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Does the carbon trading mechanism affect social and environmental benefits of the retailer-led supply chain: Strategic decisions of emissions reduction and promotion

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Governments, enterprises, and customers have become more concerned about environmental protection. Following the world's largest carbon trading market (EU ETS), China has also implemented a market-based carbon trading mechanism (CAT) to reduce CO_2. Simultaneously, customers have low-carbon preferences for environmental products. Thus, the enterprises' strategic decisions and collaboration modes have changed. This article develops the Stackelberg game model to explore the impacts of CAT and customers' low-carbon preference on the carbon emission reduction and promotion strategies in a retailer-led supply chain (such as RT-Mart, Walmart, Amazon, etc.). In this model, the retailer decides whether to promote environmentally safe products and the manufacturer decides whether to reduce CO_2. We find that carbon trading market price and customers' low-carbon preference are key factors influencing the retail price, total carbon emissions, and social welfare. Interestingly, there is not always a positive correlation between customers' low-carbon preference and social welfare. To achieve Pareto improvement of social welfare, manufacturers and retailers require co-optimization. Theoretically, our research enriches the research streams of the CAT policy and socially responsible operations of the supply chain. Moreover, managerial insights are provided for retailer-led supply chain stakeholders and emission reduction regulators, which contribute to enhancing the social and environmental benefits of the supply chains.

KEYWORDS

carbon trading, emissions reduction, consumers' low-carbon preferences, stackeberg game, promotional efforts

Introduction

Carbon dioxide, methane, ozone, and other greenhouse gasses (GHG) from industrial production processes mainly cause climate change. Among them, carbon dioxide accounted for the highest proportion of 65% (Solomon et al., 2009). Governments and enterprises are becoming more concerned about environmental protection (Fang et al., 2021). To achieve its carbon peak and carbon neutrality targets, China has implemented policies, legislations, and supporting measures for peaking CO_2 emissions in core areas and key industries, and map paths (such as the "1 + N" policy framework) to achieve carbon peaking and carbon neutrality goals (Z. Sun et al., 2022). Following the world's largest carbon trading market (EU ETS), China has also implemented a market-based carbon trading mechanism (CAT) to reduce carbon emissions. CAT is a market-based mechanism that allows carbon credits to be traded freely as a commodity. At the beginning of each accounting year, the government allocates free carbon quotas (called emissions cap) to an enterprise with high carbon emissions. The cap is always the hardest challenge in CAT. If the enterprise emits a smaller amount of CO_2 emissions than the emissions cap, it can gain additional revenue by selling surplus carbon quotas; otherwise, to avoid high fines, it has to go to the carbon trading market to buy carbon quotas (Benjaafar, Li, and Daskin 2013). Since 2011, China has established Beijing, Shanghai, Guangdong, and five other carbon trading systems. That means that CAT, which could have an impact on the enterprises' strategic decisions and collaboration modes, has created a new mechanism of the costs and returns account for enterprises.

Another factor that contributes to strategic decisions in a retailer-led supply chain is the customers' environmental preferences. In recent years, customers have become more concerned about protecting the environment and are willing to pay more for low-carbon products. Low-carbon products (e.g. natural bamboo and wood products, solar energy products, electronic signatures, and inverter air conditioners) refer to products that can save energy and reduce GHG emissions. "Carbon labels" or other channels can provide information on the emission-reduction level for consumers. The 2021 China Sustainable Consumption Report said that over 70% of consumers believe that low-carbon consumption can motivate the achievement of the "30·60" carbon peaking and carbon neutrality goals.

As mentioned previously, a manufacturer may be incentivized by CAT and customers' environmental preferences to invest in carbon reduction technologies (e.g. IRWIN's Carbon Cure CO_2 recovery technology) and projects such as Carbon Sequestration Project (Sun et al., 2020). In 2020, Alibaba conducts clean energy power trading. From January to September 2021, Alibaba traded 224 million kWh of green electricity. From 2018 to September 2021, Alibaba's Zhangbei Data Center has traded about 600 million kWh of new energy electricity and reduced carbon emissions by 523,000 tons. Meanwhile, powerful retailers (e.g. RT-Mart, Auchan, H&M, Amazon, Alibaba) have gradually more pricing power than manufacturers (Lou et al., 2020; Yuyan Wang et al., 2021), some retailer-led supply chains have occurred. These retailers become more socially responsible to protect the environment (Styles, Schoenberger, and Galvez-Martos 2012). They can install ventilation systems with heat recovery, build an eco-friendly distribution center, encourage customers to participate in environmental protection activities, and promote low-carbon products with carbon labeling by displaying them in preferential areas (Brunner et al., 2018). For instance, Walmart has established a low-carbon marketing team to carry out low-carbon public relations, and actively cooperate with the government, associations, and the media. Walmart has participated in the "Hundreds of Low-Carbon Demonstration Stores" organized by the Chain Store and Franchise Association in China. Walmart also held a 2-month long theme activity named "Focus on Climate Warming and Make the Earth Healthier". Through low-carbon marketing, Walmart transmits a good low-carbon corporate image to its suppliers and customers.

However, each stakeholder is not concerned about the entire supply chain's profits; they only act for their own maximized profits. When one enterprise makes efforts to reduce emissions or promote green/sustainable products, other companies will take a free ride to the benefit from the spillover that emerges (Gui et al., 2022). The one who invests in eco-friendly actions will feel unfair. Therefore, this contradiction can be alleviated by cooperation between the upstream and downstream stakeholders to reduce emissions.

Up to now, a thorough understanding of the impacts of CAT on its social and environmental benefits of a retailer-led supply chain and its implications to different stakeholders who are environmentally conscious is absent in the literature yet, especially in operations management (OM). To address this gap, we want to answer the following questions: 1) What are the strategic decisions of supply chain stakeholders under different scenarios considering the consumers' low-carbon preference and CAT mechanism? 2) What effects do the market price of carbon credits, emission cap, consumers' environmental behaviors, and other external parameters exert on the equilibrium solutions, total carbon emissions, and profits of the supply chain? 3) What management insights can governments and enterprises get?

We organize the rest of our article as follows: In the *Literature review* section, we review the relevant literature and identify our research gaps. In the *Model formulation* section, we describe the model formulations and derive the equilibrium solutions under each strategy combination of the retailer and the manufacturer who all make efforts to do socially responsible operations. In *The results analysis* section, we theoretically analyze the equilibrium solutions under different modes. In the *Modeling calibration and discussions* section, we conduct a numerical study and explore more managerial insights. All the proofs are postponed to Appendix A.

Literature review

Considering the CAT mechanism and consumers' environmental preference for low-carbon producing and selling, this article drives the strategic decisions for the manufacturer and retailer. There are three streams of literature related to this study: 1) sustainable supply chain management, 2) socially responsible operations of the supply chain, and 3) consumers' buying behavior based on environmental preference.

The first stream of literature related to this study is sustainable supply chain management. We refer readers to Goulder and Schen (2013), Barbosa-Povoa et al. (2018), Koberg and Longoni (2019), and Lu et al. (2022) for comprehensive reviews. Fang et al. (2021) applied the Differences in Differences (DID) method to find that government environmental regulations have a positive impact on corporate green innovation. To increase the benefits of an integrated forward/reverse logistics network and maximize the score of green design and quality indicators, Porkar et al. (2020) developed bi-objective non-linear programming. Zakeri et al. (2015) examined the supply chain performance under carbon taxes and carbon emissions trading by an analytical supply chain planning model. The results showed that the carbon trading scheme was better. Yang et al. (2020) compared the total emission reduction and operational decisions under the grandfathering and benchmarking rules for the allocation of carbon quotas. They found that the emission reduction under the grandfathering rule was greater. Above all, we concluded that these existing studies have mainly researched the impacts of macroeconomic regulations that control carbon emissions on the supply chain performance, ignoring the collaboration mode among supply chain stakeholders, especially in a socially responsible operations management.

Another stream of literature closely related to our study is the socially responsible operations of the supply chain. Some latest literature studies have investigated the low-carbon scenario or carbon-neutral potential of building operations. Xiang et al. (2022) used the decomposing structural decomposition method to assess the decarbonization progress of commercial building operations taking China and the United States (U.S.) as examples. S. Zhang et al. (2022) illustrated the potential for progressive decarbonization of global commercial building operations to achieve carbon neutrality. However, these studies did not consider the CAT mechanism.

