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Government Participation in Supply Chain Low-Carbon Technology R&D and Green Marketing Strategy Optimization

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Abstract: This paper uses the differential game approach to construct a model of cooperative emission reduction involving the government, manufacturing firms, and retail firms under different power structures. It is found that the dominant player receives more subsidies; the development of a mechanism for horizontal technology R&D among enterprises can reduce the financial pressure on the government to implement compensation strategies and improve the effectiveness and performance of supply chain emission reduction; and the government can develop differentiated subsidy schemes to achieve Pareto optimality in the supply chain and environmental performance based on different game strategies and revenue-sharing agreements by enterprises.

Keywords: emission-reduction technology development; green marketing; government involvement; low-carbon supply chain

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1. Introduction

Industrialization has caused serious damage to the Earth's ecological environment, triggering a series of large-scale and irreversible environmental problems, such as global warming, and the hazards arising from these problems have seriously threatened the sustainable development of human society. At the global level, international policies and measures have been put in place to promote global CO_2 emission reduction. At the national level, the Chinese government has enacted a series of bills to address carbon emissions and established the world's largest carbon-trading market in 2021 to achieve the goal of peak carbon neutrality as soon as possible [1]. At the enterprise level, with the increasing pressure of government regulations and corporate social responsibility, the environmental management practices of enterprises have changed from passive to proactive. As Hepburn et al. [2] point out, the current global concern about climate change was actually caused by economic development, and its essence is the result of the evolution of individual corporate behavior. In this context, governments, academia, and industry are increasingly concerned about how to achieve carbon reduction targets in supply chains under emission regulations [3].

Global environmental problems cannot be solved by any one country alone; rather, they must be solved by global action, response, and cooperation, especially between enterprises [4–6]. The low-carbon supply chain emphasizes the cooperation of upstream and downstream enterprises in the supply chain, as well as effective communication within each enterprise department, and considers environmental factors in the whole lifecycle of the supply chain to achieve the optimization of its economic, social, and environmental benefits [7,8]. In the long run, the establishment of a low-carbon supply chain can help enterprises reduce costs and improve long-term benefits, while low-carbon supply chain practices can also help enterprises improve their corporate image and fulfill their social responsibilities [8–10]. Enterprises have not only applied low-carbon concepts internally but have also carried out a variety of low-carbon cooperation practices among supply chain partners. Supply chain cooperation to reduce emissions has become a new trend in enterprise development, and some large multinational companies, such as General Motors and Hewlett-Packard, have become active advocates of low-carbon supply chains [11,12].

The economics of carbon-emission reduction are essentially an external problem [13]. The benefits brought about by some people's carbon-emission reductions are shared by all, accompanied by external benefits that are not reflected in private emission-reduction benefits [14]. The marginal social benefits of carbon-emission reduction by enterprises are greater than the marginal private benefits, and there are positive externalities [15,16]. The government provides subsidies to enterprises to reduce carbon emissions, which provides them with incentives to improve the negative externalities affecting the environment [17]. For enterprises, on the one hand, government subsidies change the external environment of their operations and expand their decision-making space [18]; on the other hand, the internalization of external costs changes the cost structure of their operations, which is accompanied by changes in their decision-making behavior [19,20]. The government plays an active role in guiding enterprises' carbon-emission reduction behaviors and helping them achieve carbon-emission reduction targets through subsidy policies [21]. Therefore, studying cooperative emission reduction among supply chain enterprises under government subsidies can not only increase the motivation of enterprises to reduce emissions but also help improve their profits and achieve a win–win situation in terms of both the environment and performance [22,23].

Inspired by real business problems, the subjects of this study are low-carbon supply chains consisting of commodity manufacturers responsible for the development of low-carbon technologies [24], retailers responsible for green marketing, and government departments responsible for the development of targeted subsidy policies [25]. Specifically, this study focuses on the following key questions:

When the government participates in a low-carbon supply chain as an independent game player, what factors influence its optimal subsidy rate to supply chain members?

1. How do consumers' green preferences and government interventions affect the low-carbon innovation activities of enterprises within the supply chain?
2. How do key model parameters, especially factors related to emission reductions and market demand, affect the optimal outcomes and contract decisions?

To answer the above questions, we designed three differential game models in two contexts: government participation and government nonparticipation. Based on the proposed models, we derived the optimal research and development (R&D) input of low-carbon technology for manufacturers, the optimal green marketing input for retailers, the optimal government subsidy effort, and the optimal cost-sharing ratio between manufacturers and retailers. Finally, we examined the role of system parameters in the low-carbon supply chain through numerical arithmetic and sensitivity analysis. The main contributions of this paper are as follows: (1) Although some of the literature on government subsidy mechanisms in a low-carbon environment has explored the impact of government subsidies, there is a lack of research that considers the government as a participant in the game of low-carbon supply chain construction. Unlike conventional research, this paper uses the government subsidy rate as a control variable to study the interaction between government subsidies and enterprises' cooperative behavior in choosing emission reduction under different game structures, with the aim of determining the optimal emission-reduction strategy and government subsidy rate for the supply chain. (2) Currently, most research is performed in a single cycle, but it is more relevant to study supply chain abatement decisions over multiple cycles. Thus, this paper studies the problem of long-term supply chain emission-reduction decisions under government subsidies based on differential games. (3) From a dynamic architecture perspective, this paper incorporates both retailer dominance and low-carbon promotion into the government–business game model to bring the problem closer to reality. A critical range is given for the relative magnitude of the profit enhancement for manufacturers and retailers from abatement cost-sharing contracts, and the determinants of the amount of product reductions are indicated. (4) This paper further incorporates government subsidies, manufacturer emission reduction and retailer promotion into the dynamic framework of supply chain cooperative emission reduction and portrays the multiple effects of product price, emission reduction, and goodwill on market demand in the form of separate multiplication functions, which is a further extension of the existing research.

2. Literature Review

Three topics that are closely related to the focus of this paper are cooperative supply chain emission reduction, consumer low-carbon preferences and market demand, and the impact of government subsidy policies on supply chain construction.

2.1. Supply Chain Emission Reduction

The growing public awareness of green products has increased the market demand for low-carbon products, thus encouraging manufacturers to "go green" through innovation [26–28]. In addition, governments around the world have stepped up their green support, which has prompted manufacturers to undertake energy-saving activities and forced companies to innovate and reform in a green way [29,30]. Thus, in the context of economic globalization, low-carbon development is no longer the responsibility of a particular company but rather needs to be a shared project of all companies within society [31,32]. Compared with traditional supply chains, low-carbon supply chains emphasize environmental factors while pursuing economic benefits [33–35]; seek a balance between the benefits of the economy, society, and the environment; and emphasize the compatibility of activities including planning [36], procurement, production, distribution, and consumption with the environment [37,38]. It has been pointed out that it is impossible for enterprises with complex industrial chains to achieve effective low-carbon supply chain management through their own efforts alone [39,40] and that the relationship between enterprises and supply chain partners also affects the performance of low-carbon innovation [41,42]. Therefore, supply chain members actively seek external R&D collaboration with their upstream/downstream partners to jointly improve the environmental performance of their products [43,44]. This behavior refers to the cooperative efforts of partners or competitors to achieve mutually beneficial results [6,45]. For example, Walmart, a global retail giant, has formulated the "Sustainability 360 Program" to achieve green development, requiring suppliers to adopt corresponding environmental protection measures and technologies to ensure that the supplied goods meet the renewable requirements of the program [46,47]. The construction of a green supply chain is carried out by guiding the industry's leading enterprises to purchase products with low pollution emissions and high environmental performance, relying on the buyer-led market mechanism of bulk commodities [48,49], thus prompting more enterprises to comply with environmental laws, regulations, and standards to achieve the green upgrading and sustainable development of the entire industrial system. As such, supply chain cooperation in water-use and emission reduction has become a new trend in enterprise development [50,51].

