

Research Article

Dynamic Strategy Analysis of Emission-Reduction Technology Investment Based on Pricing Coordination Mechanism under Cost Subsidy Policy

Yue Guan , Qiang Hou , and Jiayi Sun 

School of Management, Shenyang University of Technology, Shenyang 110870, China

Correspondence should be addressed to Qiang Hou; 18904046277@163.com

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Climate change has become a pressing concern in recent decades, and the reduction of greenhouse gas emissions is now recognised as an important strategy for redressing that concern. The carbon trading system and the provision of low-carbon cost subsidies are essential measures for reducing emissions in various countries and regions. In this context, we study the investment decision of emission reduction technology in a supply chain composed of a leading manufacturer and a following retailer under the cost subsidy policy of carbon emission reduction. We consider consumers' low-carbon preferences and utilise differential game theory and dynamic optimisation technology to construct the investment game model under a cost subsidy policy affecting manufacturers and retailers. We then identify the equilibrium strategy and the evolution path of emission reduction, profit, and social welfare according to the interest's composition and game relationship of each stakeholder. We also use numerical simulation method to analyse the evolution path of the system and the sensitivity of related parameters, so as to determine the influence of related parameters on the structure and path of the system. We conclude that under the current carbon trading system, the cost subsidy policy implemented by the government plays a positive role in promoting emission reduction investment and corporate profits of supply-chain-related enterprises.

1. Introduction

The problem of global warming has become a severe challenge for all humanity, and the main factor driving climate warming is the emission of greenhouse gases. In response to climate change, the Kyoto Protocol and the Paris Agreement have been signed by many countries, and many nations have also introduced corresponding carbon emission reduction plans. As the world's factory, China is a significant carbon emitter; it has promised to reduce carbon emission per unit of Gross Domestic Product by at least 40% in 2020 compared with 2005. To achieve this goal, in addition to macro adjustments to an industrial structure and to energy-generation systems, a series of policy innovations have been adopted at the microlevel to promote enterprise emission reduction. For example, the key innovation is the cap-and-trade system, which was piloted in 2012 and further

developed in 2017; this policy treats carbon emissions as a negative output in the production system [1]. Also, a subsidy strategy for investment in carbon emission reduction R&D technology has been implemented to promote the development of emission reduction technology. These two policies are designed to prompt manufacturing enterprises to adopt green supply chain initiatives as core environmental strategies. China's new energy vehicle industry, for example, the government subsidies and other measures under the market mechanism have made the new energy vehicle industry develop rapidly, and the innovation driven effect was obvious; their effectiveness can be gauged by their impact on enterprises' emission reduction investments and profits, as well as the overall emission reduction effect.

Building on a growing body of research in this area, and focusing on a dual policy context of carbon emission trading and cost subsidies while also taking the low-carbon

preference of consumers into account, we adopted differential game theory to analyse the relationship among governments, manufacturers, retailers, and consumers from a dynamic perspective, identifying the equilibrium strategy of each party. Then we analyzed the impact of different parameters on emission reduction, enterprise profits, and social welfare, in order to provide theoretical support for the rational decision-making on the part of the various stakeholders involved.

The theoretical importance of this paper stems from its focus on the design of an investment path for carbon emission reduction. By incorporating government into the game process and at the same time considering consumer surplus, the paper provides a theoretical basis for enhancing cooperation and exchange among supply chain enterprises with respect to carbon emission technology—particularly in the context of government participation. The management significance of this study derives from it considering such decision-making from a dynamic point of view, provides analytic support for technology investments by supply chain enterprises, as well as insights into their output decision-making processes. In addition, by analysing the impact of carbon trading system based on quota on investments in emission reduction, the study supports efforts to gauge the effectiveness of the policy. In this connection, the research gives rise to further advises for government planning and design.

2. Literature Review

With the emergence of severe weather in particular seasons as well as weather extremes, people began to pay attention to climate change factors. The carbon emission problem affecting global warming has thus moved to the forefront of concern, across many different countries and regions. The Kyoto protocol, emerging from such global concerns, was formulated in 1992. This protocol was a milestone in the development of global climate change policy-making [2]. In 2005, carbon emission trading was used by the US. Environmental Protection Agency, for the first time, as means of controlling air and water pollution, and the European Union followed suit by introducing carbon emission trading policies of its own. European countries have further explored the contribution that policy and technological changes, which can make to energy conservation initiatives as well as to the reduction of greenhouse gas emissions [3]. Likewise, in August 2021, China's national Development and Reform Commission issued a notice on studying and formulating the comprehensive plan for energy conservation and emission reduction in the 14th-five-year plan and further refining the tasks of implementing energy conservation goals, emphasizing that China will strive to achieve carbon peak by 2030 and carbon neutralization by 2060.

In recent years, scholars have conducted in-depth studies of the carbon emission market and carbon emission trading system from the perspective of supply chains. Benjaafar et al. first introduced carbon emission factors into the supply chain system; their approach modified the traditional model by associating carbon emission parameters with decision

variables, and considered the various enterprises in the supply chain in relation to these parameters and variables [4]. In addition, in proposing a new model for reducing carbon emissions, Hovelaque considered the relationships among inventory policy, total carbon emissions, price, and environment-related consumer demand [5]. For their part, Toptal studied the coordination between enterprises and suppliers by using Bayesian game theory and analyzed, from the perspective of carbon footprints, the impact of decentralised vs centralised supply chain decisions on total carbon emissions [6]. Meanwhile, Zhao et al. and Du et al. considered carbon emission constraints and trading mechanisms and analyzed the game behaviour and decision-making of supply chain enterprises [7, 8]. The research results show that carbon emissions constitute one of the critical indicators of enterprise products. Du et al. established a “carbon constraint and trading” system, consisting of a manufacturer and a carbon trading licence supplier, to study the decision-making processes and social-welfare motivations of supply chain members [9]. Zhao et al. constructed a manufacturer-led Stackelberg differential game model and analyzed the impact of manufacturers' and suppliers' cooperative emission reduction strategies on the carbon emissions associated with products [10]. Guan et al. considered the influence of consumers' low carbon preference and uncertainty of carbon emission reduction behaviour, established a stochastic differential game model based on cost-sharing coordination, and studied the equilibrium decision-making problem of upstream and downstream enterprises [11]. Zhang established a corresponding model for the incentive and restraint role of the relationship between partner suppliers and corresponding buyers on the sustainable supply chain from both internal and external perspectives and conducted a comprehensive analysis of this [12]. Taleizadeh et al. studied the competition and cooperation strategies in the pricing and production process of dual channel green supply chain [13]. Karuna et al. studied the inventory model considering the carbon emission reduction behaviour of retailers in poultry and animal husbandry [14]. Shib studied the optimal pricing and green quality strategy of members under decentralised and centralised decision-making in two-level supply chain [15]. Mahapatra et al. introduced stochastic mathematical programming into the model and analyzed the problem of cost minimization [16]. Das et al. studied the strategy selection problem of minimizing the expected total cost of members under the condition of minimizing the installation cost in a multilevel green supply chain [17].

