research fields related to this study mainly focus on two aspects: the electricity supply chain operation decision research and the carbon emission reduction technology.

2.1. Research on electricity supply chain operation decision

Existing literatures have studied operational decision-making of the electricity supply chain. For example, Dou *et al.* [2] studied an electricity supply chain dominated by electricity retailers with options trading. The results show that different risk aversion levels and income of the electricity supply chain have different impacts on electricity distribution, which provides a new approach to the electricity mix and risk assessment of the electricity supply chain. Al-nory *et al.* [3] studied an optimization model method for the electricity supply chain. The results showed how this method could provide decision-makers with the optimal supply chain operation to achieve the minimum energy change at the minimum cost. Zhu *et al.* [4] studied the pricing mechanism of renewable energy generating units with revenue-sharing contracts under a two-stage "multi-order" electricity supply chain that includes a single electricity retailer and provides different types of power energy in the hybrid power market. The results showed that the expected profit of all parties in the hybrid electricity supply chain under each decision mode is concave in the decision variables, and the greater the competition intensity of the supplier, the smaller the income-sharing ratio of the power buyer. Zou *et al.* [5] studied the impact of the interaction between futures and spot markets on the operational decisions of the electricity supply chain. They modeled the continuous behavior of producers and retailers as a Stackelberg game, in which producers act as leaders and retailers as followers. Chen *et al.* [6] studied a two-level electricity supply chain composed of a leader electricity producer and a follower electricity retailer and discussed the impact of the cap-and-trade mechanism on renewable energy investment and electricity marketing. Chen *et al.* [7] Studied a decentralized, centralized, and bargaining model of a supply chain consisting of a producer and a retailer. The results showed that the investment cost coefficient negatively affects supply chain profits and positively affects price decisions. In contrast, the probability of meeting the COVID-19 emergency positively affects supply chain profits and negatively affects price decisions. Furthermore, Chen *et al.* [8] investigated a two-channel electricity supply chain consisting of electricity producers as leaders and electricity retailers as followers, examined sustainability and price decision-making, and developed a coordinated contract to improve the performance of the electricity supply chain. The results showed that sensitivity to electricity sustainability helps to improve electricity sustainability, electricity prices, electricity demand, and the profits of supply chain firms. Generally, the decisions made by the dominant member in the electricity supply chain will impact both upstream and downstream enterprises of the whole supply chain. In addition, scholars have conducted relevant research on sustainable supply chains. For example, Binoy *et al.* [28] proposed a multi-objective mixed-integer programming model to design an electric sustainable supply chain network by considering resiliency and responsiveness. Arijit *et al.* [30] constructed a new multi-objective three-stage supply chain network and introduced an unprecedented trapezoidal interval type-2 fuzzy possibility programming method. The results show that resilience strategies are highly effective and can significantly enhance social, environmental, and economic aspects. The above literatures all involve operational decision-making of the electricity supply chain but does not study the influence of different power structures on the decision-making of electricity supply chain members.

The influence of power structure on corporate strategy and business decision-making is an important research field. Oliveira *et al.* [9] studied the inclusion of multiple producers and retailers in a supply chain model of an electricity market and compared the effects of two different market structures on the coordination of electricity supply chains and the profitability of participants. The results showed multiple equilibria in supply chain contracts and structures and that a two-part tariff is the best contract to reduce double marginalization and improve the efficiency of supply chain management. Chen *et al.* [10] studied an electricity supply chain composed of electricity producers and electricity retailers and the investment strategies of renewable energy and power service quality under different power structures. The results showed that the investment in power service quality and renewable energy was the highest under the Nash game model. These scholars have analyzed the influence of different power structures on the decision-making of electricity supply chain members. Based on the power structure, this paper also considers the competitive behavior of electricity prices and carbon emission reduction technology, further broadening the research field above.

2.2. Carbon emission reduction technology

Drake *et al.* [11] studied the influence of carbon emission tax and cap-and-trade system on enterprises' technology choices and production capacity decisions. The results showed that when enterprises combine clean and polluting technologies, production subsidies for high-investment and high-cost technologies, such as carbon capture and sequestration, increase total capacity and projected emissions. Wei *et al.* [12] studied the interaction between carbon emission reduction technology innovation and decentralized decision-making without cost sharing, decentralized decision-making, and government intervention under cost sharing and centralized decision-making. The results showed that the optimal level of carbon emission reduction technology innovation under decentralized decision-making is the same as that under centralized situations without cost sharing. Shib

[32] discussed an imperfect production system that takes into account the cost of greenhouse gases (GHG). Manufacturers have adopted green practices in supply chain management in the past to meet customer satisfaction with fair prices and product quality. A mathematical model was developed and analyzed taking into account various cost factors and interval values of key parameters. Shib [33] studied a dual-channel inventory model with uncertain market capacity for a particular product. A retailer has two options to sell products offline and online. The retailer's goal is to figure out the optimal pricing, order volume, and reorder point to maximize the average expected profit across both offline and online channels. Shib [34] studied a news supplier inventory model. Analyzed the comparison between green and non green marketing, including government subsidies and tax implementation. There is also price competition between green and non green producers. Finally, the proposed model was validated through numerical examples. Shib [35] designed two research models with the aim of occupying the market at a fair price and providing the best green quality. In Model 1, the optimal green quality and selling price of manufacturers and retailers in decentralized and centralized systems of a two-tier supply chain system were studied. Model 2 focuses on price competition between two alternative products, with the final customer demand determined by the price and quality of green products. Mathematical analysis was conducted on the proposed model, and the feasibility of the model in reality was demonstrated through numerical examples. Also, Lu *et al.* [13] explored the impact of two carbon regulations on the low-carbon technology level of new product manufacturers, and the results showed that carbon regulations could encourage manufacturers to improve the low-carbon technology level. Chen *et al.* [14] studied the carbon emission quota allocation rules under the peak-valley price policy and cap-and-trade mechanism in the electricity supply chain model made up of a single electricity generation enterprise and a single electricity retailer and their impact on low-carbon technology investment in the electricity industry. The results showed that benchmark allocation would bring higher low-carbon technology investment. Nevertheless, the total carbon emissions produced are more tremendous than the grandfathered configuration.

Furthermore, Chen *et al.* [15] studied the influence of benchmarking mechanisms on the decision-making of enterprises in the electricity supply chain. The results showed that with the increase of the unit carbon quota, the technological input and profit of carbon emission reduction of enterprises in the supply chain increased. The above literatures all involve carbon emission reduction technology but does not consider the investment decision of carbon emission reduction technology under a competitive environment. Giri *et al.* [16] studied the problem of multi-objective green four-dimensional fixed charge transport in a neutral environment, with the goal of minimizing transport costs, carbon emissions, and transport time. Then, two examples are used to illustrate the applicability and effectiveness of the proposed problem. Giri *et al.* [17] explored research into integrating H&LMW with photovoltaic systems and building sustainable closed-loop renewable energy supply chains. The use of electric gas technology to reduce carbon dioxide is considered to be an environmentally friendly method.

Only a few scholars have begun to study the decision-making of supply chains regarding carbon emission reduction technology in a competitive environment. For example, Li *et al.* [18] investigated the dual-channel green supply chain and used the Stackelberg game model to discuss the pricing and greening strategies of chain members under centralized and decentralized conditions. The retail price of a centralized green supply chain is higher than that of a decentralized green supply chain, which is in sharp contrast to the result of "double marginalization". Jamali *et al.* [19] studied the influence of different supply chain structures on the investment decisions of supply chain members in two competing supply chains. The results showed that a centralized supply chain structure could achieve a higher emission reduction level. Wang *et al.* [20] studied the balanced strategy of investing in carbon emission reduction technology in two competing supply chains under different scenarios based on whether carbon emission reduction technology is adopted. The results showed that when the competition between supply chains is intense, the government should reduce carbon tax to guide enterprises to adopt carbon emission reduction technology. Brojeswar *et al.* [21] considered an imperfect production-based competitive supply chain model for product recycling under a cap-and-trade system. Manufacturers invest in green technologies to limit carbon emissions during production. The findings suggest that governments should provide lower carbon caps to reduce excessive emissions and restrict the sale of excess carbon credits.

However, they only consider the horizontal competition between supply chains, and there are few studies on investment decision-making of carbon emission reduction technologies within supply chains in a competitive environment. Further, Chen *et al.* [22] studied the impact of different carbon cap-and-trade mechanisms on enterprises' investment in low-carbon technologies in the electricity supply chain composed of two electricity producers and a single electricity retailer under local protection. The results showed that when the unit carbon quota was larger, the investment rate of enterprises in the electricity supply chain was higher than that of other enterprises. The level of low-carbon investment, wholesale electricity prices, and the profits of electricity retailers and foreign electricity producers under the baseline method are all greater than the corresponding equilibrium solution under the grandfather method. However, the above literature did not consider the power structure of the electricity supply chain in competition between two electricity producers in terms of carbon emission reduction technology. This paper studies the influence of carbon emission reduction technology competition and price competition on the decision-making of upstream and downstream enterprises in the electricity supply chain under three different power structures.

2.3. Gap analysis and motivation

Literature review shows that many studies have been conducted on the electricity supply chain from the perspectives of power structure [2, 5, 6, 8], carbon cap-and-trade mechanism [11, 14, 19, 20], electric sustainable supply chain network [28,30], and carbon emission reduction technology [12,13,16–18]. However, there has been no thorough study of price competition in the electricity supply chain and competition in carbon reduction technologies without considering all three aspects combined. In addition, in terms of methods, no scholars have combined multi-agent simulation with the Stackelberg game.

Motivation: at present, the electricity market reform has promoted the market adjustment of electricity price, but the electricity price mechanism has not been perfected, resulting in increasingly fierce price competition in the electricity supply chain. At the same time, with global warming and excessive carbon dioxide emissions, the competition for carbon reduction technologies in the electricity supply chain enterprises is increasingly essential. Although studies have focused on price competition and carbon reduction technologies in the electricity supply chain, few studies have combined the two to explore their interaction and impact on the power structure. The purpose of this study is to analyze price competition and carbon emission reduction technology competition in the electricity supply chain to reveal their dynamic relationship and influence mechanism under different power structures. On a practical level, this not only helps to understand how the current electricity market operates but also provides policymakers with a decision to optimize electricity supply chain management and promote a green and low-carbon transition. At the academic level, this study will fill the gaps in the existing literature and provide new theoretical support for the application of electricity supply chain management and carbon emission reduction technologies.