2.2. Consumer Low-Carbon Preferences and Market Demand

Lampe and Gazda pioneered the study of corporate green marketing in the 1990s by viewing green marketing as the process by which companies take into account environmental factors in the production, use, and disposal of goods and respond with proactive coping strategies [52]. Furthermore, to reconcile social and environmental requirements with consumer needs, Paettie et al. expanded the concept of green marketing to a comprehensive management process that balances corporate profits and sustainable development based on social marketing theory [53]. In recent years, under the guidance of the government, environmental organizations, and retailers, consumers have become more environmentally conscious and have paid more attention to the environmental characteristics of products when making purchase decisions [54,55]. Some scholars have linked corporate green marketing behavior with corporate social responsibility [56], arguing that corporate green marketing is similar to environmental and sustainable marketing and that corporate green marketing strategies strengthen green brand reputation and environmental-culture-oriented driving forces [57], which have significant positive effects on corporate economic performance; this approach is also a way to fulfill corporate environmental responsibility [55,58]. In addition, the increased environmental awareness of consumers due to green marketing has forced companies to invest more in green and low-carbon development [59,60]. Wu et al., through a study of the sustainability reports of the world's top 500 companies, found that increasingly stringent emission reduction regulations and increasing consumer demand for low-carbon products have forced companies to consider sustainability requirements when making strategic decisions. Zhou et al. [61] concluded that the increase in consumer environmental awareness in recent years has contributed to the market demand for environmentally friendly products. Therefore, green marketing by retailers can not only promote the release of consumers' green consumption potential but also encourage manufacturing companies to pay more attention to the use of low-carbon production methods.

2.3. The Impact of Government Subsidy Policies on Supply Chain Construction

The manufacturing and sale of environmentally friendly goods is conducive to promoting resource conservation and environmental improvement [62]. However, in general, the production cost of environmentally friendly goods is higher than that of traditional products [63]; the purchasing power generated by consumers' environmental awareness is limited; and enterprises, as "economic agents" seeking to maximize profits, need government support to stimulate their environmentally friendly production [64,65]. According to Duan et al. [66], cost-flexible economic subsidy policies are more effective in promoting green production in enterprises than administrative command and control policies. In the international community, there are already many examples of government–business collaboration to reduce emissions. In Brazil, the agricultural sector implemented a policy of subsidizing technologies for economical irrigation systems and intensive livestock rearing for livestock enterprises in 2020, with the goal of achieving a reduction of 1.1 billion tonnes of carbon equivalent in the agricultural and livestock sector. The Chinese government enacted incentives for new energy vehicle manufacturers and sellers in 2019, including VAT exemptions, low-interest loans, and preferential tariffs, as a means to achieve carbon-emission reductions. The US government, a pioneer in carbon emissions, will provide a USD 8 billion incentive payment scheme to enterprises and potential consumers who produce clean hydrogen energy. In the EU, a low-carbon energy transition programme has been implemented for the downstream supply chain, with a targeted subsidy policy for the use of low-carbon technologies in the appliance industry. The Chinese government has introduced several subsidy policies to incentivize enterprises to engage in environmentally friendly production [67]. In 2016, the Chinese government coordinated relevant funds to support the progress of energy conservation and emission reduction through policies such as the Interim Measures for the Management of Financial Incentive Funds for Energy-saving Technical Transformation and the Interim Management Measures for the Management of Central Financial Incentives for the Elimination of Backward Production Capacity. In other words, the Chinese government rewarded business units with higher resource utilization efficiency [68,69]. These fiscal policies implemented by the government have played a major role in promoting green production among manufacturing enterprises. In addition, the effect of government subsidies on green production has also been determined by the budgets and targets of these financial subsidies [70]. Government environmental subsidies are divided into supplier, manufacturer, retailer, distributor, and consumer subsidies, depending on the recipients [71,72]. The impact of government subsidies on green production varies according to the recipients and the power structure of the supply chain [11,73]. Han et al. [74] found that government subsidies are a positive factor in supply chain operations and can stimulate manufacturers to produce low-carbon products as expected and choose a high-quality and high-price development model. Ma et al. [75] found that supply chain systems in manufacturer-dominated markets are more stable when the government implements dual low-carbon subsidies. The government should pay attention to the power structure of the market to determine the appropriate subsidy rate [11]. Li et al. [76] argued that the government should implement a differentiated subsidy policy and that when the difference in production costs between traditional and low-carbon products is large and the weight of environmental welfare and unit product emission reduction is high, the government can adopt a full subsidy system to achieve maximum environmental welfare.

Table 1 compares this paper with the existing literature on carbon emission reduction.

Table 1. Literature comparison.

Literature	Cooperation in Supply Chain Emission Reduction	Consumer Low-Carbon Preference	Government Subsidies	Cost-Sharing Contracts
Halat, et al. [77–82]	√	×	×	√
[83–88]	√	√	×	√
[13,25,89–91]	√	×	×	×
[92–96]	√	√	×	×
This paper	√	√	√	√

3. Parameter Description and Assumptions

The main parameters of this paper are described in Table 2.

Table 2. Description of the main parameters.

Notation	Definition
Π_u, Π_d	Marginal revenue for manufacturers, retailers
E	Commodity market demand
I_u	R&D investment in abatement technology for manufacturing companies
I_d	Green marketing input for retail companies
φ_u, φ_d	Government subsidy factor for manufacturers, retailers
y	Commodity emission reductions
w_u, w_d	Cost factors for manufacturer and retailer inputs
α	Sensitivity factor of emission reduction effect to input efforts of manufacturing companies
γ	Technical natural attenuation coefficient
s	Sensitivity factor of market demand to the degree of commodity abatement
ε	Impact coefficient of green marketing on market demand in retail enterprises
E_0	Demand at the initial moment of the market
y_0	Emission reduction effect at the initial moment of the commodity
ρ	Discount rate
θ	R&D incentive subsidies from retail to manufacturing companies
R	Corporate revenue

Assumption 1. *According to Jorgensen et al. [97], considering that both the abatement technology inputs of manufacturing enterprises and the marketing costs of retail enterprises have convex characteristics, the cost functions of manufacturing and retail enterprises at moment t can be expressed as follows:*

$$C_u(I_u(t)) = \frac{w_u}{2} I_u^2(t), C_d(I_d(t)) = \frac{w_d}{2} I_d^2(t) \tag{1}$$

where $w_u w_d$ is the cost factor for manufacturer and retailer inputs, I_u is the R&D investment in abatement technology for manufacturing companies, and I_d is the green marketing input for retail companies. This cost function satisfies $C_{u,d}{}'(I_{u,d}) > 0$ and $C_{u,d}{}''(I_{u,d}) > 0$, which means that the cost input of abatement technology and market promotion satisfies the effect of diminishing marginal returns.

