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# Emission Reduction Strategies of a Low-Carbon Supply Chain Considering Product Substitution and Government Subsidy

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Under the background of the low-carbon economy, considering that manufacturers produce common products and low-carbon products simultaneously and the two products are substituting, three models are set up, namely, no government subsidy, subsidy based on the research and development (R&D) cost, and subsidy based on the production volume of low-carbon products. The Stackelberg game theory is used to analyze the optimal decision of the supply chain under the three methods of government subsidy, the influence of the correlation coefficient on optimal decision-making is discussed, and the effects of different government subsidy methods on the equilibrium solutions are compared and analyzed. Finally, the results are verified and illustrated by example analysis. The study found that the government subsidy reduces the sales volume of common products but increases the sales volume of low-carbon products, the emission reduction of unit low-carbon products, total emission reductions, and manufacturer's profit. The unit emission reduction and total emission reductions are the highest when the government subsidies are according to the R&D cost, and the manufacturer's profit is the highest when the government subsidies are according to the production volume of low-carbon products. Total emission reduction and supply members' profit have a positive relationship with the subsidy coefficient and the sensitivity of consumers toward price difference and have a negative relationship with the R&D cost coefficient.

**Keywords: low-carbon supply chain, emission reduction, product substitution, government subsidy methods, Stackelberg game theory**

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## 1 INTRODUCTION

In recent years, as the international community pays attention to the environmental pollution caused by economic development, green development has gradually become the general consensus of all countries (He et al., 2019). Research shows that factors such as trade openness, urbanization, and energy use are important reasons for the increase in global carbon emissions (Sun et al., 2020), and a low-carbon supply chain management model that considers resource consumption and environmental impact emerges as the times require. At the same time, with the development of a low-carbon economy and the improvement of consumer environmental awareness (CEA), low-carbon products are increasingly favored by consumers. The production of low-carbon products by core enterprises in the supply chain can not only enhance their public image but also gain market competitive advantages (Wen et al., 2018). Therefore, in order to maintain the original production advantages and adapt to the low-carbon economy, some companies have begun to produce common products and low-carbon products simultaneously. For example, Toyota Motor Corporation produces both fuel vehicles and new energy vehicles, and Foshan Lighting produces both incandescent lamps and energy-saving lamps. Common products and low-carbon products have the same function but have different levels of emission reduction, so they are substitutable. However, producing low-carbon products requires emission reduction R&D, which will occupy the funds of enterprises' production activities, resulting in low enthusiasm for enterprises to reduce carbon emissions. In order to guide the green production of enterprises and improve their motivation, the government has adopted a series of policies, such as carbon trading (Liu et al., 2021), carbon tax (Mishra et al., 2021), and subsidies. Among them, government subsidy is one of the policies that have been applied earlier, especially in the promotional stage of low-carbon products. But the government has a variety of subsidy methods, and the effects of different subsidy methods are also different. For the government, in order to more effectively incentivize manufacturers to produce more low-carbon products with higher emission reductions, it is an important issue to analyze the impact of different subsidy methods on the low-carbon supply chain, which will also help the government to formulate subsidy methods.

Therefore, considering that manufacturers produce common products and low-carbon products simultaneously and the two products are substitutable, this study further analyzes the impact of different government subsidy methods on the low-carbon supply chain. The supply chain problems to be solved in this study are as follows: 1) what is the impact of different government subsidy methods on the equilibrium decision of supply chain members? 2) How can the government subsidize manufacturers to encourage consumers to buy low-carbon products, increase the production volume of low-carbon products, manufacturers' total emission reductions and manufacturers' enthusiasm for green production, and maximize social welfare? 3) What is the impact of changes in the sensitivity of consumers toward price difference, the R&D cost coefficient, and the subsidy coefficient on the equilibrium decisions of supply chain members?

In order to solve the aforementioned problems, this study compares three decision-making scenarios: no government subsidy (N), subsidy based on the R&D cost (C), and subsidy based on the production volume of low-carbon products (D). First, the optimal decision-making of supply chain members in each scenario is solved, and the sensitivity analysis of the equilibrium solution is carried out. Finally, an example analysis is given. Our study will provide a scientific basis for the government to formulate subsidy methods and for enterprises to make emission reduction and production decisions.

## 2 LITERATURE REVIEW

This study mainly involves two aspects of research, namely, product substitution and different methods of government subsidy, and some research studies related to these two parts will be discussed in the following paragraphs.

The research on the production of mixed products by enterprises is mainly divided into three aspects: the impact of product substitution on supply chain members, product pricing, and supply chain coordination. First, regarding the impact of product substitution on supply chain members, some scholars have found that product substitution promotes green innovation of manufacturers, achieves a win–win situation for manufacturers and retailers, and can reduce environmental damage and increase social welfare (Cao et al., 2021). Some scholars further considered the impact of product substitution and complementarity on supply chain members and proposed bundling strategies to improve members' profits (Chen et al., 2021). Second, for manufacturers to price common products and low-carbon products, some scholars (Giri et al., 2016) considered the situation of selling two substitute products and one supplementary product in a two-tier supply chain and studied the manufacturers pricing decision. Some scholars have further considered the carbon quota trading policy (Guo et al., 2018), the manufacturer's financial constraints (Qin and Li, 2021), the heterogeneity of consumers (Liu et al., 2018), the existence of search costs (Bi and Wu, 2018), product warranty issues (Wang, 2017), and the triple competitive factors of alternative products (Han et al., 2020), and so on. Finally, aiming at the coordination problem of the mixed product supply chain, some studies have found that product return contract (Zhang et al., 2015), member collaboration (Li et al., 2019), Shapley value method (Xu et al., 2014; Wang et al., 2018), multilateral compensation wholesale price contract (Hosseini-Motlagh et al., 2018), revenue-sharing and cost-sharing contracts (Wang and Wang, 2015), and cost-sharing—both pricing mechanisms (Chen et al., 2020) can achieve supply chain coordination for the production of mixed products.