A new mechanism of the costs and returns account for enterprises has been created by CAT, which could have an impact on the enterprises' operation strategies and cooperation modes with other companies (Ma et al., 2021). From the operational management point of view, Wang et al. (2019) studied the joint replenishment policy as well as the carbon trading behavior for a fresh food supply chain. They found that retailers' leader–follower structure could cause the least carbon emissions. Considering environment protection, Taleizadeh et al. (2022) developed an EOQ model based on partial trade credit combined with partial back-ordering. In this article, demand is affected by selling price and carbon emissions per unit of product. Based on the decision theory, Saunders et al. (2020) determined the optimal level of sustainability for bidding suppliers considering the buyers' environmental preferences. Min Wang et al. (2021) optimized the operational decisions of a transnational manufacturer under different carbon trading mechanisms implemented in two countries. Xu and Wang (2018) indicated that decentralized decision-making in CLSC could cause a double-marginal effect and affect the operating efficiency of the supply chain. Yuyan Wang et al. (2021) constructed three decision-making models to compare the decisions and benefits of the stakeholders. They proposed a cost-sharing contract with an altruistic preference to coordinate the retailer-led low-carbon supply chain, and found that retailers needed to share more than 1/2 of the carbon emissions cost. Based on the carbon trading mechanism, Mondal and Giri (2021) developed centralized, decentralized, retailer-led revenue sharing, and bargaining revenue sharing models. In addition, they assumed that the manufacturer, retailer, and consumers are all environmentally conscious. The results demonstrated that retailer-led revenue sharing could coordinate the supply chain and improve benefits for both stakeholders. However, they did not consider the retailer's environmental behavior, such as promoting low-carbon products by advertising or displaying them in the preferential area.

Recently, customers have become more concerned about protecting the environment and are willing to pay more for low-carbon products (Du et al., 2015; Dardanoni and Guerriero 2021). To solve the problem of carbon emissions transfer and reduction among supply chain stakeholders, Sun et al. (2020) constructed a Stackelberg differential game model with considerations of emissions reduction technology lag time and customers' environmental preferences. Tong and Du (2019) developed an actual evolutionary game process to examine the evolution of the behaviors of powerful retailers and manufacturers with consideration of CAT and customers' low-carbon preferences.

The work that is most related to ours is that of Xia et al. (2018), who indicated that customers' low-carbon preferences motivated supply chain members to make efforts to reduce carbon emissions and promote low-carbon products under the CAT system. Our work differs from that of Xia et al. (2018) in two aspects as follows. First, Xia et al. (2018) suppressed the influence of wholesale price and retailer price. In this work, we optimize both wholesale price and retailer price. Second, Xia et al. (2018) analyzed the farms'

TABLE 1 The contributions of our research.

Studies	CAT	Retailer-Led Supply Chain	Retail Price		Collaboration Mode	Demand is Sensitive to		
			Exogenous	Endogenous		Carbon Emissions	Promotion Level	Customers' Low-Carbon Preference
Saunders et al. (2020)	—	—	—	*	—	*	—	—
Xu and Wang (2018)	—	—	—	*	*	*	—	*
Yuyan Wang et al. (2021)	—	*	—	*	*	*	—	*
Zakeri et al. (2015)	*	—	*	—	—	—	—	—
Wang et al. (2019)	*	—	—	*	—	—	—	—
Min Wang et al. (2021)	*	—	*	—	*	—	—	—
Taleizadeh et al. (2022)	*	—	*	*	—	*	—	—
Sun et al. (2020)	*	—	*	—	*	*	—	*
Tong and Du (2019)	*	*	—	*	—	*	*	*
Mondal and Giri (2021)	*	*	—	*	*	*	—	*
Xia et al. (2018)	*	*	*	—	—	*	*	*
This study	*	*	—	*	*	*	*	*

environmental behavior from the perspective of coordinating the supply chain, and thus did not take into account the collaboration modes among supply chain stakeholders. From the perspective of micro-games, we characterized the farms' equilibrium strategic decisions under five scenarios.

For the convenience of the readers, a quick overview of the closely relevant previous research articles has been provided in comparative Table 1. From this table, most mentioned articles have failed to take carbon emission issues of the retailer-led supply chain structure into account. Also, most articles on carbon emissions have failed to consider the collaboration modes and the environmental preferences of the manufacturer, retailer, and consumers simultaneously in real-life situations. Therefore, our research enriches the research streams mentioned previously. That is, to address these gaps, we developed the Stackelberg game model to explore the impacts of CAT and customers' low-carbon preference on the carbon emissions reduction and promotion strategies in a retailer-led supply chain.

Model formulation

Model description

In this section, considering the CAT mechanism and customers' low-carbon preferences, we develop a Stackelberg game model to identify the optimal decisions for the manufacturer and retailer who are perfectly rational and make economic profits. In a retailer-led supply chain, the manufacturer responds to customers' environmental preferences by introducing low-carbon products to meet the demand. It sells ordinary products or low-carbon products to the retailer. The retailer sells these products to the customers. The timeline of the events is as follows (see Figure 1).

As depicted in Figure 1,

1) the effectiveness of promoting low-carbon products β can be realized by retailer's market survey or forecasting. Based on β, the retailer simultaneously and individually decides whether to invest in promoting low-carbon products (P) or not invest in promotion (NP), the promotional effort level τ_r., and low-carbon products' retail price p. The promotion cost coefficient can be denoted as h_r.

2) Based on the baseline method, the manufacturer can be allocated free carbon quotas C_g by the government. The initial carbon emissions per unit of product are e_m. In particular, carbon credits can only be bought/sold in one production period at market price p_e. The carbon trading price is only determined by the carbon market. Particularly, we assume that the technology of carbon emissions reduction will not change significantly in a short period because of the long investment cycle. The manufacturer's market survey can realize the effectiveness of carbon emissions reduction γ.

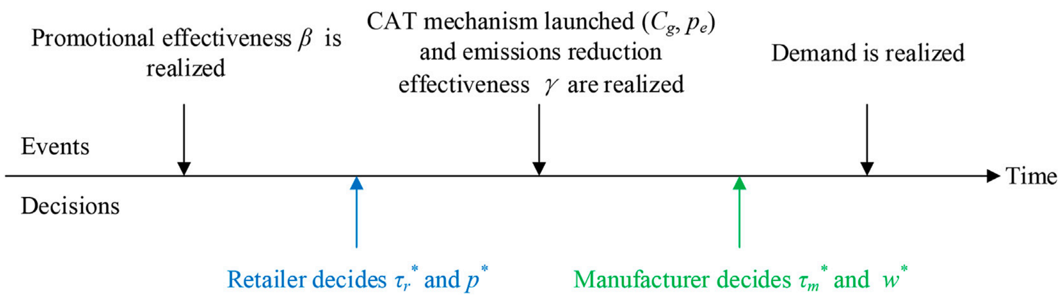

FIGURE 1
Two-echelon supply chain structure.

3) According to the retailer's decisions and information about CAT, the manufacturer acts as a follower who simultaneously and individually decides whether to invest in reducing carbon emissions (R) or not reducing carbon emissions (NR), the emissions reduction level τ_m, and the products' wholesale price w. Emissions reduction investment coefficient can be denoted as h_m. The production cost per unit of the product is fixed and environmental improvement has an increasing marginal cost.
4) Each consumer chooses to buy the products that maximize their utility. We assume the fixed potential market demand is a. The price elasticity of demand is b.

The objectives of the retailer and manufacturer are to maximize their profits. In the following, we denote the equilibrium values by an asterisk "*". When supply chain stakeholders make decentralized decisions, four strategy combinations are proposed: NN (NP, NR), PN (P, NR), NR (NP, R), and PR (PS, R). We construct the cooperation mode: SC mode when supply chain stakeholders make centralized decisions.