Assumption 2. *The trace function of the emission reduction effect of the product can be expressed as:*

$$\dot{y}(t) = \alpha I_u(t) - \gamma y(t) \tag{2}$$

where $\dot{y}(t)$ indicates the degree of commodity emission reduction at time t, α indicates the sensitivity factor of the emission reduction effect to the input efforts of manufacturing companies, $I_u(t)$ refers to the manufacturer's investment in emission reduction technology at time t, γ indicates the natural attenuation coefficient of emission reduction technology, and the above parameters are positive numbers. The equation is a first-order linear differential equation, which indicates that the emission reduction effect of products increases with the increase in emission reduction technology investment by manufacturing enterprises; that is, the emission reduction effect is a dynamic change process, and the emission reduction effect has the characteristics of natural attenuation with the aging of emission reduction equipment and other factors.

Assumption 3. *According to Dangelico et al., the sales function of goods can be set as:*

$$E(t) = sy(t) + \varepsilon I_d(t) + E_0 \tag{3}$$

where $E(t)$ represents the commodity market sales volume at time t, $y(t)$ represents the emission reduction degree of commodities,s represents the low-carbon preference degree of consumers,ε indicates the influence coefficient of retail enterprises' green marketing on market demand, and E_0 represents the demand at the initial time of the market. According to consumer behavior theory and signal theory, assuming the existence of low-carbon preference consumers in the market, with the investment of emission reduction technology by manufacturing enterprises and the promotion of green marketing by retail enterprises, product goodwill continues to improve, which has a positive impact on the market sales of products.

To simplify the model, the inventory and out-of-stock costs of manufacturers and retailers are not considered, the influence of market price and other factors on product sales is not considered, and both enterprises make decisions based on complete information.

Retail and manufacturing enterprises are leaders and followers, respectively, and constitute a Stackelberg game. The retail enterprise subsidizes its R&D investment in the emission reduction technology of the manufacturing enterprise at the proportion of θ. The government adopts subsidized regulation for manufacturing and retail enterprises, the cost subsidies for which are $\varphi_u(t)$ and $\varphi_d(t)$, respectively. The revenue functions of manufacturing and retail enterprises are as follows:

$$\begin{cases} S_u = \Pi_u E(t) - (1 - \theta(t) - \varphi_u(t))C_u(t) \\ S_d = \Pi_d E(t) - (1 - \varphi_d(t))C_d(t) - \theta(t)C_u(I_u) \end{cases} \tag{4}$$

The government has implemented a subsidy policy to provide subsidies to manufacturing enterprises in return for their investment in the R&D of emission reduction technologies and to retail enterprises in return for green marketing in the market, with the aim of maximizing their profits.

$$S_g = (\Pi_u + \Pi_d)E(t) - C_u(t) - C_d(t) \tag{5}$$

For ease of presentation, "subsidy-based regulation + fully collaborative decision" is denoted as BC, "subsidy-based regulation + Nash noncooperative decision" is denoted as BD, "subsidy-based regulation + R&D incentive contract decision" is denoted as BE, "unsubsidized + fully collaborative decision" is denoted as NC, "unsubsidized + Nash noncooperative decision" is denoted as ND, and "unsubsidized + R&D incentive contract decision" is denoted as NE.

4. Gaming Strategies without Government Subsidies

4.1. Fully Collaborative Decision Making

Under fully collaborative decision making, manufacturing and retail enterprises make decisions with the objective of maximizing their total revenue, and the objective functions of the supply chain as a whole are as follows:

$$\begin{cases} R_T = \max \int_0^{\infty} e^{-\rho t}\left\{(\Pi_u + \Pi_d)E(t) - \frac{w_u}{2} I_u^2(t) - \frac{w_d}{2} I_d^2(t)\right\}dt \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{6}$$

Both enterprises make decisions based on complete information, and the discount rate at any point in time is ρ ($\rho > 0$).

Proposition 1. *The equilibrium result of fully collaborative decision making is:*

$$\begin{gathered} I_u^{NC^*} = \frac{\alpha(\Pi_u+\Pi_d)s}{w_u(\rho+\gamma)}, I_d^{NC^*} = \frac{(\Pi_u+\Pi_d)\varepsilon}{w_d}, \\ y^{NC^{**}} = \frac{(\Pi_u+\Pi_d)s\alpha^2}{w_u\gamma(\rho+\gamma)} - \left(\frac{(\Pi_u+\Pi_d)s\alpha^2}{w_u\gamma(\rho+\gamma)} - y_0\right)e^{-\gamma t} \end{gathered} \tag{7}$$

The optimal revenue function of the supply chain is expressed as:

$$V_T{}^{NC^{**}} = \frac{(\Pi_u + \Pi_d)s}{\rho + \gamma} y^{NC^{**}} + \frac{(\Pi_u + \Pi_d)E_0}{\rho} + \frac{(\Pi_u + \Pi_d)^2\varepsilon^2}{2\rho w_d} + \frac{(\Pi_u + \Pi_d)^2\alpha^2\varepsilon^2}{2\rho w_u(\rho + \gamma)^2} \tag{8}$$

The equilibrium result is an ideal situation. Under the assumptions of rational people, incentive compatibility, and complete information, the manufacturer's investment in low-carbon technology is $\frac{\alpha(\Pi_u+\Pi_d)s}{w_u(\rho+\gamma)}$*, retailers' investment in green publicity is* $\frac{(\Pi_u+\Pi_d)\varepsilon}{w_d}$*, the product emission reduction reaches the optimal value, and the overall profit of the supply chain reaches the Pareto optimal state.*

See Appendix A for proof.

4.2. Nash Noncollaborative Decision Making

Under Nash noncooperative decision making, manufacturing and retail enterprises maximize their respective interests as their objectives. The objective functions of manufacturing and retail enterprises under this decision are as follows:

$$\begin{cases} R_u^{BD} = \max \int_0^{\infty} e^{-\rho t}\left\{\Pi_u(sy(t) + \varepsilon I_d + E_0) - \frac{w_u}{2}\left(I_u^{BD}\right)^2\right\}dt \\ R_d^{BD} = \max \int_0^{\infty} e^{-\rho t}\left\{\Pi_d(sy(t) + \varepsilon I_d + E_0) - \frac{w_d}{2}\left(I_d^{BD}\right)^2\right\}dt \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{9}$$

Proposition 2. *The equilibrium result of Nash noncooperative decision making is:*

$$I_u^{ND^{**}} = \frac{\Pi_u s\alpha}{w_u(\rho+\gamma)}, I_d^{ND^{**}} = \frac{\Pi_d \varepsilon}{w_d}, y^{ND^{**}} = \frac{\Pi_u s\alpha^2}{w_u\gamma(\rho+\gamma)} - \left(\frac{\Pi_u s\alpha^2}{w_u\gamma(\rho+\gamma)} - y_0\right)\mathrm{e}^{-\gamma t} \quad (10)$$