3. Model framework

We construct a two-level electricity supply chain game model comprising two producers and a single electricity retailer. The specific model is shown in Figure 1. The electricity producers set wholesale prices and invest in carbon emission reduction technologies. The two electricity producers provide a dual-source procurement channel for the electricity retailer, who can set the price of electricity sold to the electricity demand market. In this context, this paper considers three different power structure game models. (1) In the Stackelberg game model of electricity producers, two electricity producers first set different wholesale electricity prices and Carbon emission reduction intensity. Then, the electricity retailer buys electricity products, sets electricity prices, and sells them to the electricity market. (2) In the Stackelberg game model of the electricity retailer, the electricity retailer first sets the price of electricity sold to the electricity demand market. Then, the two electricity producers set the wholesale price and carbon emission reduction intensity. (3) In the longitudinal Nash game model, the upstream and downstream enterprises of the electricity supply chain make decisions simultaneously, and the electricity

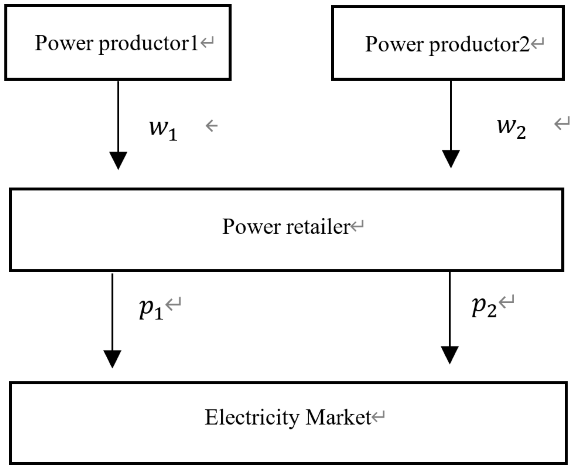

FIGURE 1. Model framework.

TABLE 1. Symbol and description.

Symbol	Description
Model parameter	
a	Potential electricity demand, $a > 0$
b	Price competition coefficient, $0 < b < 1$
d	Electricity production cost coefficient, $d > 0$
c	Carbon emission reduction technology competition coefficient, $0 < c < 1$
g	Carbon emission reduction technology cost coefficient, $g > 1 - c$
Decision variables	
w_j	Wholesale electricity price, $w_j > 0 (j = 1, 2)$
e_j	Carbon emission reduction intensity, $e_j > 0$
p_j	Electricity price, $p_j > w_j$
Other symbols	
$\pi^i_{m1}(w_1, w_2), \pi^i_{m2}(w_1, w_2), \pi^i_r(p_1, p_2,)$	Each power structure model under the profits of electricity producers and electricity retailer $(i = m, n, r)$

producers and electricity retailers simultaneously set the wholesale electricity price, carbon emission reduction intensity, and the electricity sold to the electricity market.

The symbols involved and their meanings are shown in Table 1. The lower corner mark $j = 1, 2$ represents generator 1 and generator 2, respectively. The lower corner mark m and r respectively represent electricity producer and electricity retailer. And the top corner marks $i = m, n, r$ represent the electricity producer Stackelberg game, Nash game and the electricity retailer Stackelberg game, respectively.

Assumption 1. It is assumed that consumers have low carbon preference, and the electricity market demand depends not only on the price but also on the carbon emission reduction technology invested by electricity producers and the carbon emission reduction intensity of electricity producers will cause changes in the market demand. This paper draws on Liu *et al.* [19], Xu *et al.* [20], and Ghosh and Shah [21] to construct the demand function. Assuming that the price competition coefficient of the two electricity producers is equal, that is b, the demand functions of electricity producer 1 and electricity producer 2 are, respectively:

$$q_1 = a - p_1 + bp_2 + e_1 - ce_2 \tag{1}$$

$$q_2 = a - p_2 + bp_1 + e_2 - ce_1. \tag{2}$$

Where, a is the potential market demand. p_1 and p_2 are electricity prices. Generally speaking, the higher the electricity price, the lower the electricity demand. $b(0 < b < 1)$ is the price competition coefficient such that the larger b is, the more intense the competition between the two electricity producers. e_1 and e_2 are the carbon emission reduction intensities of the two electricity producers, respectively.

Assumption 2. Assume that electricity producers can increase market demand by investing more in carbon emission reduction technologies. Generally, the greater the carbon emission reduction intensity, the higher the cost required. This paper draws on Menanteau *et al.* [22] and Requate *et al.* [23]. It is assumed that the electricity production cost and carbon emission reduction technology input cost of electricity producers are, respectively:

$$G(q_1) = \frac{1}{2} d_1 q_1^2 \tag{3}$$

$$G(q_2) = \frac{1}{2} d_2 q_2^2 \tag{4}$$

$$F(e_1) = \frac{1}{2} g_1 e_1^2 \tag{5}$$

$$F(e_2) = \frac{1}{2} g_2 e_2^2. \tag{6}$$

Where d_1 and $d_2 (d_1 > 0, d_2 > 0)$ are the cost coefficients of electricity production, and g_1 and $g_2 (g_1 > 0, g_2 > 0)$ are the cost coefficients of carbon emission reduction technology.

4. Model analysis

Given the impact of power structure on price competition and carbon emission reduction technology competition, this paper constructs a second-level electricity supply chain composed of two electricity producers and a single electricity retailer. To ensure that the equilibrium solutions are all non-negative and the Hessian matrix is negative definite, in the following analysis, the parameters should meet the following conditions: $\frac{1}{2} < b < 1$, $d > \frac{2}{1-b}$, $b \leq c < \frac{b+d+bd}{4+b+d+bd}$, $a > 0$, $g > 1 - c$.

4.1. Stackelberg game for electricity producers

In the Stackelberg game model of electricity producers, electricity producers have greater power, and electricity retailers adopt dual-source procurement. The decision-making sequence is as follows: first, the two electricity producers set different wholesale electricity prices w_1 and w_2, and decide different carbon emission reduction intensities e_1 and e_2 simultaneously. Then, the profits of two electricity producers and a single electricity retailer are respectively:

$$\pi_{m1}^{M^*} = w_1 q_1 - \frac{1}{2} d q_1^2 - \frac{1}{2} g e_1^2 \tag{7}$$

$$\pi_{m2}^{M^*} = w_2 q_2 - \frac{1}{2} d q_2^2 - \frac{1}{2} g e_2^2. \tag{8}$$

In these profit functions, w_1q_1 and w_2q_2 are revenue, $\frac{1}{2}dq_1^2$ and $\frac{1}{2}dq_2^2$ are the costs of electricity production, and $\frac{1}{2}ge_1^2$ is the costs of carbon reduction technology input.

$$\pi_r^{M^*} = (p_1 - w_1)q_1 + (p_2 - w_2)q_2. \tag{9}$$

In these profit functions, $(p_1 - w_1)q_1$ is the profit from the electricity produced by generator 1, $(p_2 - w_2)q_2$ is the profit from the electricity produced by generator 2.

According to the backward induction method, using the first-order condition of the profit of electricity retailer $\pi_r^{M^*}$ on p_1 and p_2, and letting it be zero, we can obtain:

$$p_1^{M^*} = \frac{(1-bc)e_1 + (b-c)e_2 + (1+b)(a + w_1 - bw_1)}{2-2b^2} \tag{10}$$

$$p_2^{M^*} = \frac{a + ab + (b-c)e_1 + e_2 + w_2 - b(ce_2 + bw_2)}{2-2b^2}. \tag{11}$$

Substituting equations (10) and (11) into equations (7) and (8), using the first-order conditions of the profits of the two electricity producers $\pi_{m1}^{M^*}$ and $\pi_{m2}^{M^*}$ on the two wholesale electricity prices w_1 and w_2 and the two carbon emission reduction intensities e_1 and e_2, Equilibrium wholesale electricity prices $w_1^{M^*}$ and $w_2^{M^*}$ and carbon emission reduction intensities $e_1^{M^*}$ and $e_2^{M^*}$, respectively:

$$w_1^{M^*} = \frac{a(2+d)g}{-1 + c + (4 + d - b(2+d))g} \tag{12}$$

$$w_2^{M^*} = \frac{a(2+d)g}{-1 + c + (4 + d - b(2+d))g} \tag{13}$$

$$e_1^{M^*} = \frac{a}{-1 + c + (4 + d - b(2+d))g} \tag{14}$$

$$e_2^{M^*} = \frac{a}{-1 + c + (4 + d - b(2+d))g}. \tag{15}$$

Substituting equations (12)–(15) into equations (10) and (11), the two equilibrium electricity prices $p_1^{M^*}$ and $p_2^{M^*}$ are respectively:

$$p_1^{M^*} = \frac{a(3 + d - b(2+d))g}{(1-b)(-1 + c + (4 + d - b(2+d))g)} \tag{16}$$

$$p_2^{M^*} = \frac{a(3 + d - b(2+d))g}{(1-b)(-1 + c + (4 + d - b(2+d))g)}. \tag{17}$$

Substituting equations (16) and (17) into equations (1) and (2), the two equilibrium demands $q_1^{M^*}$ and $q_2^{M^*}$ are respectively:

$$q_1^{M^*} = \frac{ag}{-1 + c + (4 + d - b(2+d))g} \tag{18}$$

$$q_2^{M^*} = \frac{ag}{-1 + c + (4 + d - b(2+d))g}. \tag{19}$$

Substituting equations (12)–(19) into equations (7)–(9), the equilibrium profit $\pi_{m1}^{M^*}$ and $\pi_{m2}^{M^*}$ of the two electricity producers and the equilibrium profit $\pi_r^{M^*}$ of the electricity retailer are respectively:

$$\pi_{m1}^{M^*} = \frac{a^2 g(-1 + (4+d)g)}{2(-1 + c + (4 + d - b(2+d))g)^2} \tag{20}$$

$$\pi_{m2}^{M^*} = \frac{a^2 g(-1 + (4+d)g)}{2(-1 + c + (4 + d - b(2+d))g)^2} \tag{21}$$

$$\pi_r^{M^*} = \frac{2a^2 g^2}{(1-b)(-1 + c + (4 + d - b(2+d))g)^2}. \tag{22}$$

Proposition 1. *Under the Stackelberg game of electricity producers, the optimal equilibrium wholesale electricity price of the two electricity producers* $w_1^{M^*}$, $w_2^{M^*}$, *carbon emission reduction intensity* $e_1^{M^*}$, $e_2^{M^*}$, *Electricity price* $p_1^{M^*}$, $p_2^{M^*}$, *demand* $q_1^{M^*}$, $q_2^{M^*}$, *electricity producers profit* $\pi_{m1}^{M^*}$, $\pi_{m2}^{M^*}$, *and electricity retailer profit* $\pi_r^{M^*}$, *can be given by equations* (12)–(22), *respectively.*

4.2. Stackelberg game of electricity retailer

In the model of the electricity retailer Stackelberg game, the electricity producers follow the decision of the electricity retailer. The decision-making sequence is as follows: first, the electricity retailer sets the electricity prices p_1 and p_2 to be sold to the electricity demand market. Then, the two electricity producers set the wholesale electricity price and the carbon emission reduction intensity (w_1, w_2, e_1, e_2). Under this game model, the retail margins u_1 and u_2 are introduced, and $p_1 = w_1 + u_1$, $p_2 = w_2 + u_2$, where u_1 and u_2 are the retail margins of electricity retailer. Then, the profits of two electricity producers and a single electricity retailer are, respectively:

$$\pi_{m1}^{R^*} = w_1 q_1 - \frac{1}{2} d q_1^2 - \frac{1}{2} g e_1^2 \tag{23}$$

$$\pi_{m2}^{R^*} = w_2 q_2 - \frac{1}{2} d q_2^2 - \frac{1}{2} g e_2^2 \tag{24}$$

$$\pi_r^{R^*} = (u_1) q_1 + (u_2) q_2. \tag{25}$$

In these profit functions, $(u_1)q_1$ is the profit from the electricity produced by generator 1, $(u_2)q_2$ is the profit from the electricity produced by generator 2. And u_1 and u_2 stand for marginal profit