On a different front, scholars have also studied the role of government subsidies with respect to emission reductions in the supply chain. Hou et al. studied the emission reduction technology investment strategy of supply chain from a dynamic perspective under subsidy policy and obtained a comparative analysis under different decision-making scenarios [18]. Using dynamic game theory, Chen et al. retrospectively analyzed the impact of different government subsidy strategies on the decision variables of each subject. The study results provide a decision basis for the development of rational approaches to government subsidies [19]. Using an

ethical model, Ezimadu and Nwozo studied collaborate strategy in two-level supply chain. The results show that with the increase of government subsidies, the strength of retail advertising increases, while the strength of the manufacturing sector decreases [20]. Focusing on green issues in supply chain competition, Madani and Rasti-Barzoki established a mathematical model of competition, which is led by the government, and a mathematical model of competition based on competing followers in supply chains (green and non-green). Their findings suggest that strategy and governance pricing problems determine the subsidies and tax rates of products (green and nongreen) [21]. Wu et al. established the variational inequality model of closed-loop supply chain networks with multiphase equilibrium and analyzed the impact of government subsidies on the optimal strategy of green supply chain [22]. Yu et al. constructed a supply chain game model based on the dual mechanism of cost subsidy and cost sharing and discussed the enterprises equilibrium decision-making in this situation [23]. Madani and Rasti-Barzoki studied green production government price subsidies by using Stackelberg game model, considering the effects of government revenue from many aspects, include ecological reconstruction, taxes, and subsidy. The research results show that, compared with taxes, subsidies can increase the revenue of government and enterprises, and more conducive to the progress of green products. Here it should be noted that, although there are in fact many forms of government subsidy behaviour, most of the studies just cited are based on the premise that the amount of the government subsidy is already known. Hence, in this previous work, governments' behaviour with respect to subsidies is not itself included in the game process. About low-carbon consumption behaviours and awareness of consumers. Using a secondary supply chain, which consisted of upstream manufacturer and downstream retailer as a case study, Taboubi considered the consumer's reference price effect and studied pricing decision-making and coordination [24]. Sánchez-Sellero took Spanish families as the research objects and explored the impact of consumer consumption habits on social economy through statistical analysis [25]. Barman et al. studied the balanced pricing and green strategy of duopoly competitive green supply chain and discussed the impact of government subsidies and other intervention means on supply chain members [26]. From the perspective of corporate social responsibility, Sana studied the impact of government subsidies and tax mechanism on the strategic choice of green or nongreen producers [27]. On the impact of other subsidies on emission reduction, Chen et al. analyzed the impact of a mixed subsidy mechanism with input and output subsidies on the sustainable development of renewable energy [28]. Nie et al., based on game theory model, studied the impact of fixed subsidies and output subsidies on carbon emission reduction [29]. Chen et al. analyzed the impact of production risk and uncertainty on the implementation efficiency of agricultural subsidy mechanism. The research results show that the government should consider the impact of uncertainty and production efficiency when formulating relevant subsidy policies [30]. Considering the influence of uncertain factors on the process of producing renewable energy, Yang et al. established a two-stage model to

analyse the impact of on grid electricity price and renewable energy combination standard on green industry [31].

From the above research results, since the carbon emission market was set up for investment purposes, scholars have conducted substantial amounts of research on the market, from different perspectives. Most of the studies have adopted a macroperspective on issues of carbon financing and environmental protection. Although many researchers consider various scenarios from both static and dynamic perspectives to study the impact of the carbon trading system on the emission-reduction investment behaviour of supply chains, they rarely consider the impact of social welfare and environmental benefits on this behaviour. Hence, from a micropoint of view, supply chains' cooperation on strategies for emission reduction and problems related to enterprise decision making need further study. In particular, decision makers need to focus on dynamic changes in the emission reduction strategies of supply chains, in the context of the carbon trading market, and to formulate corresponding response policies in time. On the other side, due to the diversity of carbon emission control methods (including total emission control and intensity control) and coordination mechanisms (including price coordination, cost sharing coordination, and hybrid coordination), researchers could choose different research perspectives and focuses.

In practice, in many countries and regions, subsidies for carbon emission-reduction technology investments are the result of what can be modelled as a game played by enterprises and governments. In accordance with this general insight, on the basis of literature [11], the research explored the effectiveness with which the carbon trading system and subsidy system have impacted supply chains' investments in emission-reduction technology. We use intensity control method and choose price coordination mechanism to expand on existing research in the field by endogenising the factor of subsidy rates and considering consumers' low-carbon preferences.

3. Construction of Differential Game Model

3.1. Relevant Problem Description. Learn from existing research, the market demand function model, which comprehensively consider the dual objectives of supply chain revenue and carbon emission reduction [32], we consider a two-level supply chain that consists of upstream manufacturer and downstream retailer. We use this supply chain to study an investment model for emission reduction that involves government subsidy and consumers with low-carbon preferences. The main decision-making framework is shown in Figure 1.

In the secondary supply chain consisted chiefly of upstream manufacturer and downstream retailer, all actors participate in the complete information dynamic game. Furthermore, so as to maximize social welfare, the government will initially determine carbon quotas according to carbon emission intensity.

To clearly describe the specific problem, the symbols in the model are defined and explained in Table 1.

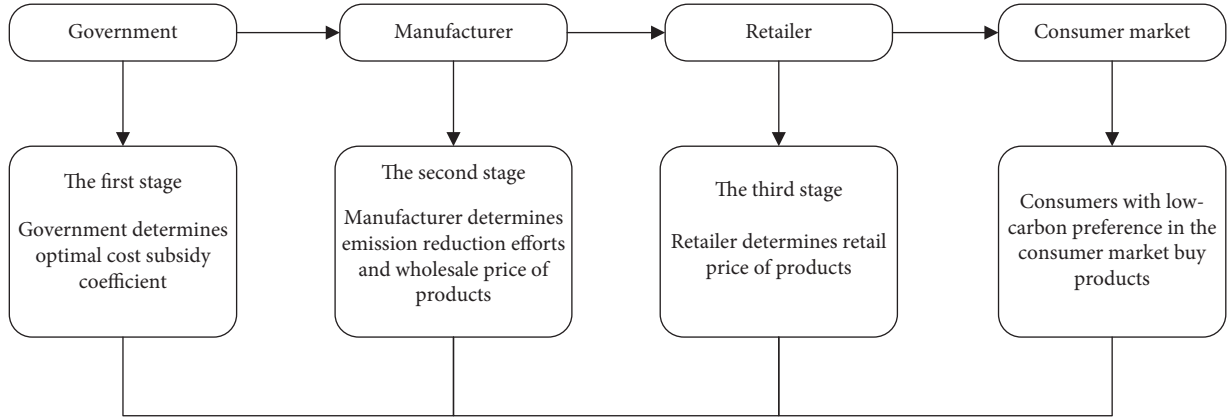


FIGURE 1: Decision diagram.