The optimal revenue functions for manufacturing and retail firms are:

$$V_u{}^{BD^{**}} = \frac{\Pi_u s}{\rho+\gamma} y^{BD^{**}} + \frac{\Pi_u E_0}{\rho} + \frac{\Pi_u \Pi_d \varepsilon^2}{\rho w_d} + \frac{(\Pi_u s\alpha)^2}{2\rho w_u(\rho+\gamma)^2} \quad (11)$$

$$V_d{}^{BD^{**}} = \frac{\Pi_d s}{\rho+\gamma} y^{BD^{**}} + \frac{\Pi_d E_0}{\rho} + \frac{\Pi_d{}^2 \varepsilon^2}{2\rho w_d} + \frac{\Pi_u \Pi_d (s\alpha)^2}{2\rho w_u(\rho+\gamma)^2} \quad (12)$$

At this time, the manufacturer and the retailer are in a noncooperative game, and the manufacturer's investment in low-carbon technology is $\frac{\Pi_u s\alpha}{w_u(\rho+\gamma)}$. Retailers' investment in green publicity is $\frac{\Pi_d \varepsilon}{w_d}$, and the profits of the manufacturer and the retailer reach the maximum value in the noncooperative state, but the supply chain as a whole has not reached the Pareto optimal state. The analysis of the equilibrium results of this decision-making model is helpful for setting reasonable constraints on manufacturers and retailers when designing contracts and for testing the effect of contract coordination.

See Appendix B for proof.

Corollary 1. *The equilibrium government subsidies to manufacturing and retail enterprises in this decision scenario are negatively related to their marginal profits and positively related to each other's marginal profits. That is, enterprises with high marginal value added tend to receive fewer subsidies, and highly subsidized enterprises crowd out subsidies from other members in the value chain. The effect of the sensitivity coefficient of market demand on the degree of commodity emission reduction, the marginal profit of manufacturing enterprises, the sensitivity coefficient of the commodity emission reduction effect on the equilibrium input of manufacturing enterprises, and government subsidies have positive effects on the emission reduction technology input of manufacturing enterprises, and the emission reduction R&D cost coefficient, natural decay rate, and discount rate are negatively correlated with the input effort of manufacturing enterprises. The equilibrium input of retail enterprises is positively correlated with their own marginal profit, the marginal profit of manufacturing enterprises, and the effect of the sensitivity coefficient of market demand on the input of emission reduction green marketing.*

4.3. Retailer-Led R&D Cost-Sharing Decisions

As consumers' awareness of emission reduction increases, it is necessary not only for manufacturing enterprises to conduct emission reduction technology R&D in the production process of goods but also for retail enterprises to communicate the emission reduction information of goods to consumers to obtain greater market demand, so that enterprises can gain more revenue. In this decision-making scenario, the retailer, as the dominant party, motivates the manufacturing enterprise to further improve its emission reduction R&D investment to provide consumers with more emission reduction and environmentally friendly products and shares the emission reduction technology R&D cost of the manufacturing enterprise, with the sharing ratio of θ. The first stage of the retailer determines the optimal public green marketing input and cost-sharing ratio for the manufacturing enterprise. In the second stage, manufacturing enterprises determine their own optimal emission reduction R&D inputs according to the optimal public green marketing inputs and cost-sharing ratio determined by retail enterprises. The objective functions of manufacturing enterprises, retail enterprises, and the government are, respectively, as follows:

$$\begin{cases} R_u^{BE} = \max\limits_{I_u^{BE} \geq 0} \int_0^\infty \mathrm{e}^{-\rho t} \{\Pi_u E - (1-\theta)C_u\} \mathrm{d}t \\ R_d^{BE} = \max\limits_{I_d^{BE} \geq 0} \int_0^\infty \mathrm{e}^{-\rho t} \{\Pi_d E - C_d - \theta C_u\} \mathrm{d}t \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{13}$$

Proposition 3. *The equilibrium outcome of the two-stage R&D cost-sharing decision is:*

$$\begin{aligned} & I_u^{NE^{**}} = \frac{(\Pi_u + 2\Pi_d)s\alpha}{2w_u(\rho+\gamma)}, I_d^{NE^{**}} = \frac{\Pi_d \varepsilon}{w_d}, \theta = \frac{2\Pi_d - \Pi_u}{\Pi_u + 2\Pi_d}, \\ & y^{NE^{**}} = \frac{(\Pi_u + 2\Pi_d)s\alpha^2}{2w_u\gamma(\rho+\gamma)} - \left(\frac{(\Pi_u + 2\Pi_d)s\alpha^2}{2w_u\gamma(\rho+\gamma)} - y_0\right)\mathrm{e}^{-\gamma t} \end{aligned} \tag{14}$$

The optimal revenue functions for manufacturing and retail firms are:

$$V_u{}^{NE^{**}} = \frac{\Pi_u s}{\rho+\gamma} y^{NE^{**}} + \frac{\Pi_u E_0}{\rho} + \frac{\Pi_u \Pi_d \varepsilon^2}{\rho w_d} + \frac{(s\alpha)^2 (2\Pi_d + \Pi_u)\Pi_u}{4\rho w_u (\rho+\gamma)^2} \tag{15}$$

$$V_d{}^{NE^{**}} = \frac{\Pi_d s}{\rho+\gamma} y^{NE^{**}} + \frac{\Pi_d E_0}{\rho} + \frac{\Pi_d{}^2 \varepsilon^2}{2\rho w_d} + \frac{(\Pi_u + 2\Pi_d)^2 (s\alpha)^2}{8\rho w_u (\rho+\gamma)^2} \tag{16}$$

At this time, the manufacturer and the retailer sign a cost-sharing contract; the manufacturer's investment in low-carbon technology is $\frac{(\Pi_u+2\Pi_d)s\alpha}{2w_u(\rho+\gamma)}$, the retailers' investment in green publicity is $\frac{\Pi_d \varepsilon}{w_d}$, the subsidy coefficient of the retail enterprise to the manufacturing enterprise is $\frac{2\Pi_d - \Pi_u}{\Pi_u + 2\Pi_d}$, and the profits of the manufacturer and the retailer reach the maximum value under the cost-sharing contract, but the supply chain as a whole has not reached the Pareto optimal state.

See Appendix C for proof.

Corollary 2. *From Proposition 5, we know that the equilibrium subsidy rate of the government to retail enterprises is twice as high as that received by manufacturing enterprises and that it is positively correlated with the marginal profit of manufacturing enterprises and negatively correlated with that of retail enterprises. The game position of value chain members can explain this result. As the dominant party in the game, retail enterprises need to not only provide a level of R&D support to the upstream manufacturing enterprises for emission reduction technology but also invest in green marketing to stimulate demand; thus, retail enterprises receive more subsidies. The R&D support provided by retail enterprises to manufacturing enterprises for emission reduction technology is negatively correlated with the marginal profit of manufacturing enterprises and positively correlated with that of retail enterprises.*

5. Game Strategies for Government Involvement

5.1. Fully Collaborative Decision Making

Under fully collaborative decision making, the government makes the decision first by specifying the ratio of subsidies to manufacturing and retail enterprises, and then manufacturing and retail enterprises make the decision with the objective of maximizing their total revenue; the objective functions of the business alliance and the government are as follows:

$$\begin{cases} R_T = max \int_0^\infty e^{-\rho t}\{(\Pi_u + \Pi_d)E(t) - (1-\varphi_u)\frac{w_u}{2}I_u^2(t) - (1-\varphi_d)\frac{w_d}{2}I_d^2(t)\}dt \\ R_g = max \int_0^\infty e^{-\rho t}\{(\Pi_u + \Pi_d)E(t) - \frac{w_u}{2}I_u^2(t) - \frac{w_d}{2}I_d^2(t)\}dt \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{17}$$