According to the backward induction method, using the profit $\pi_{m1}^{R^*}$ and $\pi_{m2}^{R^*}$ of the two electricity producers, the first-order conditions on the wholesale electricity price and carbon emission reduction intensity, and letting them be zero, we can obtain:

$$w_1^{R^*} = \frac{\left((1+d)g\left(\substack{a(1+c)-a(2+b+d+bd)g \\ -(1-bc+b^2(1+d)g-(2+d)g)u_1-(c+b(-1+g))u_2}\right)\right)}{((1+c-(2+b+d+bd)g)(-1+c+(2+d-b(1+d))g))} \tag{26}$$

$$w_2^{R^*} = \frac{\left((1+d)g\left(\substack{a(1+c-(2+b+d+bd)g) \\ -(c+b(-1+g))u_1+(-1+bc+(2+d-b^2(1+d))g)u_2}\right)\right)}{((1+c-(2+b+d+bd)g)(-1+c+(2+d-b(1+d))g))} \tag{27}$$

$$e_1^{R^*} = \frac{\left(\substack{a(1+c-(2+b+d+bd)g)+ \\ (-1+bc+(2+d-b^2(1+d))g)u_1-(c+b(-1+g))u_2}\right)}{((1+c-(2+b+d+bd)g)(-1+c+(2+d-b(1+d))g))} \tag{28}$$

$$e_2^{R^*} = \frac{\left(\substack{a(1+c-(2+b+d+bd)g) \\ -(c+b(-1+g))u_1+(-1+bc+(2+d-b^2(1+d))g)u_2}\right)}{((1+c-(2+b+d+bd)g)(-1+c+(2+d-b(1+d))g))}. \tag{29}$$

Substituting equations (26)–(29) into equation (25), using the first-order condition of electricity retailer profit $\pi_r^{R^*}$ on retail margin and letting it be zero, we can obtain:

$$u_1 = \frac{a}{2-2b} \tag{30}$$

$$u_2 = \frac{a}{2-2b}. \tag{31}$$

Substituting equations (30) and (31) into equations (26)–(29), the equilibrium wholesale electricity price $w_1^{R^*}$ and $w_2^{R^*}$ and the carbon emission reduction intensity $e_1^{R^*}$ and $e_2^{R^*}$ are respectively:

$$w_1^{R^*} = \frac{a(1+d)g}{2(-1+c+(2+d-b(1+d))g)} \tag{32}$$

$$w_2^{R^*} = \frac{a(1+d)g}{2(-1+c+(2+d-b(1+d))g)} \tag{33}$$

$$e_1^{R^*} = \frac{a}{2(-1+c+(2+d-b(1+d))g)} \tag{34}$$

$$e_2^{R^*} = \frac{a}{2(-1+c+(2+d-b(1+d))g)}. \tag{35}$$

Since retail margins u_1 and u_2 are introduced, by substituting equations (26)–(31) into equations $p_1 = w_1+u_1$ and $p_2 = w_2 + u_2$, the two equilibrium electricity prices $p_1^{R^*}$ and $p_2^{R^*}$ are:

$$p_1^{R^*} = \frac{a}{(2-2b)} + \frac{a(1+d)g}{2(-1+c+(2+d-b(1+d))g)} \tag{36}$$

$$p_2^{R^*} = \frac{a}{(2-2b)} + \frac{a(1+d)g}{2(-1+c+(2+d-b(1+d))g)}. \tag{37}$$

Substituting equations (32)–(37) into equations (1) and (2), the two equilibrium demands $q_1^{R^*}$ and $q_2^{R^*}$ are respectively:

$$q_1^{R^*} = \frac{ag}{2(-1+c+(2+d-b(1+d))g)} \tag{38}$$

$$q_2^{R^*} = \frac{ag}{2(-1+c+(2+d-b(1+d))g)}. \tag{39}$$

Substituting equations (30)–(39) into equations (20)–(22), the equilibrium profit $\pi_{m1}^{R^*}$ and $\pi_{m2}^{R^*}$ of the two electricity producers and the equilibrium profit $\pi_r^{R^*}$ of the electricity retailer are:

$$\pi_{m1}^{R^*} = \frac{a^2 g(-1+(2+d)g)}{8(-1+c+(2+d-b(1+d))g)^2} \tag{40}$$

$$\pi_{m2}^{R^*} = \frac{a^2 g(-1+(2+d)g)}{8(-1+c+(2+d-b(1+d))g)^2} \tag{41}$$

$$\pi_r^{R^*} = \frac{a^2 g}{2(-1+b)(1-c+(-2+b+(-1+b)d)g)}. \tag{42}$$

Proposition 2. *In the case of the Stackelberg game of electricity retailer, the optimal equilibrium wholesale electricity price of two electricity producers* $w_1^{R^*}$, $w_2^{R^*}$, *carbon emission reduction intensity* $e_1^{R^*}$, $e_2^{R^*}$, *electricity price* $p_1^{R^*}$, $p_2^{R^*}$, *demand* $q_1^{R^*}$, $q_2^{R^*}$, *electricity producers profit* $\pi_{m1}^{R^*}$, $\pi_{m2}^{R^*}$, *and electricity retailer profit* $\pi_r^{R^*}$, *can be given by equations* (32)*–*(42)*, respectively.*

4.3. Vertical Nash game

In the vertical Nash game model, the upstream and downstream enterprises of the electricity supply chain make decisions simultaneously. The decision-making sequence is as follows: the electricity producers and the electricity retailer simultaneously decide the wholesale electricity price, the carbon emission reduction intensity, and the price sold to the electricity market $(w_1, w_2, e_1, e_2, p_1, p_2)$. Similarly, the retail margins u_1 and u_2 are also introduced under this game model, so that $u_1 = p_1 - w_1$ and $u_2 = p_2 - w_2$ respectively represent the retail margins of electricity retailer, and $p_1 = w_1 + u_1$ and $p_2 = w_2 + u_2$ are respectively substituted into equations (7)–(9). Then, the profits of electricity producers and electricity retailer are, respectively:

$$\pi_{m1}^{N^*} = w_1 q_1 - \frac{1}{2} d q_1^2 - \frac{1}{2} g e_1^2 \tag{43}$$

$$\pi_{m2}^{N^*} = w_2 q_2 - \frac{1}{2} d q_2^2 - \frac{1}{2} g e_2^2 \tag{44}$$

$$\pi_r^{N^*} = (u_1) q_1 + (u_2) q_2. \tag{45}$$

Using the first-order condition of the profit $\pi_{m1}^{N^*}$ and $\pi_{m2}^{N^*}$ on the wholesale price (w_1, w_2) and the emission reduction intensity (e_1, e_2) of electricity, and the first-order condition of the profit $\pi_r^{N^*}$ of electricity retailer on the retail margin (u_1, u_2), and let it be zero, we can obtain:

$$u_1 = \frac{ag}{(-1+b)(1-c+(-3+b+(-1+b)d)g)} \tag{46}$$

$$u_2 = \frac{ag}{(-1+b)(1-c+(-3+b+(-1+b)d)g)} \tag{47}$$

$$w_1^{N^*} = \frac{a(1+d)g}{c-1-(-3+b+(-1+b)d)g} \tag{48}$$

$$w_2^{N^*} = \frac{a(1+d)g}{c-1-(-3+b+(-1+b)d)g} \tag{49}$$

$$e_1^{N^*} = \frac{a}{-1+c+(3+d-b(1+d))g} \tag{50}$$

$$e_2^{N^*} = \frac{a}{-1+c+(3+d-b(1+d))g}. \tag{51}$$

Substituting equations (46) and (49) into $p_1 = w_1 + u_1$ and $p_2 = w_2 + u_2$ respectively, the two equilibrium electricity prices $p_1^{N^*}$ and $p_2^{N^*}$ are:

$$p_1^{N^*} = \frac{a(2+d-b(1+d))g}{(-1+b)(1-c+(-3+b+(-1+b)d)g)} \tag{52}$$

$$p_2^{N^*} = \frac{a(2+d-b(1+d))g}{(-1+b)(1-c+(-3+b+(-1+b)d)g)}. \tag{53}$$

Substituting equations (48)–(51) into equations (1) and (2), the two equilibrium demands $q_1^{N^*}$ and $q_2^{N^*}$ are respectively:

$$q_1^{N^*} = \frac{ag}{c-1-(-3+b+(-1+b)d)g} \tag{54}$$

$$q_2^{N^*} = \frac{ag}{c-1-(-3+b+(-1+b)d)g}. \tag{55}$$

Substituting equations (46)–(55) into equations (43)–(45), the equilibrium profit $\pi_{m1}^{N^*}$ and $\pi_{m2}^{N^*}$ of the two electricity producers and the equilibrium profit $\pi_r^{N^*}$ of the electricity retailer are respectively:

$$\pi_{m1}^{N^*} = \frac{a^2 g(-1+(2+d)g)}{2(-1+c+(3+d-b(1+d))g)^2} \tag{56}$$

$$\pi_{m2}^{N^*} = \frac{a^2 g(-1+(2+d)g)}{2(-1+c+(3+d-b(1+d))g)^2} \tag{57}$$

$$\pi_r^{N^*} = \frac{2a^2 g^2}{(1-b)(-1+c+(3+d-b(1+d))g)^2}. \tag{58}$$

Proposition 3. *In the case of the Stackelberg game of electricity retailer, the optimal equilibrium wholesale electricity price of two electricity producers $w_1^{N^*}$, $w_2^{N^*}$, carbon emission reduction intensity $e_1^{N^*}$, $e_2^{N^*}$, Electricity price $p_1^{N^*}$, $p_2^{N^*}$, demand $q_1^{N^*}$, $q_2^{N^*}$, electricity producers profit $\pi_{m1}^{N^*}$, $\pi_{m2}^{N^*}$, and electricity retailer profit $\pi_r^{N^*}$, Can be given by equations (48)–(59), respectively.*

5. Sensitivity analysis

There is a unique Nash equilibrium solution in the three-game models of electricity producer Stackelberg game, electricity retailer Stackelberg game, and vertical Nash game, where, $i = \{M, R, N\}$.

Proposition 4. *As the electricity production cost coefficient d increases, both (1)* $\frac{\partial w_1^{i^*}}{\partial d} > 0$, $\frac{\partial w_2^{i^*}}{\partial d} > 0$; *(2)* $\frac{\partial p_1^{i^*}}{\partial d} > 0$, $\frac{\partial p_2^{i^*}}{\partial d} > 0$; *(3)* $\frac{\partial e_1^{i^*}}{\partial d} < 0$, $\frac{\partial e_2^{i^*}}{\partial d} < 0$; *(4)* $\frac{\partial q_1^{i^*}}{\partial d} < 0$, $\frac{\partial q_2^{i^*}}{\partial d} < 0$; *(5)* $\frac{\partial \pi_r^{i^*}}{\partial d} < 0$.