TABLE 1: Definition of parameters.

Variable	Description
p	Product retail price
a	Market size of the product
Q_E	Quantity demanded considering consumers' low carbon desires
u_M	Manufacturer's abatement cost coefficient
α	Impact coefficient of the manufacturer's emission reduction effort
g_M	Per unit product emissions quotas set by the government
c	Manufacturer's unit production cost
J_M	Profits of the manufacturer
J_T	Profits of the supply chain
SW	Social welfare
δ	Cost subsidy coefficient
w	Manufacturer's wholesale price
b	Marginal demand for the product
Z_M	Emission reduction effort by the manufacturer
E	Carbon emission reduction
σ	Relative attenuation rate for the product emission reduction function
e_M	Level of carbon emissions per unit product without a carbon emission reduction investment
ρ	Discount rate
J_R	Profits of the retailer
k	Consumer low-carbon sensitivity coefficient
p_e	Carbon trading price

3.2. Model Assumptions. According to the realistic situation of investment for emission reduction, learn from the existing research, make the following assumptions:

Hypothesis 1. The government allocates certain emission quotas according to the nature of the enterprise operation, and the emissions exceeding the quota need to be purchased from the outside. In addition, because the scale of carbon trading market in China is large, each industry accounts for a relatively small proportion of the market. Further, since each industry is a price receiver, the carbon trading price, in the model, is an exogenous variable.

Hypothesis 2. For companies that produce low-carbon products, Bergeron et al. pointed out that market demand factors are divided into non-price and price factors, and these two factors affect market demand in the form of separable multiplication [33]. Learn from the existing

function form [34, 35], considering $E(t)$ as state variables, the demand function in this paper can be expressed as

$$Q_E(t) = (a - bp(t))kE(t). \quad (1)$$

Hypothesis 3. When inventory and shortage are not considered, the abatement cost of manufacturer is a convex function, learn from the innovation cost function form [36], the abatement cost of manufacturer is

$$C(Z_M(t)) = \frac{\mu_M}{2} Z_M^2(t). \quad (2)$$

The government allocates a portion of the cost subsidies for carbon emission reduction to enterprises reducing emissions associated with their products. This allocation is directly proportional to the degree to which the enterprises are making an effort to reduce emissions [7]. Therefore, the subsidies given by government to manufacturer at time t is

$$F(Z_M(t)) = \delta \frac{\mu_M Z_M^2(t)}{2}. \quad (3)$$

Hypothesis 4. The quantity of the emission reduction related to product is treated as a state variable, which with natural constant depreciation rate. Due to the ageing of equipment and advances in available technology, and in accordance with the findings reported in reference [10], the carbon emission reduction is

$$\dot{E}(t) = \alpha Z_M(t) - \sigma E(t). \quad (4)$$

3.3. Basic Economic Relations. It is assumed that $E_{MT}(t)$ is the total carbon emission. When $E_{MT}(t) < 0$, relevant enterprises need to purchase a certain additional carbon quota from the outside. When $E_{MT}(t) > 0$, enterprises can obtain a certain additional profit by investing in emission reduction technology. Based on the constraints of carbon emission trading policy, the government has dual control over the total

carbon emission and intensity, assuming $g_M(t)$ is the upper limit of enterprise carbon emission stipulated by the government. $e_M(t)$ is the unit carbon emission level of products without carbon emission reduction technology investment. Therefore, the carbon emission trading costs can then be expressed is

$$E_{MT}(t) = p_e [g_M Q_E(t) + E(t) - e_M Q_E(t)]. \quad (5)$$

The cost subsidy is a subsidy given by the government for enterprises investing in carbon emission reduction. In this study, manufacturers invested in emission reduction technologies, whereas retailers only participated in the sales of products created with fewer emissions and did not reduce emissions themselves. Therefore, the manufacturer's profit function consists of sales revenue, carbon emission reduction cost, and carbon quota transaction cost. For its part, the retailer's profit function includes only sales revenue. For convenience of expression, t is omitted below.

The manufacturer's profit function is

$$J_M = \int_0^\infty e^{-\rho t} \left\{ (w - c)Q_E - (1 - \delta) \frac{\mu_M Z_M^2}{2} + p_e (g_M Q_E + E - e_M Q_E) \right\} dt. \quad (6)$$

The retailer's profit function is

$$J_R = \int_0^\infty e^{-\rho t} \{ (p - w)Q_E \} dt. \quad (7)$$

Further, the consumer surplus, considering the consumer's sensitivity to low-carbon products, is

$$\begin{aligned} Q_E &= (a - bp)kE, \\ p(y) &= \frac{1}{b} \left(a - \frac{y}{kE} \right), \\ CS(E) &= \int_0^{Q_E} p(y) dy - p(Q_E)Q_E, \\ &= \frac{1}{2bkE} Q_E^2 = \frac{1}{2b} (a - bp)^2 kE. \end{aligned} \quad (8)$$

The social welfare function is the sum of all individual welfare, and the social welfare is a function of each subject welfare when the utility level is used to express each subject welfare. When the government allocates a cost subsidy to enterprises for carbon emission reductions related to their products, social welfare can be represented as the sum of producer and consumer surplus minus the cost subsidy provided by the government. Thus, the social welfare is

$$SW = \int_0^\infty e^{-\rho t} \left\{ (p - c - p_e e_M + p_e g_M)Q_E - (1 - \delta) \frac{\mu_M Z_M^2}{2} + p_e E + \frac{1}{2b} (a - bp)^2 kE - \delta \frac{\mu_M Z_M^2}{2} \right\} dt. \quad (9)$$

3.4. Differential Game Model. The government, manufacturer, and retailer are participants in a Stackelberg game, such a dynamic game not only fits the reality but also can ensure the existence and stability of the equilibrium point and provide more reliable guidance for the market players. In addition, bringing the government into the game process

and making the subsidy strategy an endogenous variable not only provides more practical theoretical guidance for the strategy selection of game participants but also increases the guidance and effectiveness of the policy, and the differential game model of the dynamic system can be expressed as

$$\begin{cases} \max_{\delta}^{SW} (\delta; Z_M, w; p) \\ \text{s.t. } \max_{Z_M, w} J_M (\delta; Z_M, w; p) \\ \text{s.t. } \max_p J_R (\delta; Z_M, w; p) \\ \dot{E}(t) = \alpha Z_M(t) - \sigma E(t). \end{cases} \quad (10)$$

4. Stackelberg Equilibrium Analysis

4.1. Equilibrium Strategy. When the government grants carbon emission cost subsidies to enterprises, the government first determines the carbon reduction cost subsidy coefficient, while the manufacturer determines the degree of the emission reduction effort and the retailer determines the retail price of the product. According to the Nash equilibrium strategy under conditions of dynamic feedback, the process of the game is as follows: the government allocates carbon quotas to the supply chain with the goal of achieving emission reductions. Then the government plays a game with the manufacturer—a game with the goal of maximising social welfare—to determine the subsidy coefficient for investments in emission reduction technology. Under the situation where the cost subsidy coefficient is determined, the manufacturer determines the investment in emission

reduction technology with the goal of maximising profits and then decides the wholesale price by playing a game with the retailer. With the goal of maximising profits, the retailer plays a game with consumers with low-carbon preferences to determine the retail price. Accordingly, through the Backward Induction, the following theorems can be obtained.