The research on different government subsidy methods is mainly divided into two aspects: different government subsidy objects and different subsidy mechanisms. First, in response to the problem of different subsidy objects, government subsidy objects mainly include manufacturers, suppliers (Meng et al., 2021), and consumers (Yang et al., 2019; Xiong et al., 2020), among which manufacturers are also divided into core manufacturers, original manufacturers, and remanufacturers (Xia and Cao, 2020). Second, in response to the different government subsidy mechanisms, some scholars have studied the impact of government fixed subsidies and discount subsidies on the decision-making of supply chain members when the government subsidizes consumers (Zhang et al., 2018; Hai and Li, 2021). The impact of cost, product greenness, and product production cost subsidies on the green supply chain has been studied (Wen et al., 2018). Research shows that reasonable government subsidy is beneficial to incentivize manufacturers to improve green production levels and enhances the economic benefits of supply chain members (Feng et al., 2022).

## 3 THE MODEL

### 3.1 Problem Description and Model Assumptions

This study considers a secondary low-carbon supply chain consisting of a single manufacturer and a single retailer,

**TABLE 1** | Parameter symbols and their meanings.

| Parameter | Meaning |
|---|---|
| $i$ | Types of two products, $i = 1, 2$ represent common products and low-carbon products, respectively |
| $j$ | Methods of government subsidy, $j = N, C, D$ represent no government subsidy, government subsidy based on the R&D cost, and subsidy based on the production of low-carbon products, respectively |
| $w_i^j$ | The wholesale price of unit product $i$ in case $j$ |
| $p_i^j$ | The retail price of unit product $i$ in case $j$ |
| $q_i^j$ | Production or sales volume of product $i$ in case $j$ |
| $e^j$ | The emission reduction of unit low-carbon product in case $j$ |
| $E^j$ | Total emission reductions of the manufacture in case $j$, and $E^j = e^j q_2^j$ |
| $k$ | R&D cost coefficient |
| $v$ | R&D subsidy coefficient |
| $\lambda$ | Production volume subsidy coefficient |
| $a$ | Initial market potential |
| $\tau$ | Consumer environmental awareness (CEA) |
| $\theta$ | The sensitivity of consumers toward price difference$0 < \theta < 1$ |
| $CS^j$ | Consumer surplus |
| $\phi$ | The total government subsidy spending |
| $\pi_m^j, \pi_r^j$ | Profits of the manufacturer and retailer in case $j$, respectively |
| $\pi_g^j$ | Social benefits in case $j$ |

where the manufacturer produces both common and low-carbon products, and the retailer sells both products. Since, the manufacturer's R&D cost of emission reduction is relatively high, in order to encourage the manufacturer to reduce emissions, this study further considers the situation of the government subsidizing the manufacturer, and three models are constructed: no government subsidy (N), subsidy based on emission reduction R&D cost (C), and subsidy based on the production volume of low-carbon products (D). The relevant parameters involved in this study are shown in **Table 1**.

## 3.2 Model Basic Assumptions

On the premise of not changing the essence of the problem, the following assumptions are made on the model:

**Assumption 1:** Consider a two-stage supply chain consisting of a single manufacturer and a single retailer. The Stackelberg game is formed between the manufacturer and the retailer. The manufacturer is the leader of the game, and the retailer is the follower of the game. In the first stage of the game, the manufacturer decides the wholesale price of common products and low-carbon products and the emission reduction of unit low-carbon product. In the second stage, the retailer decides the retail price of the two products based on the manufacturer's decision.

**Assumption 2:** Common products and low-carbon products are substitutable, and $\theta$ and $\tau$ are the sensitivity of consumers to influence product demand and are the same in both products. In addition, this study assumes that when the two product types have the same specifications, the initial market potential of the two types of products is the same, and many literatures have also made the same assumption (Liu et al., 2012; Zhang et al., 2015). Therefore, the demand functions for ordinary products and low-carbon products are:

$$q_1^j = a - p_1^j + \theta\left(p_2^j - p_1^j\right) - \theta\tau e^j,$$
$$q_2^j = a - p_2^j + \theta\left(p_1^j - p_2^j\right) + (1+\theta)\tau e^j.$$

In addition, we do not consider the problem of random demand and assume that the market can be completely cleared, that is, the production volume of products is equal to the sales volume of products.

**Assumption 3:** According to the standard assumption of the classic model (the emission reduction and the R&D cost have a quadratic relationship) (Nielsen et al., 2019), therefore, the manufacturer's R&D cost of emission reduction is $\frac{1}{2}ke^{j2}$, which is a one-time investment and is borne by the manufacturer.

**Assumption 4:** Manufacturers need to pay extra R&D cost to produce low-carbon products, so in order to encourage manufacturers to produce low-carbon products, the government provides subsidies to manufacturers, and the total government subsidy spending is $\phi$. This study considers two different subsidy methods: one is that the subsidy based on the R&D cost, and the total government subsidy spending is $\phi = \lambda q_2^D$; the other is that the subsidy based on the production volume of low-carbon products, and the total government subsidy spending is $\phi = \lambda q_2^D$. Therefore, the social welfare function is (Chen and Wang, 2022): $\pi_g^j = \pi_m^j + \pi_r^j - \phi + CS^j$, among them, consumer surplus is the difference between the total amount consumers are willing to pay for the commodity and the total amount actually paid. According to the demand function of the two products, it can be known that: $CS = \frac{q_1^{j2} + q_2^{j2}}{2(1+\theta)}$.

**Assumption 5:** Considering that the R&D cost coefficient is high, at the same time, all profit objective functions discussed in this study are concave functions of decision variables, we assume that $4k - (1+\theta)\tau^2 > 0$ and $4k(1-v) - (1+\theta)\tau^2 > 0$.