Under centralized decision-making (SC mode), the manufacturer adopts a carbon emissions reduction strategy while the retailer adopts a promotion strategy. In this cooperation model, the demand D is affected by the retail price, emissions reduction level, and promotion level. The demand function is given by Equation (1).

$$D = a - bp + \gamma\tau_m + \beta\tau_r \tag{1}$$

The overall profit functions for the supply chain are provided as follows:

$$\pi_{r,m}^{SC} = (p - c_m - c_r)q - \left[e_m(1-\tau_m)q - C_g\right]p_e - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2 \tag{2}$$

where c_r denotes the retail cost, and c_m denotes the production costs. The production cost per unit of the product is fixed and the investment costs of emissions reduction and promotion will change. It is well known that the improvement of environmental and promotional levels has an increasing marginal cost. Thus, the costs of promotion and carbon emissions reduction follow a quadratic function, respectively, based on the results from Laffont and Tirole (1993) and Savaskan and Van Wassenhove (2006), i.e. $\frac{1}{2}h_r\tau_r^2$ and $\frac{1}{2}h_m\tau_m^2$. $\pi_{r,m}^{SC}$ denotes the profits of the entire supply chain.

Optimal solutions

When the manufacturer and retailer make decentralized decisions, the optimal solutions for the manufacturer and retailer in each combination strategy are present in our previous research (Tong and Mu, 2019). To proceed with the analysis, we make the following assumptions:

Assumption. $2bh_r - \beta^2 > \frac{h_r}{h_m}(\gamma + be_m p_e)^2$

This assumption shows the relationship between the various system parameters. It indicates that consumers are reasonably price-sensitive. In particular, the price elasticity of demand, b, needs to be limited. This is because, if the consumers are highly price-sensitive, the players will achieve price-war equilibrium. This assumption also shows that the retailer is promotion cost-sensitive and the manufacturer is reduction cost-sensitive. Take the manufacturer as an example, the assumption implies that if a manufacturer decides to reduce carbon emissions with his maximum effort, he can substantially improve the environmental quality of his products. That is, each stakeholder will set his level of emissions reduction/promotional efforts at the marginal cost. Based on Equation (2) established for the supply chain, the optimal solutions are shown in Theorem 1.

Theorem 1. There exists a unique optimal solution to the SC mode. The optimal promotional effort level, the emissions reduction level, production quantity, and retail price and production are as follows:

Proof. The third-order Hessian matrix for Equation (2) is $H = \begin{bmatrix} -2b & \beta & \gamma - bp_e e_m \\ \beta & -h_r & \beta e_m p_e \\ \gamma - bp_e e_m & \beta p_e e_m & 2\gamma p_e e_m - h_m \end{bmatrix}$, where the value of the first-order determinant is $H_1 = -2b$. According to the assumption, the value of the second-order determinant satisfies $H_2 > 0$, and the third-order determinant satisfies $H_3 < 0$, that is, when $2bh_m - (\gamma + be_m p_e)^2 > \frac{\beta^2 h_m}{h_r} > 0$, $\pi_{r,m}^{SC}$ is a joint concave function for p, τ_r, τ_m and has a maximum value in the range. Letting the first-order partial derivative of the profit function be zero, the unique optimal decisions can be solved.

$$(\tau_r^{SC})^* = \frac{\beta h_m [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} \tag{3}$$

$$(\tau_m^{SC})^* = \frac{h_r(\gamma + bp_e e_m)[a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + bp_e e_m)^2] - \beta^2 h_m} \tag{4}$$

$$(p^{SC})^* = \frac{h_r [a - b(c_m + c_r + e_m p_e)][h_m - e_m p_e(\gamma + be_m p_e)]}{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} + c_r + c_m + e_m p_e \tag{5}$$

$$(q^{SC})^* = \frac{bh_m h_r [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + bc_e e_m)^2] - \beta^2 h_m} \tag{6}$$

The profit of manufacturer and retailer is $(\pi_{r,m}^{SC})^* = \frac{h_r h_m [a - b(c_m + c_r + e_m p_e)]^2}{2\{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m\}} + C_g p_e$.

The results analysis

Comparison of emissions reduction levels

Proposition 1. The ratio of the emissions reduction level under the (P, R) strategy to that under the (N, R) strategy is greater than 1.

From Tong and Du (2019), we know that,

$$(\tau_m^{NR})^* = \frac{(\gamma + be_m p_e)[a - b(c_m + e_m p_e + c_r)]}{4bh_m - 2(\gamma + be_m p_e)^2}, \text{and} \tag{7}$$

$$(\tau_r^{PR})^* = \frac{\beta h_m [a - b(c_m + e_m p_e + c_r)]}{2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} \tag{8}$$

Let, $\Delta_1 = 2[2bh_m - (\gamma + be_m p_e)^2]$, $\Delta_2 = 2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m$.

Therefore,

$$\frac{(\tau_m^{PR})^*}{(\tau_m^{NR})^*} = \frac{2[2bh_m - (\gamma + be_m p_e)^2]}{2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} = \frac{\Delta_1}{\Delta_2} = \frac{\Delta_2 + \frac{\beta^2 h_m}{h_r}}{\Delta_2} > 1 \tag{9}$$

Proposition 2. implies that, under the PR strategy, the emissions reduction level is twice as high as that of the NR strategy. It means that, although the retailer does not contribute to carbon emissions reduction and low-carbon product promotion, they can benefit from the manufacturer's emission reduction as the manufacturer is a rational agent who is concerned about fairness. Compared with the PR strategy, the manufacturer has a lower willingness to reduce emissions under the NR strategy.

Comparison of profits

Proposition 3. The relationship between the profits of the retailer and the manufacturer under centralized decision-making and decentralized decision-making is: $(\pi_{r,m}^{SC})^* > (\pi_m^{PR})^* + (\pi_r^{PR})^*$.

If $2bh_m - (\gamma + be_m p_e)^2 > \frac{\beta^2 h_m}{2h_r} > 0$, we know that $(\pi_r^{NN})^* = (\pi_r^{PN})^* < (\pi_r^{NR})^* < (\pi_r^{PR})^*$. It indicates that the manufacturer and the retailer earn the most profits in PR, followed by the NR strategy combination. We can get $\pi_m^{NN} + \pi_r^{NN} = \pi_m^{PN} + \pi_r^{PN} < \pi_m^{NR} + \pi_r^{NR} < \pi_m^{PR} + \pi_r^{PR}$, which means that when a retailer promotes low-carbon products and the manufacturer reduces emissions, the profits of the entire supply chain is significantly greater than others. It is easy to get $(\pi_{r,m}^{SC})^* > (\pi_m^{PR})^* + (\pi_r^{PR})^*$ as a different method.

If the manufacturer invests in reducing carbon emissions or the retailer adopts promotional strategies, it will help increase their profits and supply chain profits. The overall profit of the retailer and the manufacturer under centralized decision-making is higher than that under decentralized decision-making. It indicates that, when the retailer adopting a promotion strategy cooperates with the manufacturer adopting a carbon emissions reduction strategy, it is beneficial for increasing the profit of the supply chain.

Comparison of total carbon emissions

Proposition 3. The relationship between the carbon emissions per unit of a product under centralized decision-making and decentralized decision-making is $E^{NN} = E^{PN} > E^{NR} > E^{PR} > E^{SC}$.

We assume that carbon emissions per unit of product under each combination are $E^i, i = NN, PN, NR, PR, SC$. Under strategy NN and strategy PN, since the manufacturer does not invest in reducing carbon emissions, the decision sequence and final strategy of the manufacturer and the retailer are consistent, so the carbon emissions per unit of the product are the same, that is, $E^{NN} = E^{PN} = e_m$. Under strategy NR, when the manufacturer makes an effort to reduce carbon emissions, the emissions reduction level is τ_m^{NR}, and then the term $E^{NR} = e_m(1 - \tau_m^{NR})$ denotes the current carbon emissions per unit of the product. Similarly, under the PR strategy combination, the carbon emissions per unit of the product are $E^{PR} = e_m(1 - \tau_m^{PR})$ after the manufacturer takes measures to reduce carbon emissions. When the manufacturer and retailer make decisions together, the carbon emissions per unit of product are $E^{SC} = e_m(1 - \tau_m^{SC})$.

According to Proposition 1, we know $\tau_m^{NR} < \tau_m^{PR} < \tau_m^{SC}$, then we can get $E^{NR} > E^{PR} > E^{SC}$; above all, $E^{NN} = E^{PN} > E^{NR} > E^{PR} > E^{SC}$ can be obtained.

Proposition 4. The relationship between the production quantities under each strategy combination is: $(q^{NN})^* = (q^{PN})^* < (q^{NR})^* < (q^{PR})^*$.