Proposition 1. *When the result of the game is equilibrium:*

$$\begin{aligned} \delta^* &= \frac{3(a - bc - bp_e e_M + bp_e g_M)^2 k}{7(a - bc - bp_e e_M + bp_e g_M)^2 k + 32 bp_e}, \\ w^* &= \frac{1}{2b} (a + bc + bp_e e_M - bp_e g_M), \\ Z_M^* &= \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \left(\frac{7}{32} A + p_e \right), \\ p^* &= \frac{1}{4b} (3a + bc + bp_e e_M - bp_e g_M). \end{aligned} \quad (11)$$

Proof. By virtue of (6) and (7), we obtained the HJB (Hamilton-Jacobi-Bellman) equations for the profit functions of the manufacturer and the retailer, represented as (12) and (13), respectively.

$$\rho V_M = \max_{Z_M \geq 0} \left\{ (w - c - p_e e_M + p_e g_M) (a - bp) k E - (1 - \delta) \frac{\mu_M}{2} Z_M^2 + p_e E + V'_M (\alpha Z_M - \sigma E) \right\}, \quad (12)$$

$$\rho V_R = \max_{p \geq 0} \{ (p - w) (a - bp) k E + V'_R (\alpha Z_M - \sigma E) \}. \quad (13)$$

When the cost subsidy rate δ is known, by taking the first derivative of the right side of (17), we obtain:

$$\begin{aligned} Z_M &= \frac{V'_M \alpha}{(1 - \delta) \mu_M}, \\ p &= \frac{a + bw}{2b}, \\ w^* &= \frac{1}{2b} (a + bc + bp_e e_M - bp_e g_M). \end{aligned} \quad (14)$$

According to the HJB equation structure for game subject, we assume that the optimal value functions (linear expression) is

$$\begin{cases} V_M = x_{21} E + x_{22}, \\ V_R = y_{21} E + y_{22}, \end{cases} \quad (15)$$

where x_{21} , x_{22} , y_{21} , y_{22} are undetermined constants. We then obtain:

$$\begin{aligned} x_{21} &= \frac{1}{\rho + \sigma} \left[\frac{1}{8b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right], \\ x_{22} &= \frac{1}{\rho} \frac{x_{21}^2 \alpha^2}{2(1 - \delta) \mu_M}, \\ y_{21} &= \frac{1}{\rho + \sigma} \frac{1}{16b} (a - bc - bp_e e_M + bp_e g_M)^2 k, \\ y_{22} &= \frac{1}{\rho} \frac{x_{21} y_{21} \alpha^2}{(1 - \delta) \mu_M}. \end{aligned} \quad (16)$$

Next, the HJB equation for social welfare can be calculated by using (11).

$$\rho V_{SW} = \max_{\delta \geq 0} \left\{ (p - c - p_e e_M + p_e g_M) (a - bp) k E - (1 - \delta) \frac{\mu_M}{2} Z_M^2 + p_e E + \frac{1}{2b} (a - bp)^2 k E - \delta \frac{\mu_M}{2} Z_M^2 + V'_{SW} (\alpha Z_M - \sigma E) \right\}. \quad (17)$$

According to the Fermat Lemma, the first derivative at the extreme point of differentiable function is equal to zero, so when the social welfare in (27) is known, by taking the first derivative of the right side of (27), we obtain the cost subsidy rate allocated by the government is

$$\delta = \frac{V_{SW}^{N'} - V_M^{N'}}{V_{SW}^{N'}}. \quad (18)$$

According to the equation structure, we assume that the optimal value function (linear expression) is

$$V_{SW} = g_{21}E + g_{22}. \quad (19)$$

Similarly, Bing the first derivative of the social welfare function for E into (20), the two sides of the equation correspond to each other, yielding:

$$\begin{cases} g_{21} = \frac{1}{\rho + \sigma} \left[\frac{7}{32b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right], \\ g_{22} = \frac{1}{\rho} \frac{g_{21}^2 \alpha^2}{2\mu_M}. \end{cases} \quad (20)$$

Then the cost subsidy rate allocated by the government and the manufacturer's efforts for emission reduction can be calculated as

$$\delta^* = \frac{3(a - bc - bp_e e_M + bp_e g_M)^2 k}{7(a - bc - bp_e e_M + bp_e g_M)^2 k + 32bp_e}, \quad (21)$$

$$Z_M^* = \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \left[\frac{7}{32b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right]. \quad (22)$$

When we assume $A = 1/b(a - bc - bp_e e_M + bp_e g_M)^2 k$, then the Proposition 1 can be obtained. \square

4.2. Evolution Path

Proposition 2. *In the scenario where the government allocates carbon emission reduction cost subsidies, the trajectories of the carbon emissions, the manufacturer's and the retailer's profits, and the social welfare optimal value function with respect to time can be calculated, as shown in (23)–(27):*

$$E(t)^* = \frac{\alpha^2}{\sigma(\rho + \sigma)\mu_M} \left(\frac{7}{32} A + p_e \right) (1 - e^{-\sigma t}), \quad (23)$$

$$J_M(t)^* = \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1}{8} A + p_e \right) \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right), \quad (24)$$

$$J_R(t)^* = \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \frac{1}{16} A \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{\rho} \right), \quad (25)$$

$$J_T(t)^* = \frac{\alpha^2 ((7/32)A + p_e)}{(\rho + \sigma)^2 \mu_M} \left[\left(\frac{3}{16} A + p_e \right) \frac{1 - e^{-\sigma t}}{\sigma} + \left(\frac{1}{4} A + p_e \right) \frac{1}{2\rho} \right], \quad (26)$$

$$SW(t)^* = \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{7}{32} A + p_e \right)^2 \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right). \quad (27)$$