## 3.3 Model Establishment and Solution

According to different government subsidy methods, the Stackelberg game model is established under no government subsidy (N), subsidy based on the R&D cost (C), and subsidy based on the

**TABLE 2** | Part of the corresponding value of the subsidy coefficient under the two government subsidy methods.

| Subsidy coefficient | Corresponding values of $\lambda$ and v | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $v$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
| $\lambda$ | 0.34 | 0.87 | 1.73 | 3.2 | 5.88 | 11.24 | 23.61 | 61.56 |

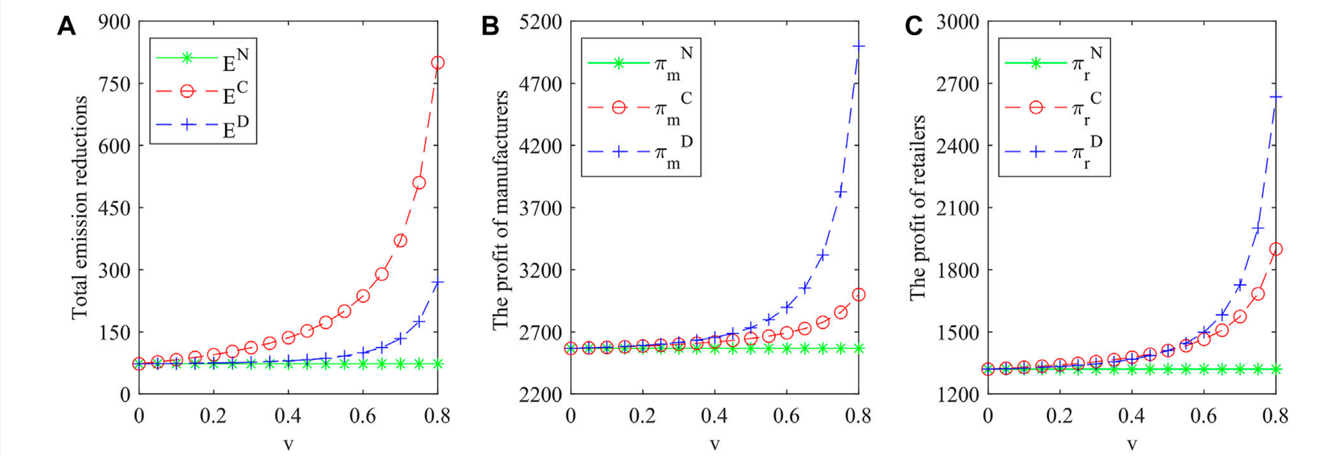


**FIGURE 1 |** Impact of different government subsidy methods on $E^j$, $\pi_m^j$, and $\pi_r^j$. **(A)** Impact of different government subsidy methods on total emission reductions. **(B)** Impact of different government subsidy methods on manufacturers' profits. **(C)** Impact of different government subsidy methods on retailers' profits.

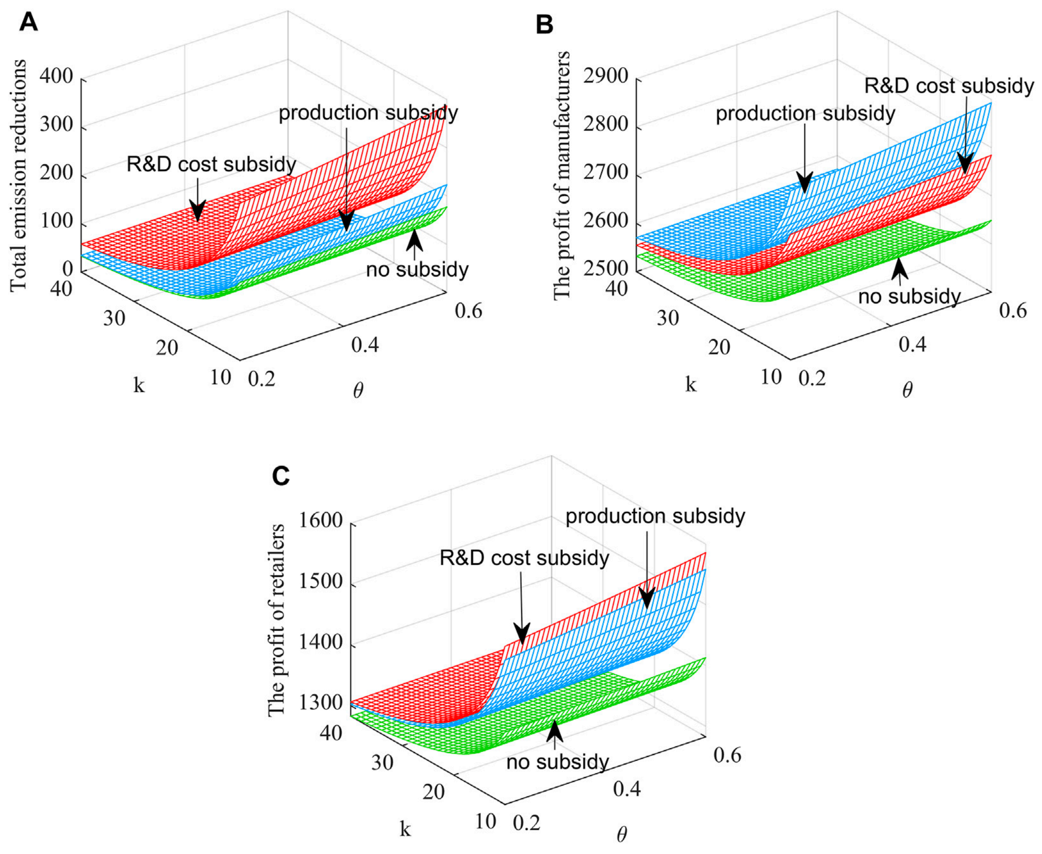


**FIGURE 2 |** Effect of parameters $\theta$ and $k$ on $E^j$, $\pi_m^j$, and $\pi_r^j$. **(A)** Effect of parameters $\theta$ and $k$ on total emission reductions. **(B)** Effect of parameters $\theta$ and $k$ on manufacturers' profits. **(C)** Effect of parameters $\theta$ and $k$ on retailers' profits.

production volume of low-carbon products (D), respectively, to study the effect of different government subsidy methods on the balanced decision-making of manufacturers and retailers.