Proposition 4. *The equilibrium result of fully collaborative decision making is:*

$$\begin{aligned} I_u^{BC^{**}} &= \frac{(\Pi_u+\Pi_d)s\alpha}{w_u(\rho+\gamma)}, I_d^{BC^{**}} = \frac{(\Pi_u+\Pi_d)\varepsilon}{w_d}, \varphi_u^{BC^*} = 0, \varphi_d^{BC^*} = 0, \\ y^{BC^{**}} &= \frac{(\Pi_u+\Pi_d)s\alpha^2}{w_u\gamma(1-\varphi_u^{a^*})(\rho+\gamma)} - \left(\frac{(\Pi_u+\Pi_d)s\alpha^2}{w_u\gamma(1-\varphi_u^{a^*})(\rho+\gamma)} - y_0\right)e^{-\gamma t} \end{aligned} \tag{18}$$

The optimal revenue function of a business alliance is:

$$V_T{}^{BC^{**}} = \frac{(\Pi_u+\Pi_d)s}{(\rho+\gamma)}y^{BC^{**}} + \frac{(\Pi_u+\Pi_d)E_0}{\rho} + \frac{(\Pi_u+\Pi_d)^2\varepsilon^2}{2\rho w_d} + \frac{(\Pi_u+\Pi_d)^2(s\alpha)^2}{2\rho w_u(\rho+\gamma)^2} \tag{19}$$

Complete collaborative decision-making is an idealized situation. Under the assumptions of rational people, incentive compatibility, and complete information, the manufacturer's investment in low-carbon technology is $\frac{\alpha(\Pi_u+\Pi_d)s}{w_u(\rho+\gamma)}$, retailers' investment in green publicity is $\frac{(\Pi_u+\Pi_d)\varepsilon}{w_d}$, the government's optimal subsidy to the two enterprises is 0, and the overall profit of the supply chain reaches the Pareto optimal state.

See Appendix D for proof.

5.2. Nash Noncollaborative Decision Making

Under Nash noncollaborative decision making, manufacturing and retail enterprises aim to maximize their respective interests. The game sequence of the government, manufacturing enterprises, and retail enterprises is as follows: the government sets its subsidy coefficients φ_u and φ_d for manufacturing and retail enterprises, retail enterprises determine the investment in public low-carbon publicity, and manufacturing enterprises determine the investment in low-carbon technology. The objective functions of manufacturing enterprises, retail enterprises, and the government under these decision-making conditions are as follows:

$$\begin{cases} R_u^{BD} = \max\limits_{I_u^{BD}\geq 0} \int_0^\infty e^{-\rho t}\left\{\Pi_u(sy(t) + \varepsilon I_d + E_0) - (1-\varphi_u)\frac{w_u}{2}\left(I_u^{BD}\right)^2\right\}dt \\ R_d^{BD} = \max\limits_{I_d^{BD}\geq 0} \int_0^\infty e^{-\rho t}\left\{\Pi_d(sy(t) + \varepsilon I_d + E_0) - (1-\varphi_d)\frac{w_d}{2}\left(I_d^{BD}\right)^2\right\}dt \\ R_g^{BD} = \max\limits_{\varphi_u,\varphi_d} \int_0^\infty e^{-\rho t}\{(\Pi_u+\Pi_d)E(t) - \frac{w_u}{2}I_u^2(t) - \frac{w_d}{2}I_d^2\}dt \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{20}$$

Proposition 5. *The equilibrium outcome of subsidy-based regulation + Nash noncooperative decision making is:*

$$I_u^{BD^{**}} = \frac{\Pi_u s\alpha}{w_u\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)}, I_d^{BD^{**}} = \frac{\Pi_d \varepsilon}{w_d\left(1-\varphi_d^{BD^*}\right)}, \varphi_u^{BD^*} = \frac{\Pi_d}{\Pi_u+\Pi_d}, \varphi_d^{BD^*} = \frac{\Pi_u}{\Pi_u+\Pi_d},$$
$$y^{BD^{**}} = \frac{\Pi_u s\alpha^2}{w_u\gamma\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)} - \left(\frac{\Pi_u s\alpha^2}{w_u\gamma\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)} - y_0\right)\mathrm{e}^{-\gamma t} \tag{21}$$

The optimal revenue functions for manufacturing and retail firms are

$${V_u}^{BD^{**}} = \frac{\Pi_u s}{\rho+\gamma} y^{BD^{**}} + \frac{\Pi_u E_0}{\rho} + \frac{\Pi_u \Pi_d \varepsilon^2}{\rho w_d\left(1-\varphi_d^{BD^*}\right)} + \frac{(\Pi_u s\alpha)^2}{2\rho w_u\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)^2} \tag{22}$$

$${V_d}^{BD^{**}} = \frac{\Pi_d s}{\rho+\gamma} y^{BD^{**}} + \frac{\Pi_d E_0}{\rho} + \frac{{\Pi_d}^2 \varepsilon^2}{2\rho w_d\left(1-\varphi_d^{BD^*}\right)} + \frac{\Pi_u \Pi_d (s\alpha)^2}{\rho w_u\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)^2} \tag{23}$$

At this time, the manufacturer and retailer are in a noncooperative game, and the manufacturer's investment in low-carbon technology is $\frac{\Pi_u s\alpha}{w_u\left(1-\varphi_u^{BD^*}\right)(\rho+\gamma)}$. *Retailers' investment in green publicity is* $\frac{\Pi_d \varepsilon}{w_d\left(1-\varphi_d^{BD^*}\right)}$, *and the optimal government subsidies to manufacturers and retailers are* $\frac{\Pi_d}{\Pi_u+\Pi_d}$, $\frac{\Pi_u}{\Pi_u+\Pi_d}$. *At this point, the profits of the manufacturer and the retailer reach the maximum value in the noncooperative state, but the supply chain as a whole has not reached the Pareto optimal state.*

See Appendix E for proof.