Proof. Based on the three HJB equations, we assume the optimal profit value functions are

$$\begin{cases} V_M = x_{21}^* E + x_{22}^*; V_R = y_{21}^* E + y_{22}^*, \\ V_T = h_{21}^* E + h_{22}^*; V_{SW} = g_{21}^* E + g_{22}^*, \end{cases}$$

$$x_{21}^* = \frac{1}{\rho + \sigma} \left(\frac{1}{8} A + p_e \right),$$

$$\begin{aligned}
x_{22}^* &= \frac{1}{\rho} \left[\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{2\mu_M} \left(\frac{1}{8}A + p_e \right) \left(\frac{7}{32}A + p_e \right) \right], \\
y_{21}^* &= \frac{1}{\rho + \sigma} \frac{1}{16}A, \\
y_{22}^* &= \frac{1}{\rho} \left[\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \frac{1}{16}A \left(\frac{7}{32}A + p_e \right) \right], \\
h_{21}^* &= \frac{1}{\rho + \sigma} \left(\frac{3}{16}A + p_e \right), \\
h_{22}^* &= \frac{1}{\rho} \left[\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{2\mu_M} \left(\frac{1}{4}A + p_e \right) \left(\frac{7}{32}A + p_e \right) \right], \\
g_{21}^* &= \frac{1}{\rho + \sigma} \left(\frac{7}{32}A + p_e \right), \\
g_{22}^* &= \frac{1}{\rho} \left[\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{2\mu_M} \left(\frac{7}{32}A + p_e \right)^2 \right].
\end{aligned} \tag{28}$$

In this context, x_{21}^* , y_{21}^* , h_{21}^* , g_{21}^* , respectively, represent the extent to which the manufacturer's profits, the retailer's profits, the supply chain profits, and social welfare change with the increase in carbon emissions. Further, x_{22}^* , y_{22}^* , h_{22}^* , g_{22}^* , respectively, represent the initial value of the

manufacturer's profits, the retailer's profits, the supply chain profits, and social welfare when the enterprise does not invest in abatement technology.

When the government allocates carbon emission reduction cost subsidies, by bring (29) into (4), we obtain:

$$\dot{E}(t) = \frac{1}{\rho + \sigma} \frac{\alpha^2}{\mu_M} \left[\frac{7}{32b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right] - \sigma E(t). \tag{29}$$

The carbon emission trajectory is

$$E(t) = \frac{\alpha^2 (1 - e^{-\sigma t})}{\mu_M \sigma (\rho + \sigma)} \left[\frac{7}{32b} (a - bc - bp_e e_M + bp_e g_M)^2 k + p_e \right] + e^{-\sigma t} E_0. \tag{30}$$

Thus, by substituting the carbon emission trajectory function into the three HJB equations, we can calculate the evolution path of the optimal value function of the long-term profits of manufacturers and retailers and long-term social welfare. \square

5. Numerical Simulation Analysis

5.1. Boundary Condition Determination. According to product pricing and market rules, the constraints can be written as

$$\begin{aligned}
\rho &\geq \sigma, \\
0 &\leq c + p_e e_M - p_e g_M \leq w \leq p \leq \frac{a}{b}.
\end{aligned} \tag{31}$$

Then we can determine that:

$$0 \leq A. \tag{32}$$

The analysis of the carbon trading price in the carbon trading market shows that, in order to prevent arbitrage behaviour on the part of enterprises, the profits of the manufacturer's carbon-emission-generating products should be higher than the cost of buying carbon quotas in the trading market. Similarly, the unit profit obtained by the retailer selling the product should also be higher than the profit from the carbon credit allocated for the unit sold.

$$(w - c - p_e e_M + p_e g_M) (a - bp) k E \geq p_e E, \tag{33}$$

$$(p - w) (a - bp) k E \geq p_e E. \tag{34}$$

Under the cost subsidy scenario:

$$\begin{cases} w = \frac{1}{2b} (a + bc + bp_e e_M - bp_e g_M), \\ p = \frac{1}{4b} (3a + bc + bp_e e_M - bp_e g_M). \end{cases} \quad (35)$$

Bring (33) into (34) and (35):

$$\begin{aligned} \frac{1}{8b} (a - bc - bp_e e_M + bp_e g_M)^2 k &\geq p_e, \\ \frac{1}{16b} (a - bc - bp_e e_M + bp_e g_M)^2 k &\geq p_e. \end{aligned} \quad (36)$$

Thus, we can determine that:

$$p_e \leq \frac{1}{16} A. \quad (37)$$

5.2. Evolution Path Simulation Analysis. To analysis the evolution trend of carbon emission reduction, profit, and social welfare under the price coordination mechanism constructed by the carbon trading and government subsidy systems, combined with the actual situation and existing research results [4–11], the model is assigned numerical values, and the simulation software is used for numerical simulation. System parameters are as follows: $\rho = 0.4$, $\sigma = 0.3$, $a = 4.5$, $b = 1.5$, $c = 4$, $\alpha = 0.8$, $p_e = 0.03$, $k = 0.5$, $u_M = 1$, $e_M = 0.6$, and $g_M = 2$. In this way, the trajectory of the manufacturer's profit, the retailer's profit, the supply chain profit, the carbon emission reduction, and social welfare evolution under the scenario of cost subsidy decision-

making can be obtained. Specific details are shown in Figure 2.

Figure 2 indicates that over time, $E(t)$, $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$ all show a non-linear upward trend, with their growth rate becoming slower and slower until it eventually reaches a certain stable level. $J_M(t)$ and $J_R(t)$ are the same at the beginning. However, $J_M(t)$ rises faster than $J_R(t)$. As time goes on, $J_M(t)$ are finally higher than $J_R(t)$. Also, initially the value and rising trend of $J_T(t)$ and $SW(t)$ are the same. Over time, however, the growth rate of $SW(t)$ is slightly higher than the growth rate of $J_T(t)$, meaning that increases in $SW(t)$ are marginally more significant than $J_T(t)$.

5.3. Sensitivity Analysis. Assuming that consumers' low-carbon preference coefficient is k , the coefficient of the impact of the manufacturer's emission reduction efforts is α , the emission reduction cost coefficient is μ_M , and the carbon trading price is p_e . We can then calculate the impact of these parameters on the optimal emission reduction effort Z_M^* , wholesale price w^* , product pricing p^* , optimal subsidy rate δ^* , emission reduction $E(t)^*$, manufacturer's profit $J_M(t)^*$, retailer's profit $J_R(t)^*$, supply chain profit $J_T(t)^*$, and social welfare evolution $SW(t)^*$. The results are shown in Table 2.

Inference 1. As consumers' low-carbon sensitivity coefficient k increases, Z_M , δ , E , $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$ increase too. However, an increase in k does not change p or w .