### 3.3.1 No Government Subsidy (N)

In order to analyze the effects of government subsidy and different subsidy methods, first, the results in the case of no government subsidy are given as the lower-line benchmark for the comparison of the effects of different government subsidy methods. The profits of manufacturers and retailers with no government subsidy are:

$$\pi_m^N = w_1 q_1 + w_2 q_2 - \frac{1}{2} k \triangle e^2, \pi_r^N = (p_1 - w_1) q_1 + (p_2 - w_2) q_2.$$

When $4k - (1+\theta)\tau^2 > 0$, the optimal value with no government subsidy is:

$$w_1^N = \frac{a}{2},\ w_2^N = \frac{a(4k - \theta\tau^2)}{2[4k - (1+\theta)\tau^2]},\ e^N = \frac{a\tau}{4\varepsilon - (1+\theta)\tau^2},$$
$$p_1^N = \frac{3a}{4},\ p_2^N = \frac{3a(4k - \theta\tau^2)}{4[4k - (1+\theta)\tau^2]},$$
$$q_1^N = \frac{a[4k - (1+2\theta)\tau^2]}{4[4k - (1+\theta)\tau^2]},\ q_2^N = \frac{ak}{4k - (1+\theta)\tau^2},$$
$$\pi_m^N = \frac{a^2[8k - (1+2\theta)\tau^2]}{8[4k - (1+\theta)\tau^2]},$$
$$\pi_r^N = \frac{a^2\{8k[4k - (1+2\theta)\tau^2] + (1+\theta)(1+2\theta)\tau^4\}}{16[4k - (1+\theta)\tau^2]^2}.$$

Detailed derivations for optimal decision in Scenarios N are presented in **Supplementary Appendix SA**.

Conclusion 1: When with no government subsidy, the impact of the sensitivity of consumers toward price difference on equilibrium solutions is: $\frac{\partial w_1^N}{\partial \theta} = 0$, $\frac{\partial w_2^N}{\partial \theta} > 0$, $\frac{\partial p_1^N}{\partial \theta} = 0$, $\frac{\partial p_2^N}{\partial \theta} > 0$, $\frac{\partial e^N}{\partial \theta} > 0$, $\frac{\partial q_1^N}{\partial \theta} < 0$, $\frac{\partial q_2^N}{\partial \theta} > 0$, $\frac{\partial \pi_m^N}{\partial \theta} > 0$, and $\frac{\partial \pi_r^N}{\partial \theta} > 0$. The impact of the R&D cost coefficient on equilibrium solutions is: $\frac{\partial w_1^N}{\partial k} = 0$, $\frac{\partial w_2^N}{\partial k} < 0$, $\frac{\partial p_1^N}{\partial k} = 0$, $\frac{\partial p_2^N}{\partial k} < 0$, $\frac{\partial e^N}{\partial k} < 0$, $\frac{\partial q_1^N}{\partial k} > 0$, $\frac{\partial q_2^N}{\partial k} < 0$, $\frac{\partial \pi_m^N}{\partial k} < 0$, and $\frac{\partial \pi_r^N}{\partial k} < 0$.

Conclusion 1 shows that when with no government subsidy the wholesale price and retail price of common products are only related to the initial market potential of two products and have nothing to do with the sensitivity of consumers toward price difference and the R&D cost coefficient. With the increase of the sensitivity of consumers toward price difference and the decrease of the R&D cost coefficient, the production volume of common products will decrease, while the wholesale price, retail price, unit emission reduction, the production volume of low-carbon products, and supply chain members' profits will increase. Proof: see **Supplementary Appendix SB**.

### 3.3.2 Subsidy Based on the R&D Cost (C)

When the government subsidizes the manufacturer based on the R&D cost, according to the aforementioned assumption, the profits of the manufacturer and the retailer are:

$$\pi_m^C = w_1 q_1 + w_2 q_2 - \frac{1}{2} k (1 - \nu) \triangle e^2,$$
$$\pi_r^C = (p_1 - w_1) q_1 + (p_2 - w_2) q_2.$$

When $4k(1-\nu) - (1+\theta)\tau^2 > 0$, using the same solution as mentioned previously, the optimal value under subsidy based on the R&D cost can be obtained as follows:

$$w_1^C = \frac{a}{2},\ w_2^C = \frac{a[4k(1-\nu) - \theta\tau^2]}{2[4k(1-\nu) - (1+\theta)\tau^2]},$$
$$e^C = \frac{a\tau}{4k(1-\nu) - (1+\theta)\tau^2},$$
$$p_1^C = \frac{3a}{4},\ p_2^C = \frac{3a[4k(1-\nu) - \theta\tau^2]}{4[4k(1-\nu) - (1+\theta)\tau^2]},$$
$$q_1^C = \frac{a[4(1-\nu) - (1+2\theta)\tau^2]}{4[4(1-\nu) - (1+\theta)\tau^2]},\ q_2^C = \frac{ak(1-\nu)}{4k(1-\nu) - (1+\theta)\tau^2},$$
$$\pi_m^C = \frac{a^2[8k(1-\nu) - (1+2\theta)\tau^2]}{8[4k(1-\nu) - (1+\theta)\tau^2]},$$
$$\pi_r^C = \frac{a^2[4k(1-\nu) - (1+2\theta)\tau^2]}{16[4k(1-\nu) - (1+\theta)\tau^2]} + \frac{a^2 k(1-\nu)[4k(1-\nu) - \theta\tau^2]}{4[4k(1-\nu) - (1+\theta)\tau^2]^2}.$$

When $\nu^C = \frac{4k(9+8\theta) - \theta(11+10\theta)\tau^2}{4k(13+12\theta)}$, social welfare, $\pi_g^C$, obtains a maximum value, that is, $\pi_g^C = \frac{a^2(12\theta+13)[32k(1+\theta) - (4\theta^2+16\theta+13)\tau^2]}{32(1+\theta)[16k(1+\theta) - (2\theta^2+14\theta+13)\tau^2]}$.