The results of Proposition 4 show that under the three-game models, as the electricity production cost coefficient d increases, the wholesale electricity price $(w_1^{i^*}, w_2^{i^*})$ and the electricity price $(p_1^{i^*}, p_2^{i^*})$ will increase. But carbon emission reduction intensity $(e_1^{i^*}, e_2^{i^*})$ and electricity demand $(q_1^{i^*}, q_2^{i^*})$ will reduce, and electricity business profits $(\pi_r^{i^*})$ will be reduced. When the electricity production cost coefficient d increases, it will inevitably lead to a rise in the overall electricity production cost of electricity producers. On the other hand, if an electricity retailer buys electricity at a high price from the two electricity producers, it will naturally increase the price of electricity sold to the electricity market. With the arrival of the era of high cost, the impact on electricity enterprises is undoubtedly vast and far-reaching. It will not only erode the already meager profits of enterprises but also make them appear highly tight in cash flow and make enterprises bear unbearable losses, directly damaging their standard production and operation activities.

Moreover, it will increase the risk of a safe and stable electricity supply, indirectly affecting people's daily life activities and the normal development of the national economy. It can be seen that high costs make electricity enterprises, especially thermal electricity enterprises, suffer greatly and fall into a dilemma of more and more losses. All these facts indicate that electricity producers should improve production efficiency and control the cost of electricity production. From the perspective of enterprise practice, the special loan for the carbon capture technical transformation project of Zhejiang Lanxi coal-fired electricity producers will be implemented in 2023, reducing production costs and improving production efficiency by "capturing" carbon dioxide to replace steam. This breakthrough has had a good demonstration effect on Zhejiang Energy Group and even the whole thermal electricity generation industry[5].

Proposition 5. *As the price competition coefficient b increases, both (1)* $\frac{\partial w_1^{i^*}}{\partial b} > 0$, $\frac{\partial w_2^{i^*}}{\partial b} > 0$; *(2)* $\frac{\partial p_1^{i^*}}{\partial b} > 0$, $\frac{\partial p_2^{i^*}}{\partial b} > 0$; *(3)* $\frac{\partial e_1^{i^*}}{\partial b} > 0$, $\frac{\partial e_2^{i^*}}{\partial b} > 0$; *(4)* $\frac{\partial q_1^{i^*}}{\partial b} > 0$, $\frac{\partial q_2^{i^*}}{\partial b} > 0$; *(5)* $\frac{\partial \pi_{m1}^{i^*}}{\partial b} > 0$, $\frac{\partial \pi_{m2}^{i^*}}{\partial b} > 0$, $\frac{\partial \pi_r^{i^*}}{\partial b} > 0$.

The results of Proposition 5 show that under the three-game models, as the price competition coefficient b increases, the wholesale electricity price $(w_1^{i^*}, w_2^{i^*})$, the electricity price $(p_1^{i^*}, p_2^{i^*})$, carbon emission reduction intensity $(e_1^{i^*}, e_2^{i^*})$, electricity demand $(q_1^{i^*}, q_2^{i^*})$ will increase. In addition, the profits $(\pi_{m1}^{i^*}, \pi_{m2}^{i^*})$ of the two electricity producers and the single electricity retailer will also increase. According to the demand function, the electricity market demand increases with the price competition coefficient b increase. From the perspective of enterprise practice, there are generally substitutes for electricity products for the electricity industry. Power retailers must also adjust their pricing strategies to make more profits.

Proposition 6. *As the competition coefficient c of carbon emission reduction technology increases, both (1)* $\frac{\partial w_1^{i^*}}{\partial c} < 0$, $\frac{\partial w_2^{i^*}}{\partial c} < 0$; *(2)* $\frac{\partial p_1^{i^*}}{\partial c} < 0$, $\frac{\partial p_2^{i^*}}{\partial c} < 0$; *(3)* $\frac{\partial e_1^{i^*}}{\partial c} < 0$, $\frac{\partial e_2^{i^*}}{\partial c} < 0$; *(4)* $\frac{\partial q_1^{i^*}}{\partial c} < 0$, $\frac{\partial q_2^{i^*}}{\partial c} < 0$; *(5)* $\frac{\partial \pi_{m1}^{i^*}}{\partial c} < 0$, $\frac{\partial \pi_{m2}^{i^*}}{\partial c} < 0$, $\frac{\partial \pi_r^{i^*}}{\partial c} < 0$.

The results of Proposition 6 show that under the three-game models, as the competition coefficient c of carbon emission reduction technology increases, the wholesale electricity price $(w_1^{i^*}, w_2^{i^*})$, the electricity price $(p_1^{i^*}, p_2^{i^*})$, carbon emission reduction intensity $(e_1^{i^*}, e_2^{i^*})$, electricity demand $(q_1^{i^*}, q_1^{i^*})$ will be reduced, and profits of electricity producers and electricity retailers $(\pi_{m1}^{i^*}, \pi_{m2}^{i^*}, \pi_r^{i^*})$ also will be reduced. First, increasing the competition coefficient c of carbon emission reduction technology leads to decreased demand in the electricity consumption

[5] https://news.bjx.com.cn/html/20230103/1280483.shtml

market. Secondly, with the enhancement of consumers' environmental protection awareness, consumers prefer low-carbon two with a single electricity retailer to sell electricity-proof products. At this time, electricity retailer are bound to change their pricing strategies and reduce the price of electricity sold to the electricity market. For both electricity producers and electricity retailers, the market demand and price are reduced, and obviously, the profits of both are also reduced.

See the Appendix for the proof.

Proposition 7. *As the cost coefficient g of carbon emission reduction technology increases, both (1)* $\frac{\partial w_1^{i^*}}{\partial g} < 0$, $\frac{\partial w_2^{i^*}}{\partial g} < 0$*; (2)* $\frac{\partial p_1^{i^*}}{\partial g} < 0$, $\frac{\partial p_2^{i^*}}{\partial g} < 0$*; (3)* $\frac{\partial e_1^{i^*}}{\partial g} < 0$, $\frac{\partial e_2^{i^*}}{\partial g} < 0$*; (4)* $\frac{\partial q_1^{i^*}}{\partial g} < 0$, $\frac{\partial q_2^{i^*}}{\partial g} < 0$*; (5)* $\frac{\partial \pi_r^{i^*}}{\partial g} < 0$.

The results of Proposition 7 show that under the three-game models, as the cost coefficient g of carbon emission reduction technology increases, the wholesale electricity price $(w_1^{i^*}, w_2^{i^*})$, the electricity price $(p_1^{i^*}, p_2^{i^*})$, carbon emission reduction intensity $(e_1^{i^*}, e_2^{i^*})$, electricity demand $(q_1^{i^*}, q_2^{i^*})$ will be reduced, sell electricity business profits $(\pi_r^{i^*})$ can also be reduced. From the electricity supply chain perspective, when the cost coefficient g of carbon emission reduction technology increases, electricity producers are motivated to reduce the investment in carbon emission reduction technology to obtain more profits. Then, the intensity of carbon emission reduction will decrease accordingly. Since consumers prefer low-carbon electricity, reducing carbon emissions will decrease the market demand for electricity. From the practical situation, at the technical level, China currently has problems such as the high cost of deep decarbonization technology or an immature supporting system, insufficient government guidance for high-cost and low-carbon technology, and insufficient enterprise investment courage. On the other hand, electricity producers should lay out and invest in low-carbon technologies that are in line with their business development strategies.

See the Appendix for the proof.

6. Model comparison

Proposition 8. *Comparing the equilibrium wholesale electricity price set by the electricity producer and the equilibrium electricity price set by the electricity retailer under the three power structures, we find that* $w_1^{M^*} > w_1^{N^*} > w_1^{R^*}$; $w_2^{M^*} > w_2^{N^*} > w_2^{R^*}$; $p_1^{R^*} > p_1^{M^*} > p_1^{N^*}$; $p_2^{R^*} > p_2^{M^*} > p_2^{N^*}$.

The results of Proposition 8 show that the wholesale electricity price is the highest in the case of electricity producer Stackelberg game. In the case of electricity retailer Stackelberg game, the wholesale electricity price is the lowest, but the electricity price is the highest. In the case of the vertical Nash game, the electricity price is the lowest. Because in the case of electricity producer Stackelberg game, electricity producers occupy a dominant position, ease the cost pressure of investing in carbon emission reduction technology, and obtain more profits by setting a higher wholesale electricity price. In the case of the electricity retailer Stackelberg game, the electricity retailer sets a higher electricity price for its own interests, while the electricity producer can only set the wholesale electricity price after observing the decision made by the electricity retailer on the electricity price. In addition, in the case of Nash game, both electricity producers and electricity retailers are rational economic actors who seek their own optimal interests through non-cooperative bidding. In such cases, due to the lack of unified leadership or coordination mechanisms, parties often resort to aggressive price war tactics, which results in the lowest electricity price at this time.

Proposition 9. *By comparing the equilibrium electricity market demand under the three power structures,* $q_1^{N^*} > q_1^{M^*} > q_1^{R^*}; q_2^{N^*} > q_2^{M^*} > q_2^{R^*}$.

The results of Proposition 9 show that in the case of the vertical Nash game, the electricity demand is the highest. In the case of electricity producer Stackelberg game, the electricity demand is greater than that of electricity retailer Stackelberg game. In conjunction with Proposition 8, firstly, it can be seen that in the case of the vertical Nash game, the electricity price set by the electricity retailer is the lowest, and consumers are sensitive to the electricity price. The lower price will attract more consumers. Secondly, in the case of electricity retailer Stackelberg game, the electricity price is higher than that of electricity producer Stackelberg game. Therefore, the electricity demand when the electricity producer dominates is greater than the electricity demand when the electricity retailer dominates.

Proposition 10. *By comparing the equilibrium carbon emission reduction intensity of electricity producers under the three power structures,* $e_1^{N^*} > e_1^{M^*} > e_1^{R^*}; e_2^{N^*} > e_2^{M^*} > e_2^{R^*}$.

The results show that in the case of the vertical Nash game, the carbon emission reduction is the largest. In the case of electricity producer Stackelberg game, the carbon emission reduction is greater than that of electricity retailer Stackelberg game. In combination with Proposition 9, we can see that in the case of the Nash game, the demand for electricity is the largest. In addition, because consumers have a preference for renewable energy electricity, the electricity producers will invest more in carbon emission reduction, so in the case of Nash game, carbon emission reduction is the most intensive. For example, the project "Digital Innovation Practice of Energy Industry Chain" Carbon Finance "Green Service System" jointly declared by State Grid Zhejiang Electric Power and Yingda Carbon Asset Management Company was recognized at the 2022 Global Industrial Chain Supply Chain Digital Economy Conference. The project optimizes carbon financial services through digital means to help enterprises achieve green and low-carbon development[6]. When the electricity retailer dominates, according to Proposition 7, the wholesale electricity price is the lowest at this time, and in order to maximize the overall profit, the electricity producer will control the input cost of carbon emission reduction. And when the electricity producers dominate, the wholesale electricity prices are the highest, and more carbon reduction can be invested. Therefore, the carbon emission reduction when the electricity producers dominate is greater than the carbon emission reduction when the electricity retailer dominates.