According to Tong and Du (2019), we can rewrite the manufacturer's production quantity under each strategy combination as

$$(q^{NN})^* = (q^{PN})^* = \frac{a - b(c_m + e_m p_e + c_r)}{4} \tag{10}$$

$$(q^{NR})^* = \frac{bh_m[a - b(c_m + e_m p_e + c_r)]}{4bh_m - 2(\gamma + be_m p_e)^2} = \frac{a - b(c_m + e_m p_e + c_r)}{4 - \frac{2(\gamma + be_m p_e)^2}{bh_m}} \tag{11}$$

$$(q^{PR})^* = \frac{bh_r h_m[a - b(c_m + e_m p_e + c_r)]}{2h_r[2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} = \frac{[a - b(c_m + e_m p_e + c_r)]}{4 - \frac{2(\gamma + be_m p_e)^2}{bh_m} - \frac{\beta^2}{bh_r}}, \text{and} \tag{12}$$

$$(q_m^{SC})^* = \frac{bh_m h_r[a - b(c_m + c_r + e_m p_e)]}{h_r[2bh_m - (\gamma + bc_e e_m)^2] - \beta^2 h_m} \tag{13}$$

Since $\frac{2(\gamma+be_m p_e)^2}{bh_m} + \frac{\beta^2}{bh_r} > \frac{2(\gamma+be_m p_e)^2}{bh_m} > 0$, we can find $(q^{NN})^* = (q^{PN})^* < (q^{NR})^* < (q^{PR})^* < (q^{SC})^*$. Based on the aforementioned two properties, we know that when the manufacturer chooses to reduce carbon emissions or the retailer chooses to invest in promoting low-carbon products, the carbon emissions per unit of the product will decrease, but the production quantity will increase accordingly. When the retailer and the manufacturer fully cooperate, the carbon emissions per unit of the product are the lowest, but the production quantity is the highest. Then, no matter under what strategy combination is used, the relationship between the total carbon emissions of the supply chain cannot be determined. That is, companies seeking to maximize their benefits will cost the environment. Therefore, the trade-off between environmental protection and economic development is crucial.

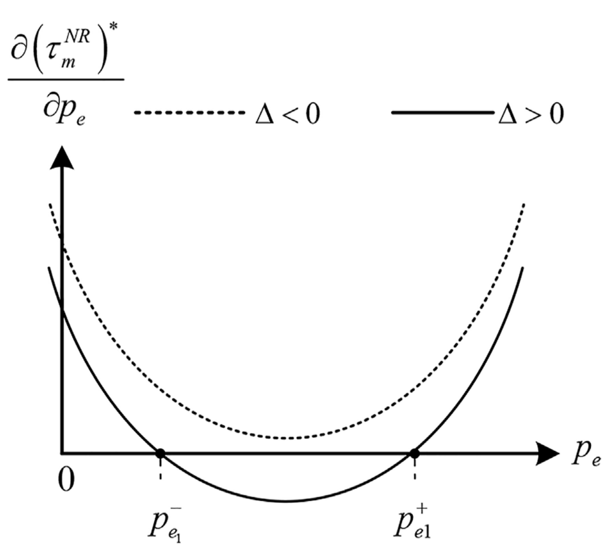

FIGURE 2
The first partial derivative of the emissions reduction level with respect to p_e under strategy NR.

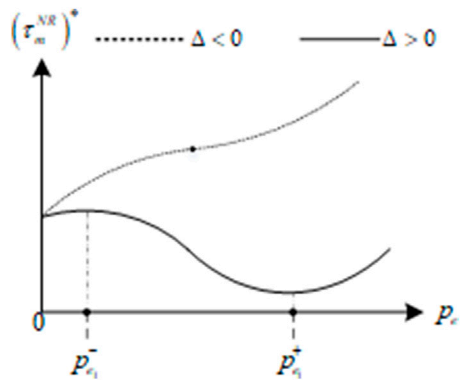

FIGURE 3
Emissions reduction level under strategy NR.

The impacts of carbon credit market price on emissions reduction level

Proposition 5. *The impacts of carbon credit market price on emissions reduction levels under strategy NR are summarized in this proposition.*

1) If $h_m < \frac{(a+1)^2}{2}$, then $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{NR})^*$ increases with the increase of p_e.

2) If $h_m > \frac{(a+1)^2}{2}$, then in the interval $\left(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}\right)$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$ and in other intervals it is opposite.

See Appendix A for proof. We can easily find that $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which means that $(\tau_m^{NR})^*$ increases with the increase of p_e. These results indicate that when the emissions reduction cost coefficient is relatively small, that is $h_m < \frac{(a+1)^2}{2}$, the manufacturer is likely to reduce carbon emissions easily. Then, with the increase of the carbon allowances' market price, the emissions reduction level increases gradually. Subsequently, due to the diminishing marginal utility of carbon emissions reduction, the emissions reduction level slows down gradually to 0 (corresponds to the lowest point in the dashed line in Figure 2 and the turning point in the dashed line in Figure 3). However, when the market price of carbon credits continues to increase, the manufacturer will choose to make more efforts to reduce emissions to gain profit from selling surplus carbon quotas. Therefore, the emissions reduction level increases with the increase of carbon trading prices.

When $h_m > \frac{(a+1)^2}{2}$, then $\Delta = 8h_m[2h_m - (a+1)^2] > 0$. In the interval $\left(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}\right)$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$ and in other intervals it is opposite (see the dotted line in Figure 2 and Figure 3).

If the value of the emissions reduction cost coefficient is relatively small, that is $h_m > \frac{(a+1)^2}{2}$, the manufacturer should invest more money in reducing carbon emissions to achieve a certain emissions reduction level. Under the carbon policies, the manufacturer chooses to reduce carbon emissions instead of buying carbon credits on the market; however, since the marginal utilities diminish, the emissions reduction level will maintain that maximum value even if the manufacturer tries to pay more money for the investment (see the corresponding vertex of $p_{e_1}^-$ in Figure 3).

When the emissions reduction hits a plateau, once the emissions reduction level attains the peak, the manufacturer will give up investing in reducing carbon emissions, which leads to a lower emissions reduction level. However, under the impact of increasing carbon trading prices and tight carbon policies, the manufacturer will want to gain more profit from carbon emissions reduction. Then, the emissions reduction level will decrease slowly (see the interval $(p_{e_1}^-, p_{e_1}^+)$ in Figure 3). Subsequently, the optimal emissions reduction level increases with the increase in the carbon trading price.

As mentioned previously, the emissions reduction level varies with the price of carbon trading and different difficulties in reducing emissions. When the manufacturer can reduce emissions easily, the market price of carbon credits has a positive relation to the emissions reduction level. Initially, compared with the high emissions reduction cost coefficient situation, the reduction level increases more rapidly under the condition of the lower emissions reduction cost coefficient.

When the emissions reduction cost coefficient is higher, the manufacturer chooses to buy carbon allowances, which leads to the emissions reduction level increasing slowly and then has negative growth. Since the carbon trading costs increase with the increase of the carbon trading price, the manufacturer will choose to invest in reducing carbon emissions again to raise the emissions reduction level.

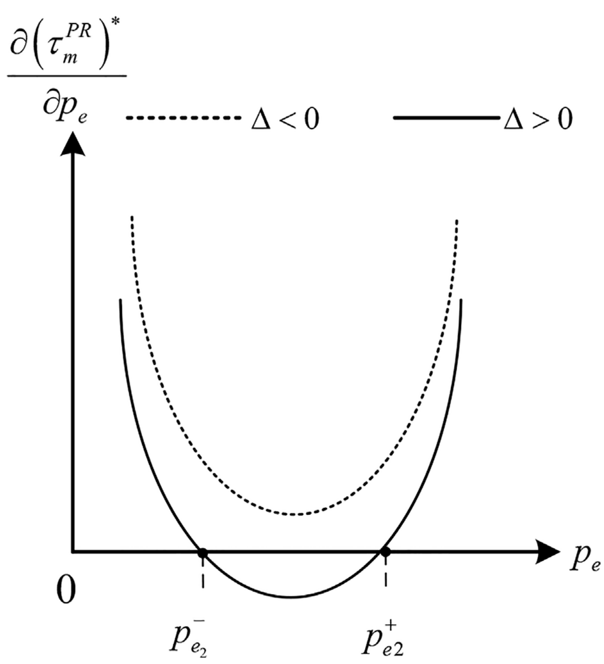

FIGURE 4
The first partial derivative of the emissions reduction level with respect to p_e under strategy PR.