Proof.

$$\begin{aligned} \frac{\partial Z_M^*}{\partial k} &= \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \frac{7B}{32} > 0 \frac{\partial w^*}{\partial k}, \\ \frac{\partial E(t)^*}{\partial k} &= \frac{7B}{32\sigma(\rho + \sigma)} \frac{\alpha^2}{\mu_M} (1 - e^{-\sigma t}) > 0, \\ \frac{\partial J_M(t)^*}{\partial k} &= \frac{B}{8(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) \left(\frac{7}{32} A + p_e \right) + \frac{7B}{32(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) \left(\frac{1}{8} A + p_e \right) > 0, \\ \frac{\partial J_R(t)^*}{\partial k} &= \frac{1}{16} \frac{B}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{\rho} \right) \left(\frac{14}{32} A + p_e \right) > 0, \\ \frac{\partial J_T(t)^*}{\partial k} &= \frac{B\alpha^2(1 - e^{-\sigma t})}{32(\rho + \sigma)^2 \mu_M \sigma} \left(7 \left(\frac{3}{16} A + p_e \right) + 6 \left(\frac{7}{32} A + p_e \right) \right) \\ &\quad + \frac{B\alpha^2}{64\rho(\rho + \sigma)^2 \mu_M} \left(7 \left(\frac{1}{4} A + p_e \right) + \frac{1}{8} \left(\frac{7}{32} A + p_e \right) \right) > 0, \\ \frac{\partial SW(t)^*}{\partial k} &= \frac{7B}{16(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) \left(\frac{7}{32} A + p_e \right) > 0, \end{aligned} \quad (38)$$

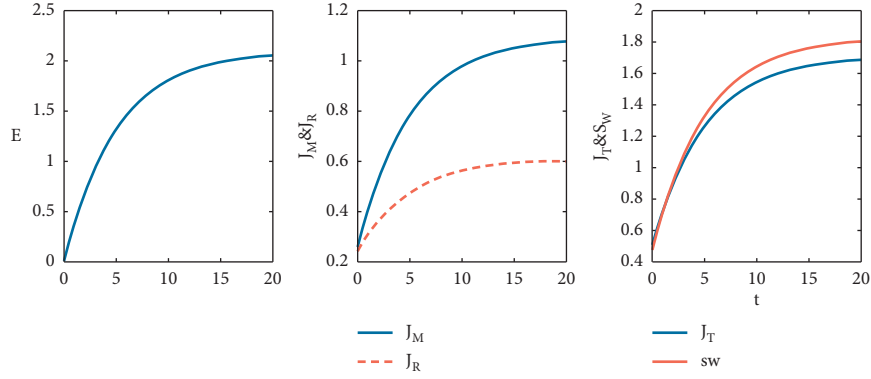


FIGURE 2: State variable trajectory under cost subsidy.

TABLE 2: Sensitivity analysis.

.	Z_M^*	w^*	δ^*	p^*	$E(t)^*$	$J_M(t)^*$	$J_R(t)^*$	$J_T(t)^*$	$SW(t)^*$
k	↑	→	↓	→	↑	↑	↑	↑	↑
α	↑	→	→	→	↑	↑	↑	↑	↑
μ_M	↓	→	→	→	↓	↓	↓	↓	↓
p_e	↑	↓	↑	↓	↑	↑	↑	↑	↑

where $B = 1/b(a - bc - bp_e e_m + bp_e g_M)^2$.

In order to verify the effectiveness of the above theoretical analysis, it is assumed that other parameters set above do not change, $k \in [0.4, 0.9]$. Relevant simulation results are shown in Figure 3.

Figure 3 reveals that with the increase of k , Z_M , and E , both show a linear upward trend. p and w remain unchanged, with p being significantly higher than w . In

addition, δ , $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$ all show a non-linear upward trend. \square

Inference 2. The impact coefficient of the manufacturer's emission reduction effort, α , is positively correlated with Z_M , E , $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$. However, changes to α do not change the δ , p , or w .

Proof.

$$\begin{aligned}
 \frac{\partial Z_M^*}{\partial \alpha} &= \frac{1}{\rho + \sigma} \frac{1}{\mu_M} \left(\frac{7}{32} A + p_e \right) > 0 \frac{\partial w^*}{\partial \alpha}, \\
 \frac{\partial E(t)^*}{\partial \alpha} &= \frac{1}{\sigma(\rho + \sigma)} \frac{2\alpha}{\mu_M} \left(\frac{7}{32} A + p_e \right) (1 - e^{-\sigma t}) > 0, \\
 \frac{\partial J_M(t)^*}{\partial \alpha} &= \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{\mu_M} \left(\frac{1}{8} A + p_e \right) \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) > 0, \\
 \frac{\partial J_R(t)^*}{\partial \alpha} &= \frac{2\alpha A}{16(\rho + \sigma)^2 \mu_M} \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{\rho} \right) > 0, \\
 \frac{\partial J_T(t)^*}{\partial \alpha} &= \frac{2\alpha((7/32)A + p_e)}{(\rho + \sigma)^2 \mu_M} \left[\left(\frac{3}{16} A + p_e \right) \frac{1 - e^{-\sigma t}}{\sigma} + \left(\frac{1}{4} A + p_e \right) \frac{1}{2\rho} \right] > 0, \\
 \frac{\partial SW(t)^*}{\partial \alpha} &= \frac{1}{(\rho + \sigma)^2} \frac{2\alpha}{\mu_M} \left(\frac{7}{32} A + p_e \right)^2 \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) > 0.
 \end{aligned} \tag{39}$$

It is assumed that other parameters set above do not change, $\alpha \in [0.4, 1.2]$. Relevant simulation results are shown in Figure 4.

Figure 4 reveals that with the increase of α , Z_M show a linear upward trend, while the δ , p , and w remain unchanged. The p is significantly higher than w . Also, E , $J_M(t)$,

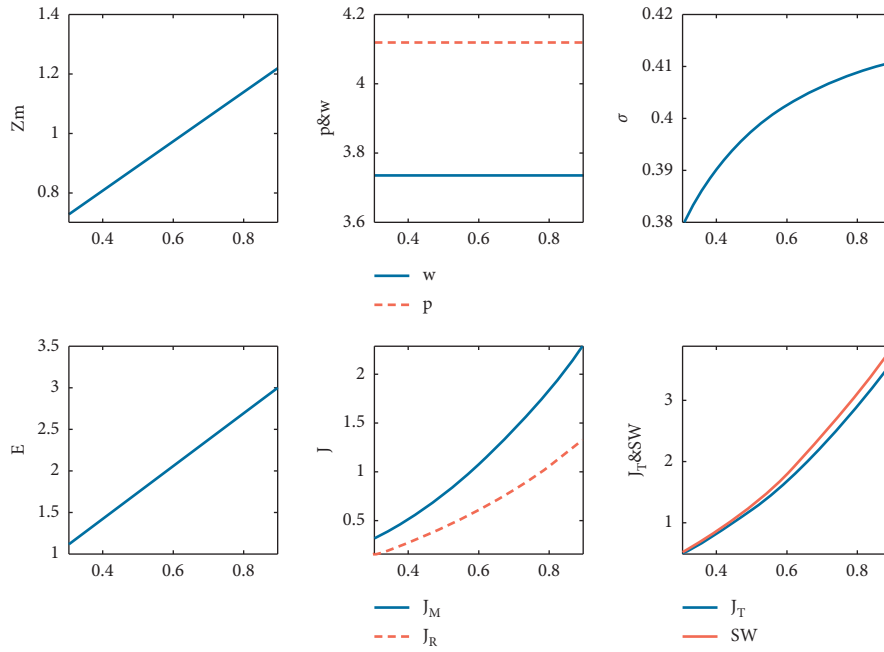


FIGURE 3: Sensitivity analysis of consumers' carbon sensitivity coefficient.