Proof: see **Supplementary Appendix SC**.

Conclusion 2: When the government subsidizes based on the R&D cost, the impact of the sensitivity of consumers toward price difference on equilibrium solutions is: $\frac{\partial w_1^N}{\partial \theta} = 0$, $\frac{\partial w_2^N}{\partial \theta} > 0$, $\frac{\partial p_1^N}{\partial \theta} = 0$, $\frac{\partial p_2^N}{\partial \theta} > 0$, $\frac{\partial e^N}{\partial \theta} > 0$, $\frac{\partial q_1^N}{\partial \theta} < 0$, $\frac{\partial q_2^N}{\partial \theta} > 0$, $\frac{\partial \pi_m^N}{\partial \theta} > 0$, and $\frac{\partial \pi_r^N}{\partial \theta} > 0$. The impact of the R&D cost coefficient on equilibrium solutions is: $\frac{\partial w_1^N}{\partial k} = 0$, $\frac{\partial w_2^N}{\partial k} < 0$, $\frac{\partial p_1^N}{\partial k} = 0$, $\frac{\partial p_2^N}{\partial k} < 0$, $\frac{\partial e^N}{\partial k} < 0$, $\frac{\partial q_1^N}{\partial k} > 0$, $\frac{\partial q_2^N}{\partial k} < 0$, $\frac{\partial \pi_m^N}{\partial k} < 0$, and $\frac{\partial \pi_r^N}{\partial k} < 0$. The impact of the R&D subsidy coefficient on equilibrium solutions is: $\frac{\partial w_1^C}{\partial \nu} = 0$, $\frac{\partial w_2^C}{\partial \nu} > 0$, $\frac{\partial p_1^C}{\partial \nu} = 0$, $\frac{\partial p_2^C}{\partial \nu} > 0$, $\frac{\partial e^C}{\partial \nu} > 0$, $\frac{\partial q_1^C}{\partial \nu} < 0$, $\frac{\partial q_2^C}{\partial \nu} > 0$, $\frac{\partial \pi_m^C}{\partial \nu} > 0$, and $\frac{\partial \pi_r^C}{\partial \nu} > 0$.

Conclusion 2 shows that when the government subsidizes based on the R&D cost the wholesale price and retail price of common products are only related to the initial market potential of two products and have nothing to do with the sensitivity of consumers toward price difference and the R&D cost coefficient. With the increase of the sensitivity of consumers toward price difference and with the increase of the R&D subsidy coefficient, the production volume of common products will decrease, while the wholesale price, retail price, unit emission reduction, the production volume of low-carbon products, and supply chain members' profits will increase.

### 3.3.3 Subsidy Based on the Production Volume of Low-Carbon Products (D)

When the government subsidizes the manufacturer based on the production volume of low-carbon products, the profits of the manufacturer and the retailer are:

$$\pi_m^D = w_1 q_1 + (w_2 + \lambda) q_2 - \frac{1}{2} k \triangle e^2,$$
$$\pi_r^D = (p_1 - w_1) q_1 + (p_2 - w_2) q_2.$$

When $4k - (1+\theta)\tau^2 > 0$, using the same solution as mentioned previously, the optimal value under subsidy based on the production volume of low-carbon products can be obtained as follows:

$$w_1^D = \frac{a}{2},\ w_2^D = \frac{4k(a-\lambda) - \tau^2[a\theta - 2\lambda(1+\theta)]}{2[4k - (1+\theta)\tau^2]},$$
$$e^D = \frac{\tau[a + \lambda(1+\theta)]}{4k - (1+\theta)\tau^2},$$
$$p_1^D = \frac{3a}{4},\ p_2^D = \frac{4k(3a-\lambda) - \tau^2[3a\theta - 4\lambda(1+\theta)]}{4[4k - (1+\theta)\tau^2]},$$
$$q_1^D = \frac{4k(a-\lambda\theta) - a(1+2\theta)\tau^2}{4[4k - (1+\theta)\tau^2]},\ q_2^D = \frac{k[a+\lambda(1+\theta)]}{4k - (1+\theta)\tau^2},$$
$$\pi_m^D = \frac{a^2[8k - (1+2\theta)\tau^2] + 4k\lambda[2a + \lambda(1+\theta)]}{8[4k - (1+\theta)\tau^2]},$$
$$\pi_r^D = \frac{a^2[4k(a-\lambda\theta) - a(1+2\theta)\tau^2]}{16[4k - (1+\theta)\tau^2]} + \frac{4k(a+\lambda) - a\theta\tau^2}{4[4k - (1+\theta)\tau^2]}.$$

When $\lambda^D = \frac{4ak^2(7+8\theta) - ak\tau^2(26\theta^2+41\theta+16) + 5a\theta(1+\theta)^2\tau^4}{4k[k(2\theta^2+6\theta+5) - (\theta^3+9\theta^2+15\theta+7)\tau^2] + 8(1+\theta)^3\tau^4}$, social welfare, $\pi_g^D$, obtains a maximum value, that is,

$$\pi_g^D = \frac{a^2\left[k^2(48\theta^3 + 132\theta^2 + 164\theta + 81) - k\tau^2(24\theta^4 + 160\theta^3 + 386\theta^2 + 373\theta + 123) + (23\theta^4 + 102\theta^3 + 159\theta^2 + 106\theta + 26)\tau^4\right]}{32(1+\theta)\left[k^2(2\theta^2 + 6\theta + 5) - k(\theta^3 + 9\theta^2 + 15\theta + 7)\tau^2 + 2(1+\theta)^3\tau^4\right]}.$$

Proof: see **Supplementary Appendix SC**.