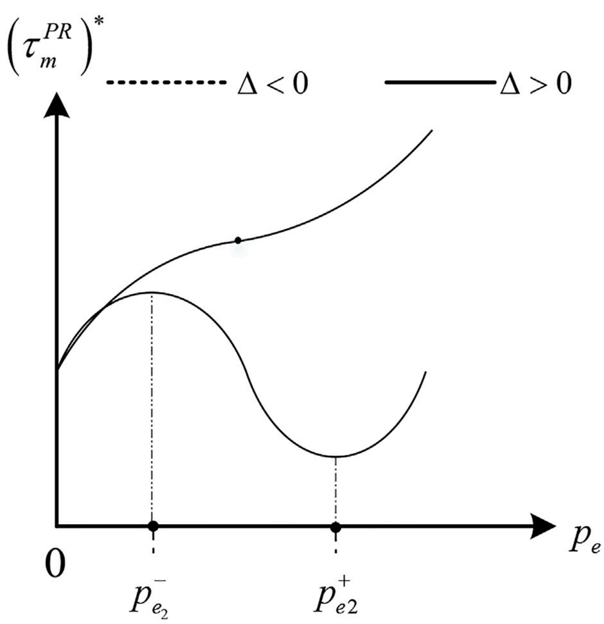

FIGURE 5
Emissions reduction level under strategy PR.

Proposition 6. *The impacts of the carbon credit market price on emissions reduction levels under strategy PR are summarized in this proposition.*

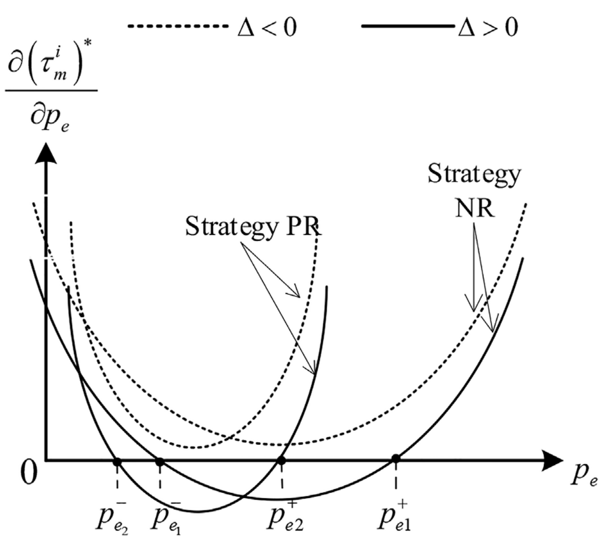

FIGURE 6
The first partial derivative of the emissions reduction level with respect to p_e. under strategies PR and NR.

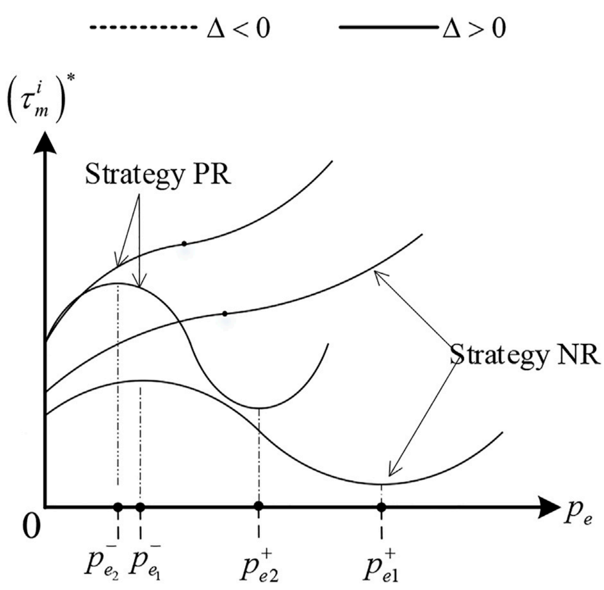

FIGURE 7
Emissions reduction level under strategies PR and NR.

1) If $h_m < \frac{(a+1)^2}{2}$, then $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{NR})^*$ increases with the increase of p_e.
2) If $h_m > \frac{(a+1)^2}{2}$, then in the interval $\left(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}\right)$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$ and in other intervals it is the opposite.
3) If $h_m < \frac{2h_r(a+1)^2}{4h_r-1}$, then $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{PR})^*$ increases with the increase of p_e.
4) If $h_m > \frac{2h_r(a+1)^2}{4h_r-1}$, then in the interval $\left(\frac{-[h_m(1-4h_r)+2h_r(a+1)]-\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)}, \frac{-[h_m(1-4h_r)+2h_r(a+1)]+\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)}\right)$, we have $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} < 0$ and in other intervals it is opposite.

In Figure 4 and Figure 5, we illustrate the observations in Proposition 6.

When $p_e = 0$, then $(\tau_m^{NR})^* = \frac{a}{4h_m-2}$, and $(\tau_m^{PR})^* = \frac{a_r}{4h_m-2-\frac{h_m}{h_r}}$. It is clear that $(\tau_m^{PR})^*|_{P_e=0} > (\tau_m^{NR})^*|_{p_e=0}$.

From the proof mentioned previously, the distance between $(p_{e_1}^-, 0)$ and $(p_{e_1}^+, 0)$ is: $A = \frac{2\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1} = \frac{\sqrt{8h_m[2h_m-(a+1)^2]}}{a+1}$. And the distance between $(p_{e_2}^-, 0)$ and $(p_{e_2}^+, 0)$ is: $B = \frac{\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{h_r(a+1)} = \frac{\sqrt{8h_m[2h_m-(a+1)^2]+\frac{h_m}{h_r^2}[2h_r(1+a)^2-h_m(8h_r-1)]}}{a+1}$.

When $-2h_r(1+a)^2 + h_m(4h_r-1) > 0$, then $2h_r(1+a)^2 - h_m(8h_r-1) < 0$. Therefore, $A > B > 0$, which implies that the opening degree of y_2 is lower than that of y_1. We can know that $p_{e_2}^- < p_{e_1}^-$ and $p_{e_1}^+ > p_{e_2}^+$, The emissions reduction level changes with the carbon credit market price under strategy NR and strategy PR are summarized in Figure 6 and Figure 7.

As shown in the aforementioned figures, the optimal emissions reduction level under the strategy PR is higher than that under the strategy NR. That is to say, if a retailer adopts a promotion strategy, the low-carbon demand and production quantity will increase. Compared with strategy NR, the manufacturer has more willingness to invest in reducing carbon emissions under strategy PR, and the optimal emissions reduction level is higher under the strategy PR. We also find that the emissions reduction level under strategy PR is more sensitive to the carbon credit market price. Owning to the retailer making efforts to promote low-carbon products, the manufacturer has incentives to invest in emissions reduction and the marginal utilities diminish more rapidly than those under strategy NR. Then, the emissions reduction level reaches a peak faster. In other words, with the retailer promoting low-carbon products, the negatively correlated area will decrease, which makes the optimal emissions reduction level higher at a relatively low-carbon credits market price than the case the retailer does not promote.

Modeling calibration and discussions

Data description

Based on the obtained theoretical results, this section uses MATLAB software to carry out numerical examples to

TABLE 2 Input parameters of the simulation.

Variables	Value	Unit	Variables	Value	Unit
a	10	Million	e_m	0.01	Ton
b	0.6	—	h_m	20	—
γ	[0,4]	—	h_r	10	—
β	0.6	—	p_e	60	RMB/Ton
c_m	0.9	Thousand RMB	C_g	1,000	Thousand Ton
$\boldsymbol{c_r}$	0.6	Thousand RMB	—	—	—

[a]Data source: Greco Consulting (Beijing) Co., Ltd., and the China Household Electrical Appliances Association (CHEAA).