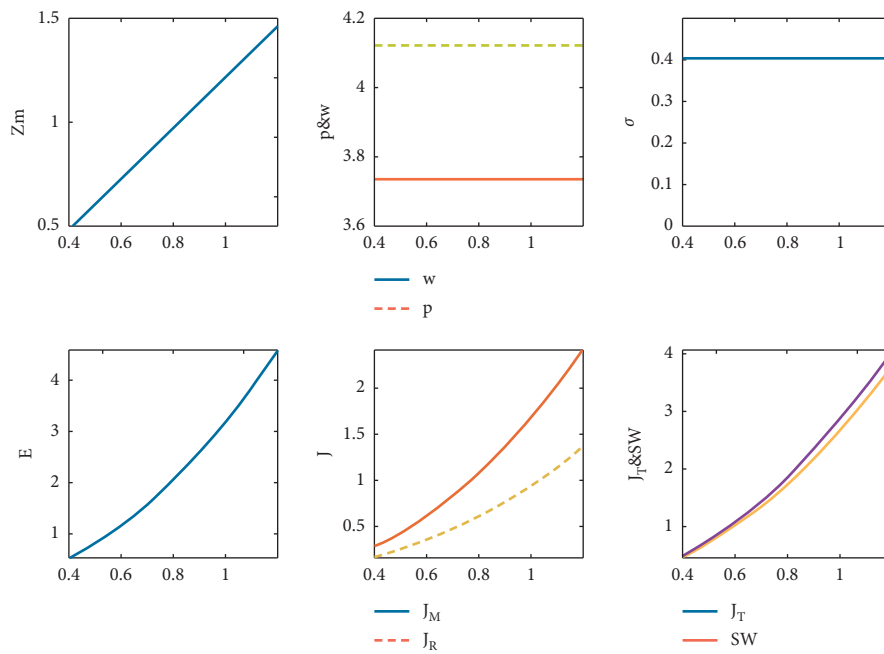


FIGURE 4: Sensitivity analysis of the impact coefficient of the manufacturer's emission reduction effort.

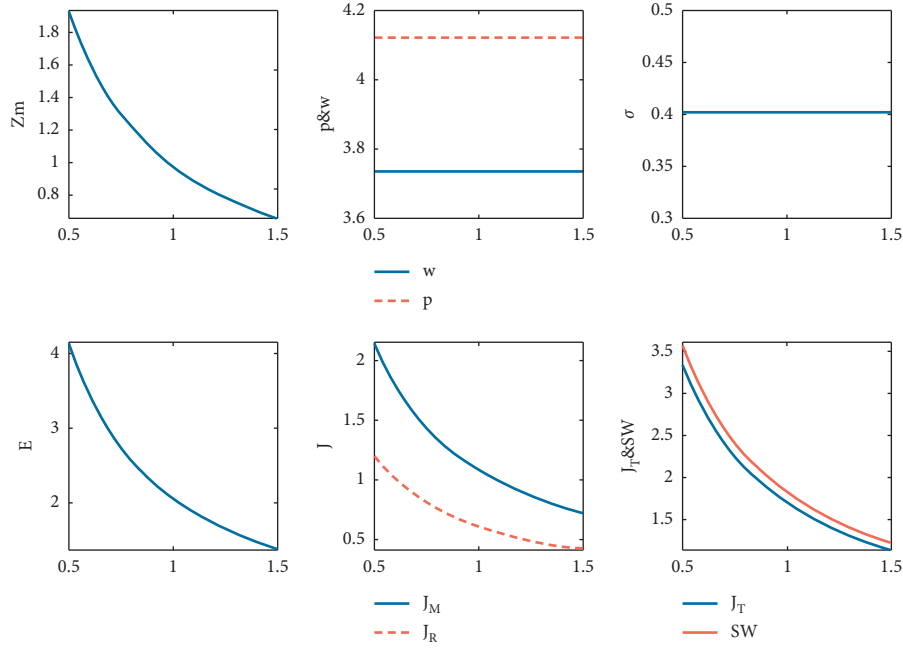


FIGURE 5: Sensitivity analysis of cost coefficient of the manufacturer's emission reduction efforts.

$J_R(t)$, $J_T(t)$, and $SW(t)$ all show a non-linear upward trend. \square

and $SW(t)$. However, changes to μ_m do not change δ , p , or w .

Inference 3. The manufacturer's abatement cost coefficient, μ_m , is negatively correlated with Z_M , E , $J_M(t)$, $J_R(t)$, $J_T(t)$,

Proof.

$$\begin{aligned}
 \frac{\partial Z_M^*}{\partial \mu_M} &= -\frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M^2} \left(\frac{7}{32} A + p_e \right) < 0, \frac{\partial w^*}{\partial \mu_M}, \\
 \frac{\partial E(t)^*}{\partial \mu_M} &= -\frac{1}{\sigma(\rho + \sigma)} \frac{\alpha^2}{\mu_M^2} \left(\frac{7}{32} A + p_e \right) (1 - e^{-\sigma t}) < 0, \\
 \frac{\partial J_M(t)^*}{\partial \mu_M} &= -\frac{\alpha^2}{(\rho + \sigma)^2 \mu_M^2} \left(\frac{1}{8} A + p_e \right) \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) < 0, \\
 \frac{\partial J_R(t)^*}{\partial \mu_M} &= -\frac{A}{16(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M^2} \left(\frac{7}{32} A + p_e \right) \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{\rho} \right) < 0, \\
 \frac{\partial J_T(t)^*}{\partial \mu_M} &= -\frac{\alpha^2 (7/32A + p_e)(3/16A + p_e)1 - e^{-\sigma t}/\sigma}{(\rho + \sigma)^2 \mu_M^2} - \frac{\alpha^2 (7/32A + p_e)(1/4A + p_e)}{2\rho(\rho + \sigma)^2 \mu_M^2} < 0, \\
 \frac{\partial SW(t)^*}{\partial \mu_M} &= -\frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M^2} \left(\frac{7}{32} A + p_e \right)^2 \left(\frac{1 - e^{-\sigma t}}{\sigma} + \frac{1}{2\rho} \right) < 0.
 \end{aligned} \tag{40}$$

It is assumed that other parameters set above do not change, $\mu_m \in [0.5, 1.5]$. Relevant simulation results are shown in Figure 5.