Conclusion 3: When the government subsidizes based on the production volume of low-carbon products, the impact of the sensitivity of consumers toward price difference on equilibrium solutions is: $\frac{\partial w_1^D}{\partial\theta} = 0$, $\frac{\partial w_2^D}{\partial\theta} > 0$, $\frac{\partial p_1^D}{\partial\theta} = 0$, $\frac{\partial p_2^D}{\partial\theta} > 0$, $\frac{\partial e^D}{\partial\theta} > 0$, $\frac{\partial q_1^D}{\partial\theta} < 0$, $\frac{\partial q_2^D}{\partial\theta} > 0$, $\frac{\partial \pi_m^D}{\partial\theta} > 0$, and $\frac{\partial \pi_r^D}{\partial\theta} > 0$. The impact of the R&D cost coefficient on equilibrium solutions is: $\frac{\partial w_1^D}{\partial k} = 0$, $\frac{\partial w_2^D}{\partial k} < 0$, $\frac{\partial p_1^D}{\partial k} = 0$, $\frac{\partial p_2^D}{\partial k} < 0$, $\frac{\partial e^D}{\partial k} < 0$, $\frac{\partial q_1^D}{\partial k} > 0$, $\frac{\partial q_2^D}{\partial k} < 0$, $\frac{\partial \pi_m^D}{\partial k} < 0$, and $\frac{\partial \pi_r^D}{\partial k} < 0$. The impact of the production volume subsidy coefficient on equilibrium solutions is: $\frac{\partial w_1^D}{\partial\lambda} = 0$, $\frac{\partial p_1^D}{\partial\lambda} = 0$, $\frac{\partial e^D}{\partial\lambda} > 0$, $\frac{\partial q_1^D}{\partial\lambda} < 0$, $\frac{\partial q_2^D}{\partial\lambda} > 0$, $\frac{\partial \pi_m^D}{\partial\lambda} > 0$, and $\frac{\partial \pi_r^D}{\partial\lambda} > 0$. When $k > \frac{(1+\theta)\tau^2}{2}$, we have $\frac{\partial w_2^D}{\partial\lambda} < 0$, and when $\frac{(1+\theta)\tau^2}{4} < k < \frac{(1+\theta)\tau^2}{2}$, we have $\frac{\partial w_2^D}{\partial\lambda} > 0$. When $k > (1+\theta)\tau^2$, we have $\frac{\partial p_2^D}{\partial\lambda} < 0$, and when $\frac{(1+\theta)\tau^2}{4} < k < (1+\theta)\tau^2$, we have $\frac{\partial p_2^D}{\partial\lambda} > 0$.

Conclusion 3 shows that when the government subsidizes based on the production volume of low-carbon products, the wholesale price and the retail price of common products are only related to the initial market potential of two products and have nothing to do with the sensitivity of consumers toward price difference and the R&D cost coefficient. With the increase of the sensitivity of consumers toward price difference, the production volume of common products will decrease, while the wholesale price, retail price, unit emission reduction, the production volume of low-carbon products, and supply chain members' profits will increase. With the increase of the production volume subsidy coefficient, the production volume of common products will decrease, while the unit emission reduction, the production volume of low-carbon products, and supply chain members' profits will increase, and the relationship between the wholesale price and the retail price of low-carbon products and the production volume subsidy coefficient are related to the R&D cost coefficient.

# 4 COMPARATIVE ANALYSIS OF DIFFERENT GOVERNMENT SUBSIDY METHODS

In order to compare and analyze the effects of different government subsidy methods, it is first necessary to solve the comparability problem between the government subsidy based on the R&D cost and the subsidy based on the production volume of low-carbon products. Based on the same government subsidy spending, this study compares and analyzes the optimal decision-making of supply chain members under different government subsidy methods. The total government subsidy spending under two government subsidy methods is:

$$\phi^C(\nu) = \frac{k\nu a^2\tau^2}{2[4k(1-\nu) - (1+\theta)\tau^2]^2},\ \phi^D(\lambda) = \frac{\lambda k[a + \lambda(1+\theta)]}{[4k - (1+\theta)\tau^2]}.$$

When $\phi^C(\nu) = \phi^D(\lambda)$, the calculation formula $\nu$ is:

$$\nu = \frac{[4k - (1+\theta)\tau^2]\{a^2\tau^2 + 16k\lambda[a + \lambda(1+\theta)] - a\tau\sqrt{\varphi(\lambda)}\}}{64k\lambda^2[a + \lambda(1+\theta)]},$$

where $\varphi(\lambda) = \sqrt{a^2\tau^2 + 32k\lambda[a + \lambda(1+\theta)]}$.

Regarding the effect of different government subsidy methods, there are the following five propositions:

Proof: see **Supplementary Appendix SD**.

**Proposition 1:** The influence of different government subsidy methods on the wholesale price and retail price of the two products is:

(1) $w_1^N = w_1^C = w_1^D$, $p_1^N = p_1^C = p_1^D$.
(2) When $k > \frac{(1+\theta)\tau^2}{2}$, $w_2^C > w_2^N > w_2^D$, and when $\frac{(1+\theta)\tau^2}{4} < k < \frac{(1+\theta)\tau^2}{2}$, $w_2^C > w_2^D > w_2^N$.
(3) When $k > (1+\theta)\tau^2$, $p_2^C > p_2^N > p_2^D$, and when $\frac{(1+\theta)\tau^2}{4} < k < (1+\theta)\tau^2$, $p_2^C > p_2^D > p_2^N$.

Management implications: different government subsidy methods will not affect the wholesale price and retail price of common products, and government subsidies will not necessarily reduce the retail price and wholesale price of low-carbon products. When the R&D cost coefficient is relatively high, the wholesale price and retail price of low-carbon products under the subsidy based on the R&D cost are the highest, followed by the one without subsidy, and the lowest under the subsidy based on the production volume of low-carbon products. When the R&D cost coefficient is medium, the wholesale price and retail price of low-carbon products under the subsidy based on the R&D cost are the highest, followed by the subsidy based on the production volume of low-carbon products, and the non-subsidy is the lowest. Therefore, if the government wants to promote consumers to buy low-carbon products, when the R&D cost coefficient is high, it should consider subsidizing the manufacture based on its production volume of low-carbon products, and when the R&D cost coefficient is medium, the government should not subsidize the manufacture.