Corollary 3. *The equilibrium government subsidies to manufacturing and retail enterprises in this decision scenario are negatively related to their marginal profits and positively related to each other's marginal profits. That is, enterprises with high marginal value added tend to receive fewer subsidies, and highly subsidized enterprises crowd out the subsidies of other members in the value chain. The sensitivity coefficient of market demand to the degree of commodity abatement, the marginal profit of manufacturing enterprises, the sensitivity coefficient of commodity abatement effect to the equilibrium input of manufacturing enterprises, and government subsidies have positive effects on the abatement technology input of manufacturing enterprises, and the abatement R&D cost coefficient, natural decay rate, and discount rate are negatively correlated with the input efforts of manufacturing enterprises. The equilibrium input of retail enterprises is positively correlated with their own marginal profit, the marginal profit of manufacturing enterprises, and the effect of the sensitivity coefficient of market demand on the input of emission reduction green marketing.*

5.3. Retail Companies Lead the Next Three Stages of R&D Incentive Decisions

As consumers' low-carbon awareness increases, not only do manufacturing enterprises need to conduct low-carbon technology R&D in the production process, but retail enterprises also need to communicate the low-carbon information of goods to consumers to obtain greater market demand so that enterprises can gain more revenue. In this decision situation, the retailer, as the leading party, motivates the manufacturing enterprises to further improve their low-carbon R&D investment to provide consumers with more low-carbon products and shares the low-carbon technology R&D cost with the manufacturing enterprises, with a sharing ratio of θ. In the first stage, the government sets the subsidy ratio for the manufacturing and retail enterprises. In the second stage, retail enterprises determine the optimal input of public green marketing and the cost-sharing ratio for manufacturing enterprises. In the third stage, manufacturing enterprises determine the optimal input of public green marketing and the cost-sharing ratio for manufacturing enterprises. In the fourth stage, manufacturing enterprises determine their own optimal low-carbon R&D inputs according to the optimal public green marketing inputs and cost-sharing ratio determined by retail enterprises. The objective functions of manufacturing enterprises, retail enterprises, and the government are as follows:

$$\begin{cases} R_u^{BE} = \max\limits_{I_u^{BE} \geq 0} \int_0^\infty \mathrm{e}^{-\rho t} \{ \Pi_u E - (1 - \varphi_u^{BE} - \theta) C_u \} \mathrm{d}t \\ R_d^{BE} = \max\limits_{I_d^{BE} \geq 0} \int_0^\infty \mathrm{e}^{-\rho t} \{ \Pi_d E - (1 - \varphi_d^{BE}) C_d - \theta C_u \} \mathrm{d}t \\ R_g^{BE} = \max\limits_{\varphi_u \geq 0 \varphi_D \geq 0} \int_0^\infty \mathrm{e}^{-\rho t} \{ (\Pi_u + \Pi_d) E - C_u - C_d \} \mathrm{d}t \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{24}$$

Proposition 6. *The equilibrium outcome of the subsidy regulation + three-stage cost compensation incentive decision is:*

$$I_u^{BE^{**}} = \frac{s\alpha(\Pi_u + 2\Pi_d)}{2w_u\left(1 - \varphi_u^{c^*}\right)(\rho + \gamma)}, I_d^{BE^{**}} = \frac{\varepsilon \Pi_d}{w_d\left(1 - \varphi_d^{c^*}\right)}, \varphi_u^{BE^*} = \frac{\Pi_u}{2(\Pi_u + \Pi_d)},$$
$$\varphi_d^{BE^*} = \frac{\Pi_u}{\Pi_u + \Pi_d}, \theta = \frac{\left(1 - \varphi_u^{BE^*}\right)(2\Pi_d - \Pi_u)}{\Pi_u + 2\Pi_d}, y^{BE^{**}} = \frac{(\Pi_u + 2\Pi_d)s\alpha^2}{2w_u\gamma\left(1 - \varphi_u^{BE^*}\right)(\rho + \gamma)} - \left(\frac{(\Pi_u + 2\Pi_d)s\alpha^2}{2w_u\gamma\left(1 - \varphi_u^{BE^*}\right)(\rho + \gamma)} - y_0\right)\mathrm{e}^{-\gamma t} \tag{25}$$

The optimal revenue functions for manufacturing and retail firms are:

$$V_u{}^{BE^{**}} = \frac{\Pi_u s}{\rho + \gamma} y^{BE^{**}} + \frac{\Pi_u E_0}{\rho} + \frac{\Pi_u \Pi_d \varepsilon^2}{\rho w_d \left(1 - \varphi_d^{BE^*}\right)} + \frac{(s\alpha)^2 (2\Pi_d + \Pi_u)\Pi_u}{4\rho w_u (1 - \varphi_u^{BE^*})(\rho + \gamma)^2} \tag{26}$$

$$V_d{}^{BE^{**}} = \frac{\Pi_d s}{\rho + \gamma} y^{BE^{**}} + \frac{\Pi_d E_0}{\rho} + \frac{\Pi_d{}^2 \varepsilon^2}{2\left(1 - \varphi_d^{BE^*}\right)\rho w_d} + \frac{(\Pi_u + 2\Pi_d)^2 (s\alpha)^2}{8\rho w_u (1 - \varphi_u^{BE^*})(\rho + \gamma)^2} \tag{27}$$

At this time, the retailer plays a dominant role in the power structure of the supply chain. The manufacturer and the retailer have signed a cost-sharing contract. The manufacturer's investment is $\frac{(\Pi_u + 2\Pi_d)s\alpha}{2w_u(\rho + \gamma)}$*; the retailers' investment in green publicity is* $\frac{\Pi_d \varepsilon}{w_d}$*; the government subsidy coefficients for retail enterprises and manufacturing enterprises are, respectively* $\frac{\Pi_u}{\Pi_u + \Pi_d}$ *and* $\frac{\Pi_u}{2(\Pi_u + \Pi_d)}$*; the cost-sharing coefficient among enterprises is* $\frac{\left(1 - \varphi_u^{BE^*}\right)(2\Pi_d - \Pi_u)}{\Pi_u + 2\Pi_d}$*; the market sales volume of the product reaches the maximum; and the profits of the manufacturer and the retailer reach the maximum value under these decision conditions.*

See Appendix F for proof.

Corollary 4. *From Proposition 5, we know that the equilibrium subsidy rate of the government to retail enterprises is twice as high as that received by manufacturing enterprises, and it is positively correlated with the marginal profit of manufacturing enterprises and negatively correlated with that of retail enterprises. The game position of the value chain members can explain this result. As the dominant party in the game, retail enterprises need to not only provide a level of R&D support to upstream manufacturing enterprises for emission reduction technology but also invest in green marketing to stimulate demand; thus, retail enterprises receive more subsidies. The R&D support provided by retail enterprises to manufacturing enterprises for emission reduction technology is negatively correlated with the marginal profit of manufacturing enterprises and positively correlated with that of retail enterprises.*

5.4. Three-Stage R&D Incentive Decision under Manufacturing Company Domination

To analyze the impact of game position on the government subsidies received by enterprises, a symmetrical three-stage R&D incentive-based decision model, similar to that in Section 5.3, is established under the dominance of the manufacturing enterprise. In this decision scenario, the manufacturing enterprise, as the dominant party, incentivizes the retailer to further increase its green marketing investment and to raise consumers' awareness of emission reduction and thus stimulate market demand for emission reduction products. The retailer's R&D cost for emission reduction technology is shared, and the sharing ratio is μ. In the first stage, the government sets the subsidy ratio for the manufacturing enterprise and the retailer. In the second stage, the manufacturing enterprise determines the optimal inputs of emission reduction technology R&D and the cost-sharing ratio for retail enterprises. In the third stage, retail enterprises determine their own optimal inputs of green marketing according to the optimal public green marketing inputs and cost-sharing ratio determined by retail enterprises. The objective functions of manufacturing enterprises, retail enterprises, and the government are as follows:

$$\begin{cases} R_u^{BM} = \max\limits_{I_u^{BM} \geq 0} \int_0^{\infty} \mathrm{e}^{-\rho t}\{\Pi_u E - (1-\varphi_u^{BM})C_u - \mu C_d\}\mathrm{d}t \\ R_d^{BM} = \max\limits_{I_d^{BM} \geq 0} \int_0^{\infty} \mathrm{e}^{-\rho t}\{\Pi_d E - (1-\varphi_d^{BM} - \mu)C_d\}\mathrm{d}t \\ R_g^{BM} = \max\limits_{\varphi_u \geq 0 \varphi_D \geq 0} \int_0^{\infty} \mathrm{e}^{-\rho t}\{(\Pi_u + \Pi_d)E - C_u - C_d\}\mathrm{d}t \\ s.t\ \dot{y}(t) = \alpha I_u(t) - \gamma y(t), y(0) \geq 0 \end{cases} \tag{28}$$