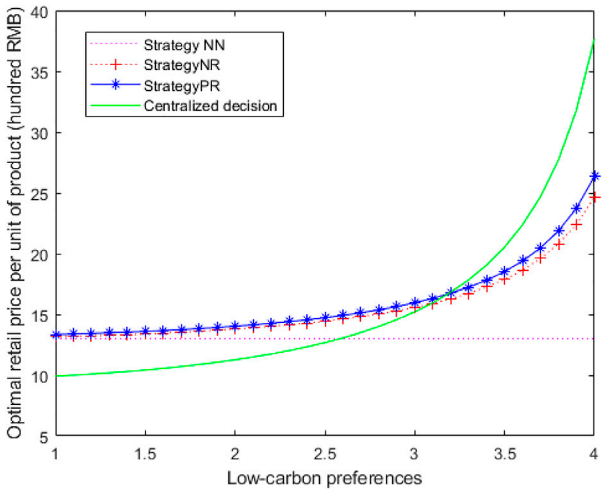

FIGURE 8
Optimal retail price responses to customers' low-carbon preference.

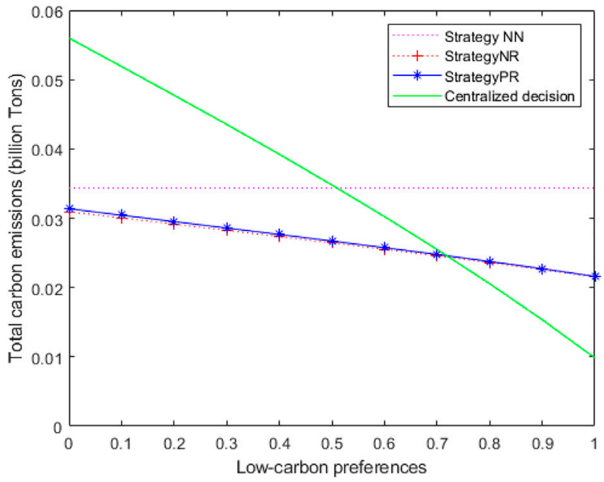

FIGURE 9
Total carbon emissions responses to customers' low-carbon preference.

focus on comparing the impact of CAT and consumers' low-carbon preference on the optimal strategy, profit, total carbon emissions, and social welfare of enterprises under different strategies. We apply the Stackelberg model to the Chinese refrigerator industry. In 2021, the Chinese company JD sold 13 million refrigerators online. Then, the potential market demand was set as 10 million. Since China launched CAT in Shanghai, the carbon trading price in Shanghai's Carbon Trading Center has been 59.5 RMB/Ton (Greco Consulting (Beijing) Co., Ltd.). Based on the baseline method, the manufacturer can be allocated free carbon credits that are set as 1 million tons. It takes 14 kWh to produce one refrigerator (Zhang et al., 2016). Thus, $e_m = 14\,kWh \times 0.785\,kWh/kg$ (Calculation of carbon emissions 2014). One-third of a refrigerator's manufacturing cost is the price of a compressor, which is 300 RMB yuan (Zhang et al., 2016). The production cost can be set as 900 RMB yuan. The values of these input parameters are shown in Table 2.

The impact of customers' low-carbon preference on the retail price per unit of a product

To investigate the influence of customers' low-carbon preference on the optimal retail price, we set the interval of customers' low-carbon preference as [1, 4] with an interval of 0.1.

Figure 8 presents that under decentralized decision-making, if the manufacturer does not invest in reducing carbon emissions, there will be no low-carbon products in the market. Then, the consumers' low-carbon preference has no impact on the retail price per unit of a product of strategy combination NN and strategy combination PN. Since the implementation of the manufacturer's carbon emissions reduction strategy and the retailer's promotion strategy requires a certain investment, they will pass the investment cost to the consumer. Then, the retail price per unit of the product under the centralized decision-making mode and PR strategy is generally higher than other strategy combinations when the retailer does take measures to promote low-carbon products.

It is interesting that when customers' low-carbon preference varies in the range of [1, 4], the retail price per unit of the product under the NN strategy is higher than that of other strategy combinations. It is very likely that there are only ordinary products in the market, and the manufacturer and the retailer make more profits by raising the wholesale price and retail prices. After that, the retail price increases with the increase in consumers' low-carbon preferences. At this time, the manufacturer invests more in reducing carbon emissions, and retail starts promoting low-carbon products to make profits through "small profits but quick turnover". However, since the low-carbon technologies gradually meet the ceilings, the increase in investment costs for carbon emissions reduction and promotion, and retail costs will cause the profit margins of the manufacturer and retailer to gradually be compressed. Therefore, the retail price has to increase.

In the centralized decision-making mode, when customers' low-carbon preference varies in the range of [1, 3.2], the retail price per unit of a product is always lower than that in the decentralized decision-making mode, but the profit is the highest. It indicates that, when the retailer and the manufacturer cooperate, the products will be cheap and environmentally friendly, so the demand will increase, and the total profit of the supply chain will be sustainable. We also find that, under a centralized decision-making mode, when the low-carbon preference coefficient is over 3.2, the optimal retail price per unit of the product will exceed any other strategy combinations. It means that, when consumers' low-carbon preference coefficient is high enough, the retail price per unit of low-carbon products will be higher than that of ordinary products.

The impact of customers' low-carbon preference on the total carbon emissions

To investigate the influence of customers' low-carbon preference on the total carbon emissions, we set the interval of the customers' low-carbon preference as [0, 1] with an interval of 0.1.

Figure 9 shows that under decentralized decision-making, when the manufacturer does not adopt carbon emissions reduction technologies, the total carbon emissions are higher than in the other two cases. When the consumers' low-carbon preference varies between [0, 0.7], the total carbon emissions under the centralized decision-making mode are higher than those under the decentralized decision-making mode. This is because, under a centralized decision-making mode, although consumers are willing to pay more for low-carbon products, the manufacturer and the retailer need to share the benefits of the premium consumers' pay. In other words, the shared benefits are not enough to balance the investment costs for carbon emissions reduction and promotion, so the effect of carbon emissions reduction is not much higher than that under decentralized decision-making. In the short term, under a certain emissions reduction level, the promotion will increase the production quantity and total carbon emissions. On the contrary, under a decentralized decision-making mode, the manufacturer can share most of the premium consumers' pay. In addition, the effect of carbon emissions reduction will not be too bad. Although the sales volume is not as good as that of the centralized decision-making mode, the total carbon emissions will be slightly lower. Under the decentralized decision-making mode, as consumers' low-carbon preferences continue to increase, manufacturer's carbon emissions reduction actions are slow. When the customers' low-carbon preferences coefficient is higher than 0.7, the total carbon emissions are higher than those in the centralized decision-making mode.

The impacts of the carbon credit market price and customers' low-carbon preference on total carbon emissions

To investigate the combined impacts of the carbon credit market price and customers' low-carbon preferences on total carbon emissions, we set the interval of customers' low-carbon preferences as [0, 2] with an interval of 0.1, and carbon credit market price as [50, 70] with an interval of 1. Figure 10 shows that the customers' low-carbon preferences have a greater impact on the total carbon emissions. Regardless of the carbon price, consumers who are willing to pay more for low-carbon products can always reward the manufacturer and retailer.

Within a limited range, the total carbon emissions of the supply chain decrease as consumers' low-carbon preference and carbon credit market price both increase, except in the NN mode. It means that as long as the manufacturer adopts a reduction strategy, total carbon emissions will finally be reduced. This is because, if the manufacturer does not reduce emissions, once the emissions exceed the cap, he will have to buy the carbon credits at a high price. If the manufacturer adopts a reduction strategy, he can earn additional revenue by selling the surplus carbon credits at a high market price. On the other hand, the manufacturer and retailer could gain the benefits from premium consumers who will pay for low-carbon products. The higher the carbon price and consumers' low-carbon preference, the more incentive for the manufacturer to reduce emissions and the retailer to promote low-carbon products. Then, the total carbon emissions will become lower and lower.