**Proposition 2:** The influence of different government subsidy methods on the production volume of the two products is:

(1) When $k > \frac{[a+2\lambda(1+\theta)]\tau^2}{4\lambda}$, we have $q_1^N > q_1^C > q_1^D$ and $q_2^D > q_2^C > q_2^N$.
(2) When $\frac{(1+\theta)\tau^2}{4} < k < \frac{[a+2\lambda(1+\theta)]\tau^2}{4\lambda}$, we have $q_1^N > q_1^D > q_1^C$ and $q_2^C > q_2^D > q_2^N$.

Management implications: government subsidy will reduce the production volume of common products and increase the production volume of low-carbon products. If the government wants to encourage the manufacturer to increase the production volume of low-carbon products, when the R&D cost coefficient is high, it should consider subsidizing the manufacture based on the production volume of its low-carbon products, and when the R&D cost coefficient is medium, the government should consider subsidizing the manufacture based on its R&D cost.

**Proposition 3:** The influence of different subsidy methods on the emission reduction of unit low-carbon product and total emission reductions is as follows: $e^C > e^D > e^N$, $E^C > E^D > E^N$.

Management implications: government subsidy will increase the emission reduction of unit low-carbon product and total emission reductions, and the emission reduction of unit low-carbon product and total emission reductions are in the same order. When the government wants to increase emission reductions, it should consider subsidizing the manufacturer based on its R&D costs.

**Proposition 4:** The influence of different subsidy methods on the profits of manufactures and retailers is as follows:

(1) $\pi_m^D > \pi_m^C > \pi_m^N$.
(2) When $\frac{(1+\theta)\tau^2}{4} < k < \frac{2\lambda(1+\theta)[a+\lambda(1+\theta)]\tau^2 - a^2\tau^2}{4\lambda[2a+\lambda(1+\theta)]}$, we have $\pi_r^C > \pi_r^D > \pi_r^N$, and when $k > \frac{2\lambda(1+\theta)[a+\lambda(1+\theta)]\tau^2 - a^2\tau^2}{4\lambda[2a+\lambda(1+\theta)]}$, the ordering of retailers' profits under different government methods is related to the values of parameters $k$, $a$, $\tau$, $\lambda$, and $\theta$, but there is always: $\pi_r^D > \pi_r^N$.

Management implications: when the government wants to increase the manufacturers incentive to reduce emissions, it should consider subsidizing the manufacture based on its production volume. If the government wants to increase the retailer's sales incentive, when the R&D cost coefficient is medium, it should consider subsidizing the manufacture based on its R&D cost.

**Proposition 5:** The influence of different subsidy methods on the optimal solution of social welfare is:

(1) When $k \in (0, \alpha_1) \cup (\alpha_2, \alpha_3)$ and $k > \frac{(2\theta^2+14\theta+13)\tau^2}{16(1+\theta)}$, or when $k \in (\alpha_1, \alpha_2) \cup (\alpha_3, \infty)$ and $k < \frac{(2\theta^2+14\theta+13)\tau^2}{16(1+\theta)}$, we have $\pi_g^C > \pi_g^D$.
(2) When $k \in (0, \alpha_1) \cup (\alpha_2, \alpha_3)$ and $k < \frac{(2\theta^2+14\theta+13)\tau^2}{16(1+\theta)}$, or when $k \in (\alpha_1, \alpha_2) \cup (\alpha_3, \infty)$ and $k > \frac{(2\theta^2+14\theta+13)\tau^2}{16(1+\theta)}$, we have $\pi_g^D > \pi_g^C$.

Management implications: the size of social welfare under different government subsidy methods is related to the R&D cost coefficient. If the government wants to maximize social welfare, it should make a decision according to the R&D cost coefficient.

# 5 EXAMPLE ANALYSIS

In order to illustrate the validity of the model and verify the correctness of the conclusions and propositions, this study uses MATLAB to conduct an example analysis to compare the impact of different government subsidy methods and related parameters on the total emission reduction, $E^j$, the manufacturers profit, $\pi_m^j$, and the retailers profit, $\pi_r^j$. The values of the relevant parameters in the model are: $a = 100$, $\theta = 0.5$, $\tau = 2$, $k = 20$, and the value range of $v$ is 0.1~0.9; the corresponding production volume subsidy coefficient $\lambda$ is obtained by solving the relational formula, and the partial corresponding values of $\lambda$ and $v$ are shown in **Table 2**. The effect of different government subsidy methods on $E^j$, $\pi_m^j$, and $\pi_r^j$ is compared.

**Figures 1A–C** show the effects of changes in R&D subsidy coefficients, $v$, on total emission reductions, $E^j$, manufacturers' profits, $\pi_m^j$, and retailers' profits, $\pi_r^j$, under different government subsidy methods.

It can be seen from **Figures 1A–C** that total emission reductions and profits of manufacturers and retailers are proportional to the government subsidy coefficient. It can be seen from **Figure 1A** that total emission reduction is the highest when the government subsidizes the manufacture based on its R&D cost, the second is when the government subsidizes the manufacture based on its production volume of low-carbon products, and the smallest when the subsidy is not adopted. Combined with Proposition 3, it can be seen that, when the government subsidizes the manufacture based on its R&D cost, the emission reduction of unit low-carbon products and total emission reductions are the highest. Therefore, when the government wants to increase emission reductions, it should consider subsidizing the manufacture based on its R&D costs.

It can be seen from **Figure 1B** that when the government subsidizes the manufactures according to their production volume of low-carbon products, the manufacturers' profit is the highest, followed by subsidies based on R&D costs, and the smallest when the subsidy is not adopted. Combining with **Figure 1A**, we know that in the early stage of the manufacturers emission reduction R&D, the government should subsidize the manufacturer according to its production volume of low-carbon products, thereby increasing the enthusiasm of manufacturers. Also, in the late stage of the manufacturer's emission reduction R&D, the government should subsidize the manufacture according to its R&D cost, and the total emission reduction can be maximized at this time.