Proposition 7. *The equilibrium outcome of this decision is:*

$$I_u^{BM^{**}} = \frac{\Pi_u s\alpha}{w_u(\rho+\gamma)\left(1-\varphi_u^{BM^*}\right)}, I_d^{BM^{**}} = \frac{(2\Pi_u+\Pi_d)\varepsilon}{2w_d\left(1-\varphi_d^{BM^*}\right)}, \varphi_u^{BM^*} = \frac{\Pi_d}{\Pi_u+\Pi_d},$$
$$\varphi_d^{BM^*} = \frac{\Pi_d}{2(\Pi_u+\Pi_d)}, \mu = \frac{2\Pi_u-\Pi_d}{2\Pi_u+\Pi_d}, y^{BM^{**}} = \frac{\Pi_u s\alpha^2}{w_u\gamma\left(1-\varphi_u^{BM^*}\right)(\rho+\gamma)} - \left(\frac{\Pi_u s\alpha^2}{w_u\gamma\left(1-\varphi_u^{BM^*}\right)(\rho+\gamma)} - y_0\right)\mathrm{e}^{-\gamma t} \tag{29}$$

The optimal revenue functions for manufacturing and retail firms are:

$${V_u}^{BM^{**}} = \frac{\Pi_u s}{\rho+\gamma}y^{BM^{**}} + \frac{\Pi_u E_0}{\rho} + \frac{(2\Pi_u+\Pi_d)\varepsilon^2}{8\rho\left(1-\varphi_d^{BM^*}\right)w_d} + \frac{(\Pi_u s\alpha)^2}{\rho w_u\left(1-\varphi_u^{BM^*}\right)(\rho+\gamma)^2} \tag{30}$$

$${V_d}^{BM^{**}} = \frac{\Pi_d s}{\rho+\gamma}y^{BD^{**}} + \frac{\Pi_d E_0}{\rho} + \frac{{\Pi_d}^2\varepsilon^2}{4\left(1-\varphi_d^{BM^*}\right)\rho w_d} + \frac{\Pi_u\Pi_d(s\alpha)^2}{2\rho w_u\left(1-\varphi_u^{BM^*}\right)(\rho+\gamma)^2} \tag{31}$$

At this time, the manufacturer occupies a dominant position in the power structure of the supply chain, and the manufacturer and the retailer have signed a cost-sharing contract. The manufacturer is $\frac{\Pi_u s\alpha}{w_u(\rho+\gamma)\left(1-\varphi_u^{BM^*}\right)}$*, the retailer's investment in green publicity is* $\frac{(2\Pi_u+\Pi_d)\varepsilon}{2w_d\left(1-\varphi_d^{BM^*}\right)}$*, and the government subsidy coefficients for retail enterprises and manufacturing enterprises are* $\frac{\Pi_d}{2(\Pi_u+\Pi_d)}$ *and* $\frac{\Pi_d}{\Pi_u+\Pi_d}$*. The cost-sharing coefficient between enterprises is* $\frac{2\Pi_u-\Pi_d}{2\Pi_u+\Pi_d}$*, the market sales volume of the product reaches the maximum, and the profits of the manufacturer and the retailer reach the maximum value under the decision scenario.*

The proof is similar to that of Proposition 6.

5.5. Analysis of Results

The following corollary can be obtained from the equilibrium results of the above model.

Corollary 5. *In the absence of government subsidies, when the marginal profits of manufacturing and retail enterprises satisfy $2\Pi_d > \Pi_u$, the equilibrium R&D investment and product market demand of manufacturing enterprises reach the maximum under the fully cooperative decision scenario, the next highest under the cost compensation decision scenario, and the minimum under the Nash noncooperative decision scenario. Pareto improvement is achieved for the corresponding parameters of the noncooperative decision; when $2\Pi_d < \Pi_u$ is satisfied, the equilibrium R&D input and product market demand of manufacturing enterprises reach the maximum under the fully collaborative decision scenario, the next highest under the Nash noncooperative decision scenario, and the minimum under the cost compensation decision scenario.*

Proof.

$$I_u^{NC^*} - I_u^{BE^{**}} = \frac{\alpha \Pi_u s}{2w_u(\rho+\gamma)} > 0,\ I_u^{NC^*} - I_u^{ND^{**}} = \frac{\Pi_d s\alpha}{w_u(\rho+\gamma)} > 0,\ I_u^{BE^{**}} - I_u^{ND^{**}} = \frac{(2\Pi_d - \Pi_u)s\alpha}{2w_u(\rho+\gamma)} =$$

$$\begin{cases} > 0, 2\Pi_d > \Pi_u \\ \leq 0, 2\Pi_d \leq \Pi_u \end{cases},\ \frac{\partial y^{BE^{**}}}{\partial I_u^{BE^{**}}} = \alpha\left(1 - \mathrm{e}^{-\gamma t}\right) > 0,\ \frac{\partial E}{\partial y} = s > 0$$

□

Corollary 6. *When there is no government subsidy and when the marginal profits of manufacturing and retail enterprises satisfy $3\Pi_u > 4\Pi_d > \Pi_u$, the revenue of manufacturing enterprises under the R&D incentive decision scenario is greater than that of retail enterprises, and when it satisfies $3\Pi_u < 4\Pi_d$, the revenue of manufacturing enterprises under the R&D incentive decision scenario is lower than that of retail enterprises; thus, in management practice, enterprise managers should choose appropriate incentive policies according to the actual marginal profit situation to encourage long-term cooperative emission reduction behavior among enterprises and achieve a win–win situation in terms of cooperation.*

Proof.

$$V_u{}^{BE^{**}} - V_u{}^{BD^{**}} = \Delta_1, V_d{}^{BE^{**}} - V_d{}^{BD^{**}} = \Delta_2, \Delta_1 - \Delta_2 = \frac{\gamma\left(16\Pi_d{}^2 + 3\Pi_u{}^2 + 16\Pi_u\Pi_d\right)}{4w_u\gamma(\rho+\gamma)}\mathrm{e}^{-\gamma t} =$$

$$\begin{cases} > 0, 3\Pi_d > 2\Pi_u > \Pi_u \\ \leq 0\ \ , 3\Pi_d < 2\Pi_d \end{cases}$$

□

Corollary 7. *The government subsidies provided to manufacturing enterprises under the Nash noncooperative and R&D incentive decisions are equal to and higher than the subsidy rate under the fully collaborative decision. When the marginal profits of manufacturing and retail enterprises satisfy $2\Pi_d > \Pi_u$, the government subsidies provided to retail enterprises are, from highest to lowest, the Nash noncooperative decision, the R&D incentive decision, and the fully collaborative decision scenario. When the marginal profits of the retail enterprises satisfy $2\Pi_d < \Pi_u$, the government subsidy rates for the retail enterprises are, from highest to lowest, the R&D incentive decision, the Nash noncooperative decision, and the fully collaborative decision scenario. After comparing the equilibrium subsidies of Propositions 6 and 7, it is clear that the size of the government subsidies provided to enterprises under different game decision scenarios is related to whether the enterprises occupy the dominant position in the game.*