The impact of customers' low-carbon preference on social welfare

To investigate the influence of customers' low-carbon preference on the total profit of the manufacturer and the retailer, we set the interval of the customers' low-carbon

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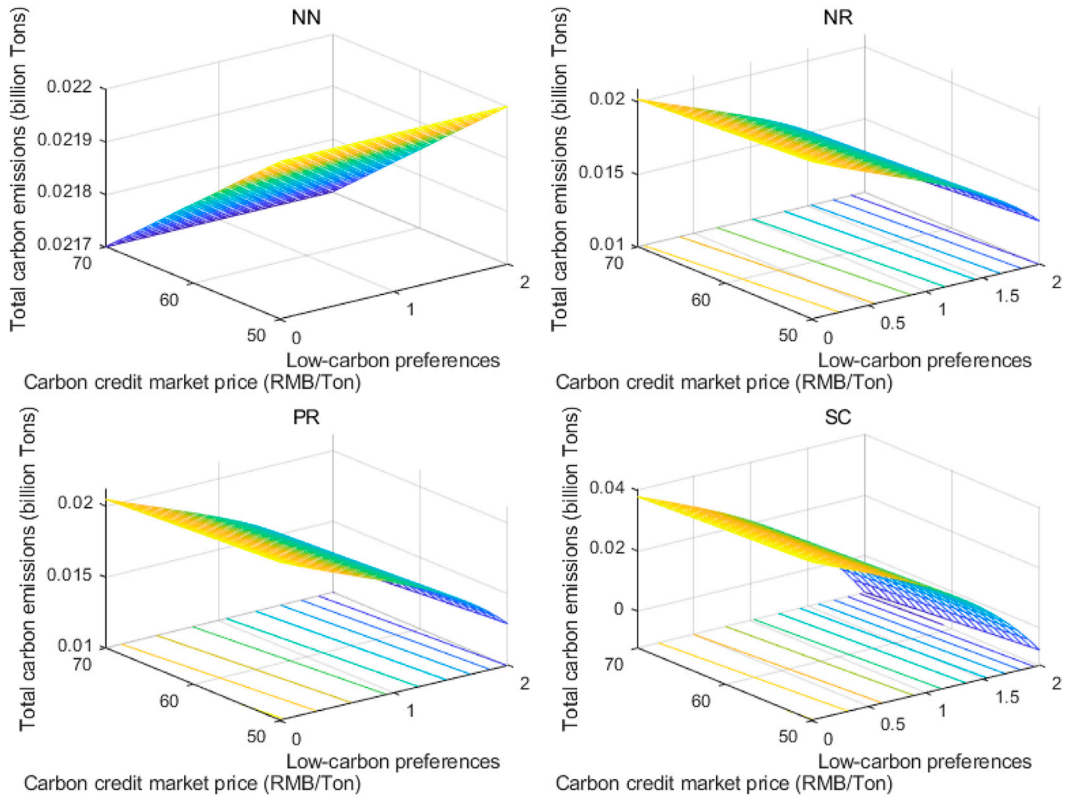

FIGURE 10
Total carbon emissions responses to customers' low-carbon preference and carbon trading price.

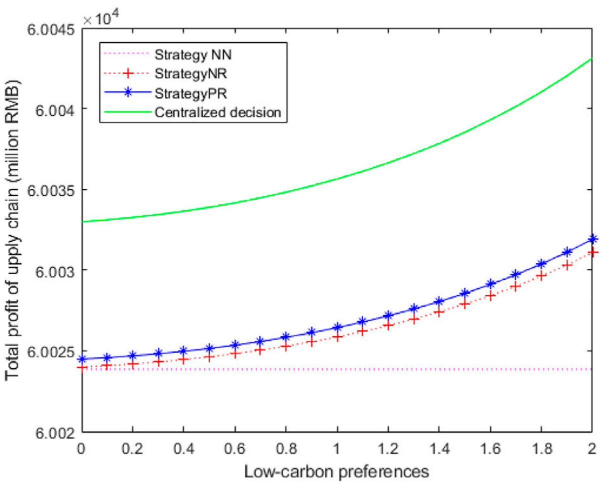

FIGURE 11
Profits of supply chain responses to customers' low-carbon preference.

preference as [0, 2] with an interval of 0.1. Figure 11 shows that within a limited range, the overall profit of the supply chain increases as consumers' low-carbon preference increases, and the profit of the supply chain under centralized decision-making is always higher than that under decentralized decision-making.

Under decentralized decision-making, if the manufacturer does not invest in reducing carbon emissions, there will be no low-carbon products in the market. Then, consumers' low-carbon preference has no impact on the supply chain profits of the strategy combination NN and strategy combination PN. As consumers become more environmentally aware and become willing to pay more for low-carbon products, market demand is most affected by customers' low-carbon preferences. If the retail price per unit of a product increases within a reasonable range, consumers will also be willing to buy. It is easy to find that when the retail price per unit of a product no longer dominates the consumers' buying behavior, the market will be similar to the auction market. That is, as long as consumers like low-carbon products, the products will not be unsalable, which is very friendly to the manufacturer and retailer. The profit of the supply chain will increase unabated. However, in real life, on one hand, low-carbon products do not occupy the entire market. On the other hand, consumers tend to consume rationally. So, to buy products with the highest cost performance, consumers will have to

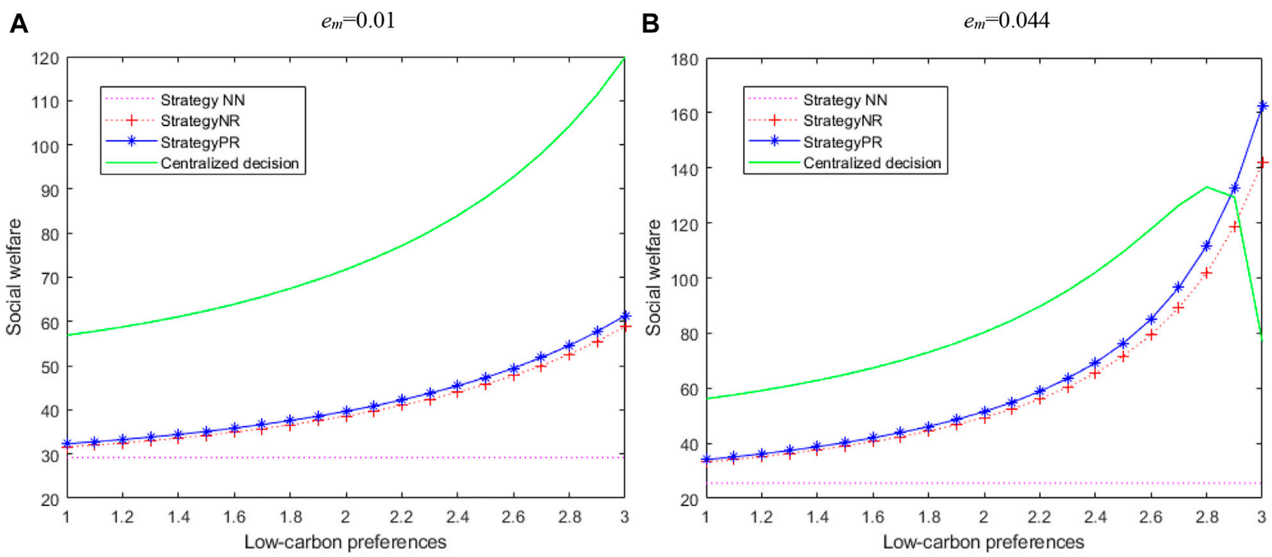

FIGURE 12
Social welfare responses to customers' low-carbon preference.

trade-off between the retail price and emissions reduction level.

Without considering externalities, social welfare is the sum of producer surplus and consumer surplus (Tang and Du, 2019). The social welfare in this study can be expressed by Equation 17:

$$S = \int_0^{q^*} \left(\frac{a - x + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) dx - \frac{1}{2} h_m \tau_m^2 - \frac{1}{2} h_r \tau_r^2 \tag{14}$$

We can rewrite social welfare as

$$S = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q^* - \frac{q^{*2}}{2b} - \frac{1}{2} h_m \tau_m^2 - \frac{1}{2} h_r \tau_r^2 \tag{15}$$

Then, the social welfare of each strategy is as follows:

$$S_{NN} = S_{PN} = \left(\frac{a}{b} - c_m - c_r \right) q_{NN}^* - \frac{(q_{NN}^*)^2}{2b} \tag{16}$$

$$S_{NR} = \left(\frac{a + \gamma\tau_m}{b} - c_m - c_r \right) q_{NR}^* - \frac{(q_{NR}^*)^2}{2b} - \frac{1}{2} h_m \tau_m^2 \tag{17}$$

$$S_{PR} = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q_{PR}^* - \frac{(q_{PR}^*)^2}{2b} - \frac{1}{2} h_m \tau_m^2 - \frac{1}{2} h_r \tau_r^2, \text{ and} \tag{18}$$

$$S_{SC} = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q_{SC}^* - \frac{(q_{SC}^*)^2}{2b} - \frac{1}{2} h_m \tau_m^2 - \frac{1}{2} h_r \tau_r^2 \tag{19}$$

The influence of customers' low-carbon preference on social welfare is shown in Figure 12.