Figure 5 reveals that with the increase of μ_m , Z_M , E , $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$, all show a non-

linear downward trend, and μ_m has no effect on δ , p , or w . \square

Inference 4. The carbon trading price, p_e , is positively correlated with Z_M , E , $J_M(t)$, $J_R(t)$, $J_T(t)$, and

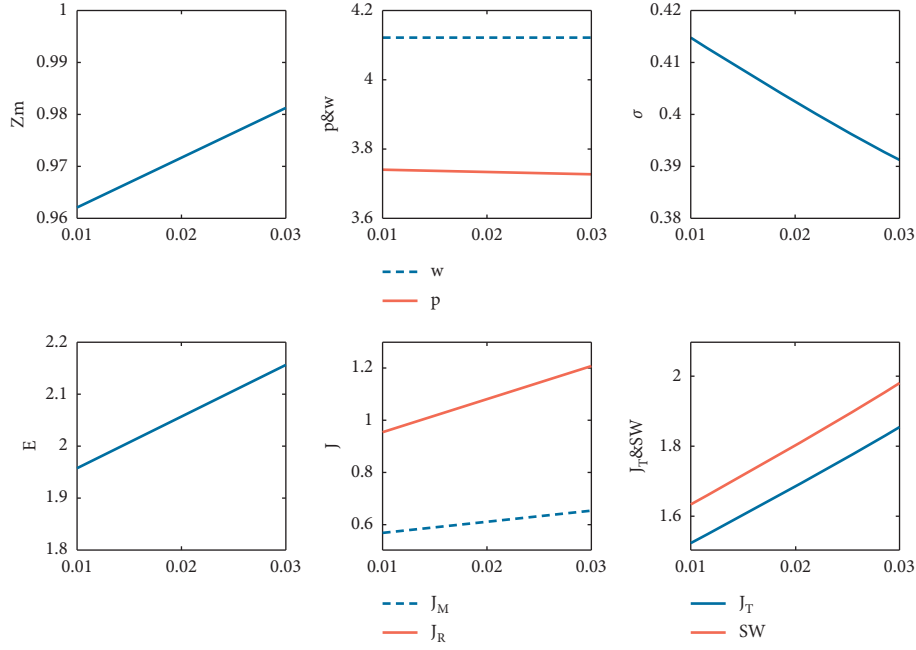


FIGURE 6: Sensitivity analysis of carbon trading price.

$SW(t)$. In addition, with the increase of p_e , δ , p , and w decrease.

Proof.

$$\begin{aligned} \frac{\partial Z_M^*}{\partial p_e} &= \frac{1}{\rho + \sigma} \frac{\alpha}{\mu_M} \left(\frac{7C}{32} + 1 \right) > 0 \frac{\partial w^*}{\partial p_e}, \\ \frac{\partial p^*}{\partial p_e} &= \frac{1}{4} (e_M - g_M) < 0, \\ \frac{\partial E(t)^*}{\partial p_e} &= \frac{1}{\sigma(\rho + \sigma)} \frac{\alpha^2}{\mu_M} (1 - e^{-\sigma t}) \left(\frac{7C}{32} + 1 \right) > 0, \\ \frac{\partial J_M(t)^*}{\partial p_e} &= \frac{\alpha^2 \left((1 - e^{-\sigma t} / \sigma) + (1/2\rho) \right) \left[(51A/128)(C + 1) + p_e \left((11C/32) + 2 \right) \right]}{(\rho + \sigma)^2 \mu_M} > 0, \\ \frac{\partial J_R(t)^*}{\partial p_e} &= \frac{\alpha^2 \left((1 - e^{-\sigma t} / \sigma) + 1/\rho \right) \left[C \left((7/16)A + p_e \right) + A \right]}{16(\rho + \sigma)^2 \mu_M} > 0, \\ \frac{\partial J_T(t)^*}{\partial p_e} &= \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1 - e^{-\sigma t}}{\sigma} \right) \left(A \left(\frac{21C}{256} + \frac{13}{32} \right) + p_e \left(\frac{13}{32} C + 2 \right) \right) \\ &\quad + \frac{1}{(\rho + \sigma)^2} \frac{\alpha^2}{\mu_M} \left(\frac{1}{2\rho} \right) \left(A \left(\frac{7C}{64} + \frac{15}{32} \right) + p_e \left(\frac{15}{32} C + 2 \right) \right) > 0, \\ \frac{\partial SW(t)^*}{\partial p_e} &= \frac{2\alpha^2 \left((1 - e^{-\sigma t} / \sigma) + (1/2\rho) \right) \left((7/32)A + p_e \right) \left((7/32)C + 1 \right)}{(\rho + \sigma)^2 \mu_M} > 0, \end{aligned} \tag{41}$$

where $C = 2k(a - bc - bp_e e_M + bp_e g_M)(g_M - e_M)$.

It is assumed that other parameters set above do not change, $p_e \in [0.01, 0.03]$. Relevant simulation results are shown in Figure 6.

Figure 6 reveals that with the increase of p_e , Z_M , E , $J_M(t)$, $J_R(t)$, $J_T(t)$, and $SW(t)$, all show a linear upward trend. Also, with the increase of p_e , δ , p , and w , all show a linear downward trend. \square

6. Conclusions

In the dual policy context of carbon trading and cost subsidies for investments in carbon emission reduction technology and taking into account the low-carbon preferences of consumers, we establish a dynamic game model of government, manufacturer, retailer, and consumer by using a differential game method. We use this model to analyse the equilibrium strategy and the evolution path of carbon emission reductions with respect to products, profits, and social welfare. Then we analyse the sensitivity of the main parameters. The significant findings include the following:

Through the numerical simulation of scalar value assignments, we can obtain the optimal strategy for the supply chain under cost subsidies: over time, the reduction of carbon emissions related to products, social welfare, and manufacturer's, retailer's, and supply chain's profits all grow. Further, the difference between manufacturer profits and retailer profits gets larger and larger, while the difference between social welfare levels and supply chain profits increases slightly. However, the rate of increase for social welfare and supply chain profits gets slower and slower, such that both eventually reach a certain stable level. At the same time, this paper analyses the impact of different parameters on the optimal strategies of each game subject. The study finds that the consumer's low-carbon preference coefficient, manufacturer's emission-reduction efforts' influence coefficient, and the carbon trading price positively impact emission reduction, supply chain profit, and social welfare. But the impacts vary. On the other side, the manufacturer's abatement cost coefficient negatively impacts them.

The theoretical significance of this paper is to take the government as the interest subject to participate in the game process and consider the consumer surplus, which provides a theoretical basis for strengthening the cooperation and exchange of supply chain enterprises in carbon emission technology. The management significance of this study is to provide analytical support for the technology investment of supply chain enterprises from a dynamic perspective and deeply understand its output decision-making process. It provides constructive suggestions for the further planning and design of relevant subjects. In a comprehensive consideration of endogenous government subsidies and consumers' low-carbon preferences, we established a two-stage decision model for optimising investment in supply chain emission reduction technology. In addition, in the model established in this paper, the emission reduction process only considers the attenuation characteristics such as equipment

aging and does not consider the impact of random factors on the carbon emission reduction process, and different subjects' preferences for price, fairness, and so on are not taken into account. Therefore, it will be our next research direction to establish a game model considering the influence of random factors, different preferences of relevant subjects, and even different cooperation modes among subjects.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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