It can be seen from **Figure 1C** that the retailer's profit is the lowest when the government does not subsidize the manufacturer. When $\nu < 0.5$, the retailer's profit is the highest when the government subsidizes the manufacturer according to its R&D cost, and when $\nu > 0.5$, the retailer's profit is the highest when the government subsidizes the manufacture according to its production volume of low-carbon products. Combining with Proposition 4, we know that the order of retailer's profit is related to the values of the parameters, $k$, $a$, $\tau$, $\lambda$, and $\theta$.

## 5.1 Effects of Changes on $\theta$ and k

The effects of the sensitivity of consumers toward price difference and R&D cost coefficient on manufacturers total emission reductions, manufacturers profit, and retailer's profit are shown in **Figures 2A–C**. The values of relevant parameters in the model are: $a = 100$, $\tau = 2$, and $\nu = 0.4$.

As can be seen from **Figures 2A–C**, with the increase of the sensitivity of consumers toward price difference and the decrease of the R&D cost coefficient, the total emission reductions, manufacturer's profit, and retailer's profit will increase.

Management implications: first, the increase of the sensitivity of consumers toward price differences is reflected in the improvement of CEA; therefore, the government, manufacturers, and retailers should increase the promotion of low-carbon products. Second, the R&D level of the manufacturer determines its R&D cost coefficient, and as the manufacturer's emission reduction technology matures, the R&D cost coefficient of the manufacture will decrease. In addition, the manufacturer can also consider outsourcing emission reduction production to professional emission reduction agencies, thereby reducing the cost for manufacturers to produce low-carbon products.

# 6 CONCLUSION AND MANAGEMENT IMPLICATIONS

## 6.1 Conclusion

There are many studies on product substitutability and different government subsidy methods, but little literature considers the impact of different government subsidy methods on the decision-making of mixed manufacturers. Therefore, considering that manufacturers produce common products and low-carbon products at the same time and the two products are substituted, this study constructs a game model of low-carbon supply chain decision-making under three government subsidy methods and then discusses the influence of relevant coefficient on optimal decision-making, and the optimal decision-making of supply chain members under different government subsidy methods is also compared. Through theoretical analysis and example analysis, the results show that: 1) the wholesale price and retail price of common products under different government subsidy methods remain unchanged, but the government subsidy will reduce the sales volume of common products. 2) Government subsidy will not necessarily reduce the wholesale price and retail price of low-carbon products. When the R&D cost coefficient is high, the wholesale price and retail price of low-carbon products under the subsidy based on the R&D cost subsidy are the highest and the lowest under the subsidy based on the production volume of low-carbon products, and when the R&D cost coefficient is medium, the wholesale price and retail price of low-carbon products under the subsidy based on the R&D cost subsidy are the highest and the lowest when the subsidy is not adopted. 3) Government subsidy will increase the emission reduction of unit low-carbon products, total emission reductions, and the production volume of low-carbon products. The emission reduction of unit low-carbon product and total emission reduction are the highest when the government subsidizes the manufacture according to its R&D cost subsidy. When the R&D cost coefficient is high, the production volume of low-carbon products under the subsidy based on the manufacturer's production volume is the highest, and when the R&D cost coefficient is medium, the production volume of low-carbon products under the subsidy based on the manufacturer's R&D cost is the highest. 4) Government subsidy will increase manufacturers' profit, and when the government subsidizes the manufacture according to its production volume of low-carbon products, the manufacturers profit is the largest. The size of retailers' profit and social welfare under different government subsidy methods is related to the value of these parameters, $k$, $a$, $\tau$, $\theta$, $\nu$ and $\lambda$. 5) Through example analysis, it is found that with the increase of the sensitivity of consumers toward price difference and the government subsidy coefficient, with the decrease of the R&D cost coefficient, the total emission reductions and the profits of supply chain members will increase.

## 6.2 Management Implications

Our study has the following management implications for the government and manufacturers:

The practical implications of the research results for the government are as follows: first, if the government wants to promote consumers to buy low-carbon products, when the R&D cost coefficient is high, the government should consider subsidizing the manufactures based on their production volume of low-carbon products, and when the R&D cost coefficient is medium, the government should not subsidize.

Second, if the government wants to increase the production volume of low-carbon products, when the R&D cost coefficient is high, the government should consider subsidizing the manufactures based on their production volume of low-carbon products. When the R&D cost coefficient is medium, the government should consider subsidizing the manufactures based on their R&D cost.

Third, if the government wants to increase the emission reduction of unit low-carbon products and total emission reductions, it should consider subsidizing the manufactures based on their R&D cost.

Fourth, if the government wants to increase the enthusiasm of manufacturers for emission reduction R&D, it should consider subsidizing the manufactures based on their production volume of low-carbon products.

Finally, it can be found that there is a contradiction between the government's goal of maximizing total emission reductions and the manufacturer's goal of maximizing their own profits. In order to coordinate this contradiction, in the early stage of the manufacturers emission reduction R&D, the government should subsidize the manufactures based on their production volume of low-carbon products, thereby increasing the enthusiasm of the manufacturer for emission reduction R&D, and in the late stage of the manufacturers emission reduction R&D, the government should subsidize the manufactures based on their R&D cost.

The practical implications of the research results for manufacturers are as follows: first, the sensitivity of consumers toward price difference is proportional to the manufacturers profit, and the R&D cost coefficient is inversely proportional to the manufacturers profit. Therefore, manufacturers can increase CEA by promoting low-carbon products, thereby increasing the sensitivity of consumers toward price differences. Second, manufacturers can also strive to improve the maturity of emission reduction R&D technologies to reduce the R&D cost coefficient or outsource low-carbon links to professional energy-saving service companies to reduce R&D costs.

## 6.3 Limitations

However, this study only considers government subsidizing manufacturers; however, the government may also encourage manufacturers to reduce emissions by subsidizing retailers or consumers. In addition, the government can also consider issues such as the government's participation in supply chain emission reductions by levying carbon taxes and implementing carbon trading. It is also possible to consider the cooperation of supply chain members to reduce emissions and coordinate the supply chain through contracts.

## 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

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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