Figure 12A shows that when the initial carbon emissions of a product are 0.01, that is the level of emissions reduction is high, the social welfare under centralized decision-making is always higher than that under decentralized decision-making. As long as the manufacturer and retailer adopt sustainable strategies, it is good for society and the environment, However, Figure 12B shows that when the level of emissions reduction is low (em = 0.044) and customers' low-carbon preference continues to increase beyond 2.8, the social welfare under centralized decision-making declines rapidly. This is because, although consumers are willing to pay more for low-carbon products, consumer surplus decreases as purchase cost increases. The figure shows that as consumers' low carbon preference increases, the profits of the supply chain will increase accordingly, but this increased profit comes at the expense of consumer surplus. Therefore, if the profits of the manufacturer and retailer increase based on the remaining consumer surplus unchanged or slightly increased, the social welfare will be Pareto-improved. That is, while reducing production costs or raising retail prices, the manufacturer and retailer can increase consumer utility by the same amount by investing in carbon emissions reduction or promoting low-carbon products.

These observations offer the following management insights for policy-makers and entities in low-carbon products who promote and produce.

1) When the consumers' low-carbon preference coefficient is low, the manufacturer can single-handedly minimize the total carbon emissions of the supply chain by adopting low-carbon technology. At the same time, the retailer can take a free ride.

2) When the carbon price and consumers' low-carbon preference are high enough, the optimal retail price will always be higher than that of ordinary products. Each stakeholder can make decisions to maximize self-profits. However, it inevitably brings about a double-marginal effect and affects the total profits of the supply chain in any collaboration mode under a decentralized scenario.
3) To obtain the highest total profits and lowest carbon emissions, the manufacturer and retailer can centrally make the strategic decisions of emissions reduction and promotion decisions. But the social welfare declines rapidly because it is affected by the initial carbon emissions per unit of a product and the carbon trading price of the CAT mechanism.
4) To keep social welfare from being reduced, retailers can appropriately lower the retail price, or stakeholders can save the cost of investing in reducing carbon emissions and promoting low-carbon products. Social welfare will increase when the level of emissions reduction in society is high enough, which requires all manufacturers to make efforts to adopt low-carbon technology. At the same time, retailers and customers need to be environmentally friendly.

In brief, under the CAT mechanism, manufacturers and retailers need to adjust their strategic decisions of emissions reduction and promotion at any time according to the initial carbon emissions of a product and different consumers to balance the trade-off between social and environmental benefits of the retailer-led supply chain.

Conclusion

Governments, enterprises, and customers pay more attention to protecting the environment, such as manufacturers investing in low-carbon technologies, retailers making efforts to promote low-carbon products, and consumers having low-carbon preferences. Specifically, among other strategies, CAT has reduced carbon emissions effectively. Considering CAT and consumer environmental preferences, we developed a Stackelberg game model that characterizes gaming and cooperative behaviors of the manufacturer and retailer. The equilibrium solutions under each strategy combination in a decentralized decision-making mode have been solved. The key findings are summarized in the following terms. 1) It is the most economical and environmentally friendly when the manufacturer makes efforts to reduce emissions and the retailer invests in promoting low-carbon products. 2) Sensitivity experiments showed that the CAT mechanism, emissions reduction level, the promotional effort level, and the customers' environmental preferences could influence the optimal solutions of the manufacturer and retailer in the decentralized decision-making mode and cooperative mode. 3) The manufacturer is willing to invest in reducing emissions when the carbon trading prices are high. However, the emissions reduction level does not always increase with carbon trading prices unless the allocation of carbon credits is sufficient. 4) When the customers' low-carbon preference coefficient is large enough, the total carbon emissions are highest when the manufacturer and retailer make decisions together, and the social welfare of the centralized decision-making mode is lower than that of a decentralized decision-making mode when the retailer takes a promotion strategy and the manufacturer takes an emissions reduction strategy. These findings can be useful for both the government and stakeholders in the supply chain.

There are several interesting extensions to this work. We assume that: 1) the levels of emissions reduction and promotion efforts are the same for all low-carbon products, 2) stakeholders are perfectly rational, and 3) markets and CAT have not changed over time. Then, more actual models can be developed to understand the stakeholders' behavior and predict the market trend. Second, in a real market, the supply chain, consisting of multiple stakeholders, the coordination, and profit-sharing mechanism of the supply chain network based on a multi-agent game, needs further research. Finally, we only considered one carbon emissions policy. Other nuanced models could be constructed to identify how stakeholders make better long-term decisions under complex policies to reduce carbon emissions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, WT and HL; methodology, software, and formal analysis, WT; data curation, JD; writing—original draft preparation, WT; writing—review and editing, HL and JD; supervision, HL; funding acquisition, HL. All authors have read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer LX declared a shared affiliation with the author WT to the handling editor at the time of review.

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Appendix A: For ease of reference, Equation (x) in the article is referred to as (E.x) in this appendix

Proof of Proposition 5

From our previous research (Tong and Mu, 2019), we can get the optimal carbon emissions reduction under strategy NR is $(\tau_m^{NR})^* = \frac{(1+p_e)(a-p_e)}{4h_m-2(1+p_e)^2}$. Then, the first partial derivative of $(\tau_m^{NR})^*$ with respect to p_e is shown as follows: $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} = \frac{(1+a)p_e^2+[2(1+a)-4h_m]p_e+2h_m(a-1)+a+1}{2[(1+p_e)^2-2h_m]^2}$. Let $y_1 = (1+a)p_e^2 + [2(1+a)-4h_m]p_e + 2h_m(a-1)+a+1$, where $(1+a)>0$.

When $h_m < \frac{(a+1)^2}{2}$, then $\Delta = 8h_m[2h_m-(a+1)^2] < 0$. The quadratic curve $y_1(p_e)$ has no roots, which implies that there is always $y_1 > 0$. We can easily find that $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$.

When $h_m > \frac{(a+1)^2}{2}$, then y_1 has two roots $(p_{e_1}^-, 0)$ and $(p_{e_1}^+, 0)$, that is $(\frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, 0)$ and $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, 0)$. This implies that in the interval $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1})$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$. In other intervals it is opposite.

Q.E.D.

Proof of Proposition 6

From our previous research (Tong and Mu, 2019), we can get the optimal carbon emissions reduction under strategy PR, which is $(\tau_m^{PR})^* = \frac{h_r(1+p_e)(a-p_e)}{2h_r[2h_m-(1+p_e)^2]-h_m}$. Then, the first partial derivative of emissions reduction level with respect to p_e under strategy PR is shown as follows:

$$\frac{\partial(\tau_m^{PR})^*}{\partial p_e} = \frac{2(1+a)h_r p_e^2 + [-2h_m(4h_r-1)+4(a+1)h_r]p_e + h_m(a-1)(4h_r-1)+2h_r(a+1)}{\frac{[h_m(4h_r-1)-2h_r(1+p_e)^2]^2}{h_r}}$$

Let $y_2 = 2(1+a)h_r p_e^2 + [-2h_m(4h_r-1)+4(a+1)h_r]p_e + h_m(a-1)(4h_r-1)+2h_r(a+1)$. Note that we do not consider $4h_r - 1 < 0$ because the promotion cost coefficient is always greater than 1.

When $h_m < \frac{2h_r(a+1)^2}{4h_r-1}$, then $\Delta = h_m(4h_r-1)[-2h_r(1+a)^2 + h_m(4h_r-1)] < 0$. There always exists $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} > 0$.

When $h_m < \frac{2h_r(a+1)^2}{4h_r-1}$, then $\Delta = h_m(4h_r-1)[-2h_r(1+a)^2 + h_m(4h_r-1)] > 0$. y_2 also has two roots $(p_{e_2}^-, 0)$ and $(p_{e_2}^+, 0)$. In the interval $(\frac{-[h_m(1-4h_r)+2h_r(a+1)] - \sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)}, \frac{-[h_m(1-4h_r)+2h_r(a+1)]+\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)})$, we can get $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} < 0$ and in other intervals it is the opposite.