Proposition 11. *Comparing three kinds of power structures of the balance of electricity producers and electricity retailer profits, there are* $\pi_{m1}^{M^*} > \pi_{m1}^{N^*} > \pi_{m1}^{R^*}; \pi_{m2}^{M^*} > \pi_{m2}^{N^*} > \pi_{m2}^{R^*}; \pi_r^{R^*} > \pi_r^{N^*} > \pi_r^{M^*}$.

The result of Proposition 11 shows that for the profits of the electricity producers, the profits of the electricity producers are the largest in the case of electricity producer Stackelberg game. Secondly, in the case of Nash game, then in the case of the electricity retailer Stackelberg game, the profits of the electricity producers are the smallest. For electricity retailer profit, the opposite is true. In the case of the electricity retailer Stackelberg game, the profit of electricity retailer is the largest. Secondly, in the case of Nash game, then in the case of electricity producer Stackelberg game, the profit of the electricity retailer is the smallest. Both upstream and downstream enterprises in the electricity supply chain benefit the most when they are in a dominant position, because both electricity producers and electricity retailer prioritize their own interests and make decisions first. In combination with Propositions 8, 9 and 10, it can be seen that when the electricity producer takes the lead, the electricity producer, as the "leader" takes the lead in making decisions, setting a higher wholesale electricity price, reducing part of the investment in carbon emission reduction and reducing the cost at once, so it can obtain the maximum profit at this time. When the electricity retailer is dominated, the electricity retailer sets the highest electricity price, and the electricity producers set a lower wholesale electricity price to stabilize the electricity demand after observing the decision-making behavior of the electricity retailer, so the profit of the electricity retailer is the largest at this time. When the electricity producers and the electricity retailer make decisions at the same time, the electricity producers and the electricity retailer have the same rights, and the overall profit of the electricity supply chain will be considered to be the best, so their respective profits are smaller than the profits when they are dominated by each other.

7. Extension model

Because of the complexity of the model, we use a multi-agent approach here to conduct the study. This approach has become an important technique in supply chain management.

[6]https://cs.zjol.com.cn/jms/202212/t20221208_25162030.shtml

7.1. Model framework

We establish an electricity supply chain consisting of two-generation agents and one electricity retailer agent. Unlike the static model in Section 3, we build a dynamic model here, consisting of multiple periods, each with the same process. In the case of a supply chain led by an electricity producer, all events are described below.

(1) The two electricity producers set their own wholesale electricity price $w_{1,t}^M$, $w_{2,t}^M$ and carbon emission reduction intensity $e_{1,t}^M$, $e_{2,t}^M$ based on their past experiences.
(2) Electricity price $p_{1,t}^M$, $p_{2,t}^M$ decision-making by electricity retailers.
(3) Power retailers meet market demand according to equations (1) and (2)
(4) Power retailers count profits and prepare for decisions in the next cycle.
(5) Go to (1)

7.2. Subject behavior of electricity producers

It is assumed here that electricity producers are bounded rational, and due to the complexity of individual ability and the external environment, they cannot make optimal decisions but seek a satisfactory result through adaptive learning methods. Electricity producers dynamically adjust wholesale electricity prices and Carbon emission reduction intensities in each cycle to optimize their profits. The profit functions of the two electricity producers are as follows:

$$\pi_{m1,t}^M\left(w_{1,t}^M, e_{1,t}^M\right) = w_{1,t}^M\left(a - p_{1,t}^M + bp_{2,t}^M + e_{1,t}^M - ce_{2,t}^M\right) - \frac{1}{2}d_1\left(q_{1,t}^M\right)^2 - \frac{1}{2}g_1\left(e_{1,t}^M\right)^2 \tag{59}$$

$$\pi_{m2,t}^M\left(w_{2,t}^M, e_{2,t}^M\right) = w_{2,t}^M\left(a - p_{2,t}^M + bp_{1,t}^M + e_{2,t}^M - ce_{1,t}^M\right) - \frac{1}{2}d_2\left(q_{2,t}^M\right)^2 - \frac{1}{2}g_2\left(e_{2,t}^M\right)^2. \tag{60}$$

It should be noted that the heterogeneity of electricity producers is considered here, so $d_1 \neq d_2, g_1 \neq g_2$.

Wholesale electricity price and carbon emission reduction intensity are decided according to the following rules.

$$w_t^M, e_t^M = \begin{cases} w_0, e_0 & t \leq n \\ w_{t-1}^M + \Delta w, e_{t-1}^M + \Delta e & t > n \quad \pi_{\mathrm{m},t-1}^M > \frac{1}{n}\sum_{j=t-(n+1)}^{t-2} \pi_j^M \\ w_{t-1}^M - \Delta w, e_{t-1}^M - \Delta e & t > n \quad \pi_{\mathrm{m},t-1}^M \leq \frac{1}{n}\sum_{j=t-(n+1)}^{t-2} \pi_j^M. \end{cases} \tag{61}$$

w_t and e_t are equal to the initial values for the first n periods, during which the electricity producer is in the learning and accumulation phase of the environment. After n periods, the electricity producer uses the previous data to learn and make decisions, and if the profit in the last period is greater than the recent average, it will increase the wholesale price and carbon emission reduction intensity. Otherwise, the wholesale price and Carbon emission reduction intensities will be reduced.

7.3. Subject behavior of electricity retailer

Power retailer providers are also bounded rational subjects. The profit function of electricity retailer per cycle is as follows:

$$\begin{aligned} \pi_{r,t}^M\left(p_{1,t}^M, p_{2,t}^M\right) = &\left(p_{1,t}^M - w_{1,t}^M\right)\cdot\left(a - p_{1,t}^M + bp_{2,t}^M + e_{1,t}^M - ce_{2,t}^M\right) \\ &+ \left(p_{2,t}^M - w_{2,t}^M\right)\cdot\left(a - p_{2,t}^M + bp_{1,t}^M + e_{2,t}^M - ce_{1,t}^M\right). \end{aligned} \tag{62}$$

The electricity price shall be decided as follows:

$$p_t^M = \begin{cases} p_0 & t \leq n \\ p_{t-1}^M + \Delta p & t > n \quad \pi_{r,t-1}^M > \frac{1}{n}\sum_{j=t-(n+1)}^{t-2} \pi_j^M \\ p_{t-1}^M - \Delta p & t > n \quad \pi_{r,t-1}^M \leq \frac{1}{n}\sum_{j=t-(n+1)}^{t-2} \pi_j^M. \end{cases} \tag{63}$$

TABLE 2. The values of parameters in this experiment.

Parameters	Value
a	500, 600, 700, 800, 900
b	0.3, 0.4, 0.5, 0.6, 0.7
c	0.1, 0.2, 0.3, 0.4, 0.5
d_1	2,3,4,5,6
d_2	0,1, 0.3, 0.5, 0.7, 0.9
g_1	2,3,4,5,6
g_2	0.1, 0.3, 0.5, 0.7, 0.9

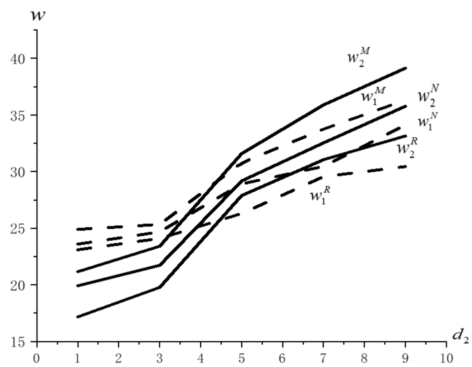

FIGURE 2. Power production cost heterogeneity *versus* the wholesale electricity prices.

7.4. Simulation design

Multi-agent modelling is a useful tool for investigating the dynamic problem. This method uses massive data from a computer to develop virtual experiments. We design all parameters in Table 2. These parameters are set with multiple values to reduce the randomness. Each profile of parameters is an independent experiment. There are 5^7 experiments in total. Each simulation is run 100 times with various random seeds and each time is 5000 periods. The values of decision variables and parameters are as follows:

$$w_0 = 15, p_0 = 40, e_0 = 5, w[15, 40], p[40, 100], e[5, 50], w = 0.5, p = 0.5, e = 0.5, n = 10$$

7.5. Refine results

(1) Keep $g_1 = g_2$ perform sensitivity analysis on parameter d_2, and compare the size of decision variables and profits in the three modes.

According to Figure 2, firstly, with the increase in electricity production cost coefficient d_2, the wholesale electricity price of the two electricity producers under the three power structures shows an increasing trend. When the electricity production cost coefficient d_2 increases, the increase in the production cost borne by the electricity producer will inevitably lead the electricity producer to increase the wholesale electricity price to maintain its own interests. Secondly, the wholesale price of electricity is the highest in the case of the Stackelberg game between electricity producers and the lowest in the case of the Stackelberg game between electricity retailers. In the case of the Stackelberg game between electricity producers, electricity producers occupy a completely dominant position and gain more profits by setting a higher wholesale electricity price. However, in the case of the electricity retailer's Stackelberg game, the electricity retailer sets a higher electricity

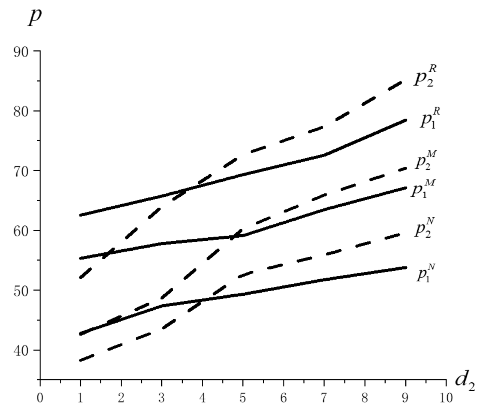

FIGURE 3. Power production cost heterogeneity *versus* the selling electricity prices.

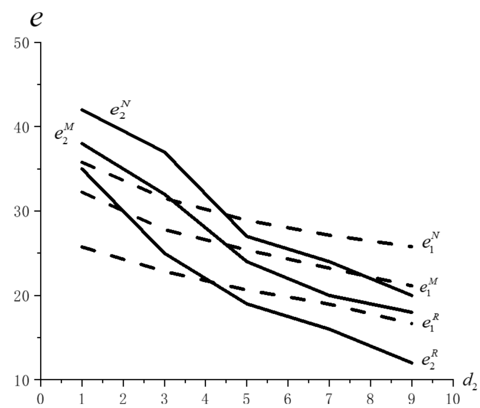

FIGURE 4. Power production cost heterogeneity *versus* the carbon emission reduction intensity.

price for its own interests. In contrast, the electricity producer can only set the wholesale electricity price after observing the electricity retailer's decision on the electricity price.

It can be seen from Figure 3 that, first of all, with the increase in electricity production cost coefficient d_2, the electricity price under the three power structures shows an upward trend because the increase in production cost leads to higher wholesale electricity prices set by electricity producers, and electricity retailers buy electricity at a high price, which will naturally increase the electricity price sold to the electricity market. Secondly, the electricity price is the highest in the case of the Stackelberg game of electricity retailer. In the case of the vertical Nash game, the electricity price is the lowest. Because in the case of the Stackelberg game of electricity retailers, electricity retailers occupy a completely dominant position and make more profits by setting a higher electricity price.

According to Figure 4, firstly, with the increase in electricity production cost coefficient d_2, the carbon emission reduction intensity under the three power structures shows a downward trend because the electricity production cost increases, and in order to control the total cost, electricity producers will reduce the investment in carbon emission reduction technology. Hence, the intensity of carbon emission reduction decreases. Secondly, in the case of the vertical Nash game, the carbon emission reduction is the largest. Furthermore, the carbon emission reduction intensity is the smallest in the case of the Stackelberg game of electricity retailers. Combined with Figure 3, it can be seen that in the case of the vertical Nash game, the electricity price is the lowest,

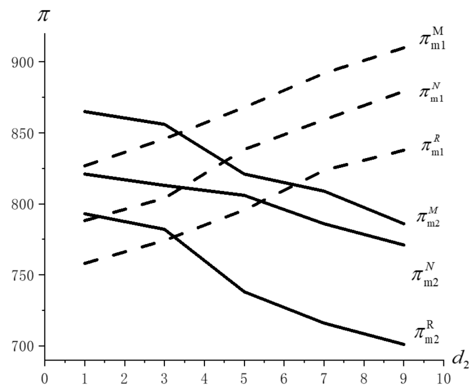

FIGURE 5. Power production cost heterogeneity *versus* the electricity producers' profits.

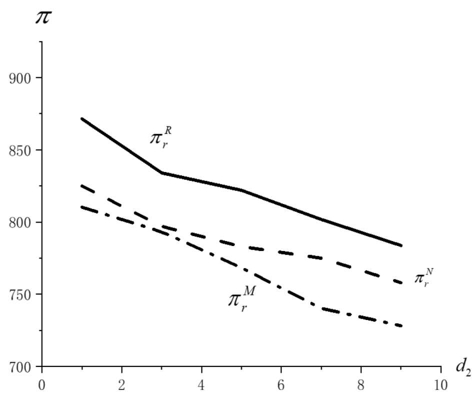

FIGURE 6. Electricity production cost heterogeneity *versus* the electricity retailers profit.

and the demand in the electricity market is the highest. At this time, electricity producers and electricity retailers observe that the demand for electricity side with low carbon preference increases, prompting electricity producers to invest more in carbon emission reduction technology. Therefore, the intensity of carbon emission reduction in the vertical Nash game is greater than that of the Stackelberg game of electricity producers.

According to Figure 5, firstly, with the increase of electricity production cost coefficient d_2, the profit of electricity producer 1 shows an upward trend, and that of electricity producer 2 shows a downward trend under the three power structures. The increase in the production cost of electricity producer 2 will inevitably lead to an increase in its wholesale electricity price. Secondly, in the case of the Stackelberg game between electricity producers and electricity retailers, the electricity producers get the largest profit. In the case of the Stackelberg game of electricity retailers, the profit of electricity producers is the smallest. Because both electricity producers and electricity retailer will prioritize their own interests and make decisions first. When the electricity producers have a large channel power, the electricity producers have the incentive to reduce production costs and increase wholesale electricity prices, and the largest electricity producers' profits.

It can be seen from Figure 6 that, first of all, with the increase in electricity production cost coefficient d_2, the profits of electricity retailers under the three electricity structures all show a downward trend. Secondly, in the case of the electricity retailer's Stackelberg game, the electricity retailer's profit is the highest, whereas, in the case of the Stackelberg game between electricity producers, the profit of the electricity retailer is the lowest. Because when the electricity retailer has greater channel power, the electricity retailer has the incentive to set a

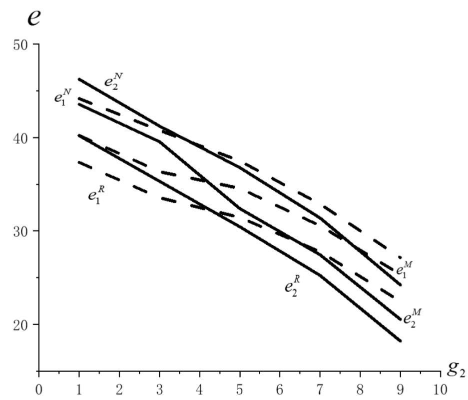

FIGURE 7. Cost heterogeneity *versus* the carbon emission reduction efforts.

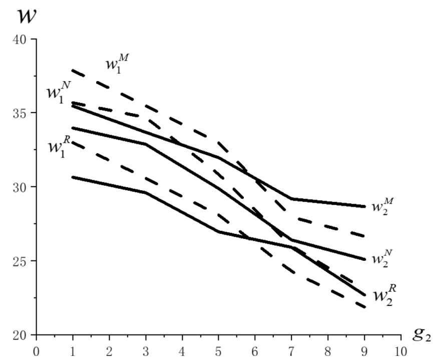

FIGURE 8. Cost heterogeneity *versus* the wholesale electricity prices.

higher electricity price, and the profit of the electricity retailer is the largest at this time. When the electricity producer has greater channel power, the electricity producer sets a higher wholesale electricity price first, which is equivalent to increasing the purchase cost of the electricity retailer, so the profit of the electricity retailer is the smallest at this time.

(2) Keep $d_1 = d_2$ and conduct sensitivity analysis on the parameters g_2.

As can be seen from Figure 7, firstly, as the cost coefficient g_2 of carbon emission reduction technology increases, the carbon emission reduction intensity under the three power structures all show a decreasing trend. Because when the cost coefficient g_2 of carbon emission reduction technology increases, electricity producers control the total cost to obtain more profits, electricity producers have the motivation to reduce the investment in carbon emission reduction technology, and then the carbon emission reduction intensity decreases accordingly.

According to Figures 8 and 9, firstly, as the cost coefficient g_2 of carbon emission reduction technology increases, the wholesale electricity price and electricity price under the three power structures all show a decreasing trend. Because when the cost coefficient g_2 of carbon emission reduction technology increases, combined with Figure 7, it can be seen that the carbon emission reduction intensity decreases accordingly, and because consumers have a preference for low-carbon electricity, the demand for the electricity market decreases after the reduction of carbon emission reduction intensity. No matter what kind of power structure, Power producers and electricity retailers observe a decrease in consumers' demand for electricity and reduce the wholesale and electricity prices, respectively.

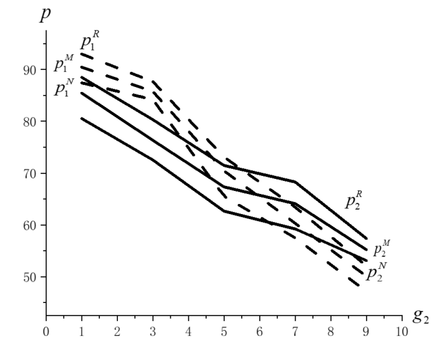

FIGURE 9. Cost heterogeneity *versus* the selling electricity prices.

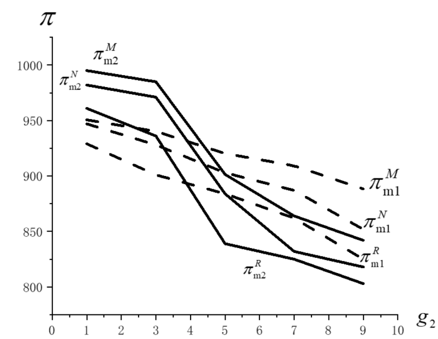

FIGURE 10. Cost heterogeneity *versus* the electricity producers' profits.

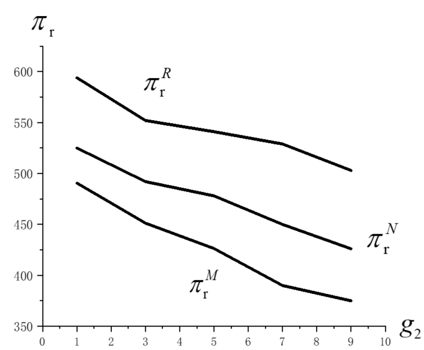

FIGURE 11. Cost heterogeneity *versus* the electricity retailer's profit.

It can be seen from Figures 10 and 11 that, firstly, with the increase in the cost coefficient g_2 of carbon emission reduction technology, the profits of electricity producers and electricity retailers under the three power structures all show a decreasing trend. Because when the cost coefficient g_2 of carbon emission reduction technology increases, combined with Figures 8, 9 and 10, it can be seen that at this time, the electricity demand, the wholesale electricity price of electricity producers, and the electricity price of electricity retailers are all decreasing, which makes the profits of both electricity producers and electricity retailer decrease with the increase of the cost coefficient g_2 of carbon emission reduction technology.

8. Conclusion

This paper studies the price competition and carbon emission reduction technology competition and the impact of three power structures, namely the Stackelberg game of electricity producers, the Stackelberg game of electricity retailers, and the vertical Nash game, on the electricity price and carbon emission reduction technology investment decisions of electricity supply chain members. By comparing the equilibrium solution results under different game scenarios, the main research results are as follows:

(1) In the case of electricity producer Stackelberg game, the wholesale price is the highest, and the electricity producers get the most profit. In the case of the electricity retailer Stackelberg game, the electricity price is the highest, and the electricity retailer gets the most profit. Still, the electricity demand is the least.

(2) In the case of the vertical Nash game, electricity producers have the largest carbon emission reduction, the largest market demand, and the lowest electricity price. However, in the case of the Stackelberg game of electricity retailers, electricity producers' carbon emission reduction is the smallest, market demand is the smallest, and electricity price is the highest. This means that in order to achieve maximum carbon reduction, electricity producers and electricity retailers should make decisions at the same time.

(3) With the increase in the cost coefficient of electricity production, the wholesale price and the price of electricity will increase. Carbon emission reductions, electricity demand, and electricity retailer's profits have all fallen. So, power producers should develop new technologies to control production costs. As the cost coefficient of carbon emission reduction technology increases, wholesale electricity prices, electricity prices, carbon emission reduction, electricity demand, and electricity retailers' profits all decline. In addition, wholesale electricity price, electricity price, carbon emission reduction, electricity demand, and the profits of electricity producers and electricity retailers will increase with the increase of price competition coefficient b. But they all decrease as the carbon reduction technology competition coefficient c increases.

The above conclusions have some management implications for both the government and electricity supply chain enterprises. From the perspective of the government, first of all, the government should introduce relevant laws, regulations, policies, and regulatory measures to guide the non-cooperative game between electricity producers and electricity retailers, because, in the case of Nash game, carbon emission reduction is the greatest. Secondly, carbon emission reduction efforts increase with the reduction of electricity production costs. The government can introduce appropriate production subsidy policies and carbon emission reduction technology research and development subsidy policies, on the one hand, to reduce the cost pressure on electricity producers, and on the other hand, to encourage electricity producers to invest in carbon emission reduction technology. Finally, in general, incentivized price competition leads all parties to lower prices, and interestingly, the higher the price competition coefficient, the higher the price of electricity. Therefore, when there is excessive competition, the government should formulate and improve laws and regulations to prohibit unfair competition and guide electricity retailers to set reasonable prices. From the perspective of upstream and downstream enterprises in the electricity supply chain, first of all, electricity producers and electricity retailers should avoid excessive competition for carbon emission reduction technology, and the carbon emission reduction competition coefficient is inversely proportional to their profits. Secondly, electricity producers and electricity retailers respectively get the highest profits when they are dominated by each other.

This article has some limitations, which future research may take the opportunity to improve upon. First, this paper assumes that the research is carried out under the condition of information symmetry. In practice, there are many situations where information asymmetry is present. Thus, future research can consider price competition and carbon reduction technology competition under the condition of information asymmetry. Second, this paper only considers the electricity supply chain model composed of two electricity producers and a single electricity retailer. In practice, there may be multiple producers and multiple retailers in an electricity supply chain. Thus, in the future, an electricity supply chain model consisting of multiple electricity producers and multiple electricity retailers can be considered. In addition, this paper employed only basic game theory and multi-agent simulation experiments as research methods. Future studies may consider a broader array of research methodologies, such as the novel multi-criteria decision-making approach employed by Binoy *et al.* [29].

Appendix A. Proof of Proposition 4

Proof. The first order conditions of wholesale electricity price, carbon emission reduction intensity, electricity price and electricity demand on electricity production cost coefficient d under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial w_1^{M^*}}{\partial d} = \frac{\partial w_2^{M^*}}{\partial d} = \frac{ag(-1+c+2g)}{(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial w_1^{R^*}}{\partial d} = \frac{\partial w_2^{R^*}}{\partial d} = \frac{ag(-1+c+g)}{2(-1+c+(2+d-b(1+d))g)^2} > 0$$
$$\frac{\partial w_1^{N^*}}{\partial d} = \frac{\partial w_2^{N^*}}{\partial d} = \frac{ag(-1+c+2g)}{(-1+c+(3+d-b(1+d))g)^2} > 0$$
$$\frac{\partial e_1^{M^*}}{\partial d} = \frac{\partial e_1^{M^*}}{\partial d} = \frac{a(-1+b)g}{(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial e_1^{R^*}}{\partial d} = \frac{\partial e_2^{R^*}}{\partial d} = \frac{a(-1+b)g}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial e_1^{N^*}}{\partial d} = \frac{\partial e_2^{N^*}}{\partial d} = \frac{a(-1+b)g}{(-1+c+(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial p_1^{M^*}}{\partial d} = \frac{\partial p_2^{M^*}}{\partial d} = \frac{ag(-1+c+g)}{(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial p_1^{R^*}}{\partial d} = \frac{\partial p_2^{R^*}}{\partial d} = \frac{ag(-1+c+g)}{2(-1+c+(2+d-b(1+d))g)^2} > 0$$
$$\frac{\partial p_1^{N^*}}{\partial d} = \frac{\partial p_2^{N^*}}{\partial d} = \frac{ag(-1+c+g)}{(-1+c+(3+d-b(1+d))g)^2} > 0$$
$$\frac{\partial q_1^{M^*}}{\partial d} = \frac{\partial q_2^{M^*}}{\partial d} = \frac{a(-1+b)g^2}{(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial q_1^{R^*}}{\partial d} = \frac{\partial q_2^{R^*}}{\partial d} = \frac{a(-1+b)g^2}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial q_1^{N^*}}{\partial d} = \frac{\partial q_2^{N^*}}{\partial d} = \frac{a(-1+b)g^2}{(-1+c+(3+d-b(1+d))g)^2} < 0.$$

The first order conditions of the electricity retailer profits on electricity production cost coefficient d under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial \pi_r^{M^*}}{\partial d} = \frac{4a^2g^3}{(1-c-(4+d-b(2+d))g)^3} < 0$$
$$\frac{\partial \pi_r^{R^*}}{\partial d} = \frac{a^2g^2}{2(1-c-(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial \pi_r^{N^*}}{\partial d} = \frac{4a^2g^3}{(1-c-(3+d-b(1+d))g)^3} < 0.$$

□

Proof of Proposition 5

Proof. The first order conditions of wholesale electricity price, carbon emission reduction intensity, electricity price and electricity demand on price competition coefficient b under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial w_1^{M^*}}{\partial b} = \frac{\partial w_2^{M^*}}{\partial b} = \frac{a(2+d)^2g^2}{(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial w_1^{R^*}}{\partial b} = \frac{\partial w_2^{R^*}}{\partial b} = \frac{a(1+d)^2g^2}{2(-1+c+(2+d-b(1+d))g)^2} > 0$$
$$\frac{\partial w_1^{N^*}}{\partial b} = \frac{\partial w_2^{N^*}}{\partial b} = \frac{a(1+d)^2g^2}{(-1+c+(3+d-b(1+d))g)^2} > 0$$
$$\frac{\partial e_1^{M^*}}{\partial b} = \frac{\partial e_1^{M^*}}{\partial b} = \frac{a(2+d)g}{(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial e_1^{R^*}}{\partial b} = \frac{\partial e_2^{R^*}}{\partial b} = \frac{a(1+d)g}{2(-1+c+(2+d-b(1+d))g)^2} > 0$$
$$\frac{\partial e_1^{N^*}}{\partial b} = \frac{\partial e_2^{N^*}}{\partial b} = \frac{a(1+d)g}{(-1+c+(3+d-b(1+d))g)^2} > 0$$
$$\frac{\partial p_1^{M^*}}{\partial b} = \frac{\partial p_2^{M^*}}{\partial b} = \frac{ag(-1+c+(10+6d+d^2+b^2(2+d)^2-2b(6+5d+d^2))g)}{(-1+b)^2(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial p_1^{R^*}}{\partial b} = \frac{\partial p_2^{R^*}}{\partial b} = \frac{1}{2}a\left(\frac{1}{(-1+b)^2} + \frac{(1+d)^2g^2}{(-1+c+(2+d-b(1+d))g)^2}\right) > 0$$
$$\frac{\partial p_1^{N^*}}{\partial b} = \frac{\partial p_2^{N^*}}{\partial b} = \frac{ag(-1+c+(5+4d+d^2+b^2(1+d)^2-2b(2+3d+d^2))g)}{(-1+b)^2(-1+c+(3+d-b(1+d))g)^2} > 0$$
$$\frac{\partial q_1^{M^*}}{\partial b} = \frac{\partial q_2^{M^*}}{\partial b} = \frac{a(2+d)g^2}{(-1+c+(4+d-b(2+d))g)^2} > 0$$
$$\frac{\partial q_1^{R^*}}{\partial b} = \frac{\partial q_2^{R^*}}{\partial b} = \frac{a(1+d)g^2}{2(-1+c+(2+d-b(1+d))g)^2} > 0$$
$$\frac{\partial q_1^{N^*}}{\partial b} = \frac{\partial q_2^{N^*}}{\partial b} = \frac{a(1+d)g^2}{(-1+c+(3+d-b(1+d))g)^2} > 0.$$

The first order conditions of the electricity producers profits and the electricity retailer profits on price competition coefficient b under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial \pi_{m1}^{M^*}}{\partial b} = \frac{\partial \pi_{m2}^{M^*}}{\partial b} = \frac{a^2(2+d)g^2(-1+(4+d)g)}{(-1+c+(4+d-b(2+d))g)^3} > 0$$
$$\frac{\partial \pi_{m1}^{R^*}}{\partial b} = \frac{\partial \pi_{m2}^{R^*}}{\partial b} = \frac{a^2(1+d)g^2(-1+(2+d)g)}{4(-1+c+(2+d-b(1+d))g)^3} > 0$$
$$\frac{\partial \pi_{m1}^{N^*}}{\partial b} = \frac{\partial \pi_{m2}^{N^*}}{\partial b} = \frac{a^2(1+d)g^2(-1+(2+d)g)}{(-1+c+(3+d-b(1+d))g)^3} > 0$$
$$\frac{\partial \pi_r^{M^*}}{\partial d} = \frac{2a^2g^2(1-c+(-8-3d+3b(2+d))g)}{(-1+b)^2(1-c-(4+d-b(2+d))g)^3} > 0$$
$$\frac{\partial \pi_r^{R^*}}{\partial d} = \frac{a^2g(1-c+(-3-2d+2b(1+d))g)}{2(-1+b)^2(1-c-(2+d-b(1+d))g)^2} > 0$$

$$\frac{\partial \pi_r^{N^*}}{\partial d} = \frac{2a^2g^2(1-c+(-5-3d+3b(1+d))g)}{(-1+b)^2(1-c+(-3+b-d+bd)g)^3} > 0.$$

□

Proof of Proposition 6

Proof. The first order conditions of wholesale electricity price, carbon emission reduction intensity, electricity price and electricity demand on carbon reduction technology competition coefficient c under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial w_1^{M^*}}{\partial c} = \frac{\partial w_2^{M^*}}{\partial c} = \frac{a(2+d)g}{(1-c-(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial w_1^{R^*}}{\partial c} = \frac{\partial w_2^{R^*}}{\partial c} = \frac{a(1+d)g}{2(1-c-(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial w_1^{N^*}}{\partial c} = \frac{\partial w_2^{N^*}}{\partial c} = \frac{a(1+d)g}{(1-c-(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial e_1^{M^*}}{\partial c} = \frac{\partial e_1^{M^*}}{\partial c} = \frac{a}{(1-c-(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial e_1^{R^*}}{\partial c} = \frac{\partial e_2^{R^*}}{\partial c} = \frac{a}{2(1-c-(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial e_1^{N^*}}{\partial c} = \frac{\partial e_2^{N^*}}{\partial c} = \frac{a}{(1-c-(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial p_1^{M^*}}{\partial c} = \frac{\partial p_2^{M^*}}{\partial c} = \frac{a(3+d-b(2+d))g}{(-1+b)(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial p_1^{R^*}}{\partial c} = \frac{\partial p_2^{R^*}}{\partial c} = \frac{ag(-1+c+g)}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial p_1^{N^*}}{\partial c} = \frac{\partial p_2^{N^*}}{\partial c} = \frac{a(2+d-b(1+d))g}{(-1+b)(-1+c+(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial q_1^{M^*}}{\partial c} = \frac{\partial q_2^{M^*}}{\partial c} = \frac{ag}{(1-c-(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial q_1^{R^*}}{\partial c} = \frac{\partial q_2^{R^*}}{\partial c} = \frac{ag}{2(1-c-(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial q_1^{N^*}}{\partial c} = \frac{\partial q_2^{N^*}}{\partial c} = \frac{ag}{(1-c-(3+d-b(1+d))g)^2} < 0.$$

The first order conditions of the electricity producers profits and the electricity retailer profits on carbon reduction technology competition coefficient c under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial \pi_{m1}^{M^*}}{\partial c} = \frac{\partial \pi_{m2}^{M^*}}{\partial c} = \frac{a^2g(-1+(4+d)g)}{(1-c-(4+d-b(2+d))g)^3} < 0$$
$$\frac{\partial \pi_{m1}^{R^*}}{\partial c} = \frac{\partial \pi_{m2}^{R^*}}{\partial c} = \frac{a^2g(-1+(2+d)g)}{4(1-c-(2+d-b(1+d))g)^3} < 0$$
$$\frac{\partial \pi_{m1}^{N^*}}{\partial c} = \frac{\partial \pi_{m2}^{N^*}}{\partial c} = \frac{a^2g(-1+(2+d)g)}{(1-c-(3+d-b(1+d))g)^3} < 0$$

$$\frac{\partial \pi_r^{M^*}}{\partial c} = \frac{4a^2g^2}{(b-1)(-1+c+(4+d-b(2+d))g)^3} < 0$$
$$\frac{\partial \pi_r^{R^*}}{\partial c} = \frac{a^2g}{2(-1+b)(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial \pi_r^{N^*}}{\partial c} = \frac{4a^2g^2}{(b-1)(-1+c+(3+d-b(1+d))g)^3} < 0.$$

□

Proof of Proposition 7

Proof. The first order conditions of wholesale electricity price, carbon emission reduction intensity, electricity price and electricity demand on carbon reduction technology cost coefficient g under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial w_1^{M^*}}{\partial g} = \frac{\partial w_2^{M^*}}{\partial g} = \frac{a(-1+c)(2+d)}{(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial w_1^{R^*}}{\partial g} = \frac{\partial w_2^{R^*}}{\partial g} = \frac{a(-1+c)(1+d)}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial w_1^{N^*}}{\partial g} = \frac{\partial w_2^{N^*}}{\partial g} = \frac{a(-1+c)(1+d)}{(-1+c+(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial e_1^{M^*}}{\partial g} = \frac{\partial e_1^{M^*}}{\partial g} = \frac{a(4+d-b(2+d))}{(1-c-(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial e_1^{R^*}}{\partial g} = \frac{\partial e_2^{R^*}}{\partial g} = \frac{a(2+d-b(1+d))}{2(1-c-(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial e_1^{N^*}}{\partial g} = \frac{\partial e_2^{N^*}}{\partial g} = \frac{a(-3+b-d+bd)}{(-1+c+(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial p_1^{M^*}}{\partial g} = \frac{\partial p_2^{M^*}}{\partial g} = \frac{a(-1+c)(-3-d+b(2+d))}{(-1+b)(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial p_1^{R^*}}{\partial g} = \frac{\partial p_2^{R^*}}{\partial g} = \frac{a(-1+c)(1+d)}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial p_1^{N^*}}{\partial g} = \frac{\partial p_2^{N^*}}{\partial g} = \frac{a(-1+c)(-2+b-d+bd)}{(-1+b)(-1+c+(3+d-b(1+d))g)^2} < 0$$
$$\frac{\partial q_1^{M^*}}{\partial g} = \frac{\partial q_2^{M^*}}{\partial g} = \frac{a(-1+c)}{(-1+c+(4+d-b(2+d))g)^2} < 0$$
$$\frac{\partial q_1^{R^*}}{\partial g} = \frac{\partial q_2^{R^*}}{\partial g} = \frac{a(-1+c)}{2(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial q_1^{N^*}}{\partial g} = \frac{\partial q_2^{N^*}}{\partial g} = \frac{a(-1+c)}{(-1+c+(3+d-b(1+d))g)^2} < 0.$$

The first order conditions of the electricity retailer profits on carbon reduction technology cost coefficient g under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game are:

$$\frac{\partial \pi_r^{M^*}}{\partial g} = \frac{4a^2(-1+c)g}{(b-1)(-1+c+(4+d-b(2+d))g)^3} < 0$$

$$\frac{\partial \pi_r^{R^*}}{\partial g} = \frac{a^2(-1+c)}{2(b-1)(-1+c+(2+d-b(1+d))g)^2} < 0$$
$$\frac{\partial \pi_r^{N^*}}{\partial g} = \frac{4a^2(-1+c)g}{(-1+b)(1-c+(-3+b-d+bd)g)^3} < 0.$$

□

Proof of Proposition 8

Proof. By comparing the wholesale electricity price and electricity price under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game, we can obtain:

$$w_1^{M^*} - w_1^{R^*} = \frac{ag(3+d-c(3+d)-4g+2bg+3(-1+b)dg+(-1+b)d^2g)}{2(1-c-(2+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} > 0$$
$$w_1^{M^*} - w_1^{N^*} = \frac{ag(-1+c+2g)}{(-1+c+(3+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} > 0$$
$$w_1^{R^*} - w_1^{N^*} = \frac{a(1+d)g(1-c+(-1+b)(1+d)g)}{2(-1+c+(2+d-b(1+d))g)(-1+c+(3+d-b(1+d))g)} < 0$$
$$p_1^{M^*} - p_1^{R^*} = \frac{a(-1+c+g)(-1+c+d(g-bg))}{2(1-b)(1-c+(-2+b-d+bd)g)(-1+c+(4+d-b(2+d))g)} < 0$$
$$p_1^{M^*} - p_1^{N^*} = \frac{ag(-1+c+g)}{(-1+c+(3+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} > 0$$
$$p_1^{R^*} - p_1^{N^*} = \frac{a(-1+c+g)(-1+c-(-1+b)(1+d)g)}{2(1-b)(1-c+(-3+b-d+bd)g)(1-c+(-2+b-d+bd)g)} > 0.$$

□

Proof of Proposition 9

Proof. By comparing the electricity demand under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game, we can obtain:

$$q_1^{M^*} - q_1^{R^*} = \frac{ag(1-c+(-1+b)dg)}{2(1-c-(2+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} > 0$$
$$q_1^{M^*} - q_1^{N^*} = \frac{a(-1+b)g^2}{(-1+c+(3+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} < 0$$
$$q_1^{R^*} - q_1^{N^*} = \frac{ag(1-c+(-1+b)(1+d)g)}{2(-1+c+(2+d-b(1+d))g)(-1+c+(3+d-b(1+d))g)} < 0.$$

□

Proof of Proposition 10

Proof. By comparing the carbon emission reduction under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game, we can obtain:

$$e_1^{M^*} - e_1^{R^*} = \frac{a(-1+c+d(g-bg))}{2(-1+c+(2+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} > 0$$
$$e_1^{M^*} - e_1^{N^*} = \frac{a(-1+b)g}{(-1+c+(3+d-b(1+d))g)(-1+c+(4+d-b(2+d))g)} < 0$$

$$e_1^{R^*} - e_1^{N^*} = \frac{a - ac + a(-1+b)(1+d)g}{2(-1+c+(2+d-b(1+d))g)(-1+c+(3+d-b(1+d))g)} < 0.$$

□

Proof of Proposition 11

Proof. By comparing the electricity producers profits and the electricity retailer profits under the three models of electricity producer Stackelberg game, electricity retailer Stackelberg game and vertical Nash game, we can obtain:

$$\pi_{m1}^{M^*} - \pi_{m1}^{R^*} = \frac{\left\{\begin{array}{c} a^2g(-3+(22+9d-2b(2+3d))g - \begin{pmatrix} 48+44d+9d^2+ \\ b^2d(4+3d) - 4b(6+11d+3d^2) \end{pmatrix} g^2 \\ + \left(32+48d+22d^2+3d^3+b^2\begin{pmatrix} 8+24d+ \\ 18d^2+3d^3 \end{pmatrix} - 2b\begin{pmatrix} 16+36d \\ +20d^2+3d^3 \end{pmatrix}\right) g^3 + \\ c^2(-3+(14+3d)g) + c\left(\begin{pmatrix} 6+2(-6(3+d)+b(2+3d))g+ \\ (6(8+6d+d^2)-2b(12+16d+3d^2))g^2 \end{pmatrix}\right) \end{array}\right\}}{8(-1+c+(2+d-b(1+d))g)^2(-1+c+(4+d-b(2+d))g)^2} > 0$$

$$\pi_{m1}^{M^*} - \pi_{m1}^{N^*} = \frac{a^2g^2\begin{pmatrix} 2c^2-2c-g+2c(4+d)g+(4+d)g^2- \\ b^2g\begin{pmatrix} -3+4g \\ +d(-2+3g) \end{pmatrix} - 2b\begin{pmatrix} c+cdg- \\ (-1+g)(-1+(4+d)g) \end{pmatrix} \end{pmatrix}}{2(-1+c+(3+d-b(1+d))g)^2(-1+c+(4+d-b(2+d))g)^2} > 0$$

$$\pi_{m1}^{R^*} - \pi_{m1}^{N^*} = \frac{a^2g(1-(2+d)g)\begin{pmatrix} 3+3c^2+2(-5-3d+3b(1+d))g+(-1+b)(1+d) \\ (-7-3d+3b(1+d))g^2 - 2c(3+(-5-3d+3b(1+d))g) \end{pmatrix}}{8(-1+c+(2+d-b(1+d))g)^2(-1+c+(3+d-b(1+d))g)^2} < 0$$

$$\pi_r^{M^*} - \pi_r^{R^*} = \frac{a^2g\begin{pmatrix} 1+c^2+2(-1+b)(2+d)g+ \\ \begin{pmatrix} 8+4d+d^2+b^2(2+d)^2 \\ -2b(6+4d+d^2) \end{pmatrix} g^2 - 2c(1+(-1+b)(2+d)g) \end{pmatrix}}{2(1-b)(1-c+(-2+b-d+bd)g)(-1+c+(4+d-b(2+d))g)^2} < 0$$

$$\pi_r^{M^*} - \pi_r^{N^*} = \frac{2a^2g^3(2-2c+(-7+3b-2d+2bd)g)}{(-1+c+(3+d-b(1+d))g)^2(-1+c+(4+d-b(2+d))g)^2} < 0$$

$$\pi_r^{R^*} - \pi_r^{N^*} = \frac{g(a-ac+a(-1+b)(1+d)g)^2}{2(-1+b)(1-c+(-2+b-d+bd)g)(-1+c+(3+d-b(1+d))g)^2} > 0.$$

□

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Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability statement

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution statement

Wei Chen: Writing-review & editing, Supervision, Project administration, Methodology, Investigation, Data curation. Mengyao Cui: Writing-original draft, Software, Methodology, Data curation. Matthew Quayson: Methodology, Investigation, Data curation. Heng Du: Project administration, Methodology, Visualization, Validation.

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