Proof.

$$\varphi_d^{BE^*} = \varphi_d^{BD^*} = \frac{\Pi_u}{\Pi_u+\Pi_d},\ \varphi_d^{BC^*} = 0 \rightarrow \varphi_d^{BE^*} = \varphi_d^{BD^*} > \varphi_d^{BC^*};\ \varphi_d^{BE^*} - \varphi_d^{BD^*} = \frac{\Pi_u-2\Pi_d}{\Pi_u+\Pi_d} =$$

$$\begin{cases} > 0, 2\Pi_d < \Pi_u \\ \leq 0, 2\Pi_d \geq \Pi_u \end{cases};\ \varphi_u^{BE^*} = \frac{\Pi_u}{\Pi_u+\Pi_d} > \varphi_d^{BE^*} = \frac{\Pi_u}{2(\Pi_u+\Pi_d)},\ \varphi_u^{BM^*} = \frac{\Pi_d}{\Pi_u+\Pi_d} > \varphi_d^{BM^*} = \frac{\Pi_d}{2(\Pi_u+\Pi_d)}$$

□

Corollary 8. *When government subsidies are applied to both manufacturing and retail enterprises, manufacturing enterprises' emission reduction technology investment efforts, retail enterprises' promotional investment, the optimal trajectory of emission reduction effect, and product market demand all reach the maximum level under the fully synergistic R&D incentive decision scenario. When $2\Pi_d > \Pi_u$ is satisfied, government subsidies boost the revenue of both types of enterprises, but the revenue boost is greater for the retail enterprise that holds the leading position in the game.*

Proof. Compare Proposition 1 with Proposition 5.

$$I_u^{BC^{**}} = I_d^{BE^{**}} = \frac{(\Pi_u + \Pi_d)s\alpha}{w_u(\rho+\gamma)},\ I_d^{BC^{**}} = I_d^{BE^{**}} = \frac{(\Pi_u + \Pi_d)\varepsilon}{w_d},\ y^{BC^{**}} = y^{BE^{**}},\ E^{BC^{**}} = E^{BE^{**}}$$

□

Corollary 9. *From the above inference, it can be seen that the net income under the cost compensation decision scenario is greater than that under the Nash noncooperative decision scenario, but if an enterprise wants to take the cost compensation decision, it should meet the requirements of $R_u^{BE} - R_u^{BD} > 0$, $R_d^{BE} - R_d^{BD} > 0$. In this paper, a profit-sharing contract will be designed as a supplement to the incentive decision of technology sharing, and the total net income of the two enterprises will be shared reasonably. Suppose that the profit split rate obtained by the manufacturer is ψ. The retailer receives a revenue split of $1-\psi$. The net income split ratio of manufacturers and retailers should meet the following conditions:*

$$\begin{cases} \psi\ R_T^{BE} \geq R_u^{BD} \\ (1-\psi)\ R_T^{BE} \geq R_d^{BD} \end{cases}$$

By solving the inequality system, $\psi \in [\frac{R_u^{BD}}{R_T^b}, 1 - \frac{R_d^{BD}}{R_T^b}]$, the manufacturer wants the profit split rate to be as close as possible to $\frac{1-R_d^{BD}}{R_T^{BE}}$, while the retailer wants the split rate to be as close as possible to $\frac{R_u^{BD}}{R_T^{BE}}$. According to the Ariel Rubinstein bargaining model, the parameter ψ can be determined by the negotiation ability of the decision-making participants. ψ It is closely related to the core competitiveness level, negotiation cost, and risk preference of decision-makers. The larger the ψ value, the stronger the negotiation ability of the manufacturing enterprise, and the greater the profits. Let the discount factor of the manufacturer and retailer be ρ_u, ρ_d. The retailer conducts the first round of bidding, and the net income division ratio of the two enterprises can be obtained as follows:

$$\psi = \frac{\rho_u(1-\rho_d)}{1-\rho_u\rho_d}\left(\frac{R_T^{BE} - R_d^{BD} - R_u^{BD}}{R_T^{BE}}\right) + \frac{R_u^{BD}}{R_T^{BE}}, 1-\psi = 1 - \frac{\rho_u(1-\rho_d)}{1-\rho_u\rho_d}\left(\frac{R_T^{BE} - R_d^{BD} - R_u^{BD}}{R_T^{BE}}\right) - \frac{R_u^{BD}}{R_T^{BE}}$$

Therefore, the net income of manufacturers and retailers is:

$$R_u^{BE} = \psi\ R_T^{BE},\ R_u^b = (1-\psi)\ R_T^{BE}$$

That is, the lower the negotiation cost or the stronger the core competitiveness of the decision-making body, the more net income will be shared.

6. Example Analysis

To further explain the relationship between decision parameters and present the conclusion more intuitively, in this section, we chose a specific case study through which to carry out a calculation experiment.

The promotion and application of new energy vehicles can decrease the transport sector's dependence on fossil fuels and is simultaneously an effective way to promote economic transformation and upgrading and energy system change. In the past decade or so, the development of China's NEV industry has achieved remarkable successes worldwide. Therefore, we investigated the secondary supply chain composed of a new energy vehicle manufacturer and dealers in Shanghai, China. By analyzing the reports provided by the manufacturers, we set the parameter values and conducted sensitivity analysis. The marginal revenue of the low-carbon technology R&D of upstream manufacturers and the marginal cost of downstream retailers are $w_u = 17$ and $w_d = 11.3$, the marginal income of the low-carbon technology R&D of upstream manufacturers is $\Pi_u = 19.5$, and the retailer's marginal income is $\Pi_d = 16$. The relevant sensitive parameters were set as follows: $\alpha = 0.75$, $\varepsilon = 0.7$, and $\gamma = 0.2$. The discount rate for two firms over an infinite period of time, with values determined by referring to the market interest rate with inflationary compensation, was assumed to be $\rho = 0.9$.

Figure 1a reflects the following two points: (1) Regardless of the existence of R&D incentives among enterprises, the returns of manufacturing and retail enterprises with government participation are higher than the corresponding returns without government participation, and the introduction of government subsidies can achieve Pareto improvements in the returns of manufacturing and retail enterprises. (2) The improvement effect of government subsidies on manufacturing enterprises is greater than that on retail enterprises. As the retailer incentivizes the R&D of the emission reduction technology of the manufacturing enterprises, it further stimulates the R&D investment in emission reduction technology by manufacturing enterprises, which also leads to more market demand, so both parties' gains can obtain Pareto improvement, and the decrease in the R&D cost of manufacturing enterprises' emission reduction technology makes their net gain greater than that of retailers.

Figure 1b reflects the relationships among the sizes of the overall enterprise benefits under three decision scenarios with government participation, as follows: centralized decision benefits = R&D incentive decision benefits > Nash noncooperative decision scenario. This figure also reflects the relationships without government participation, as follows: fully collaborative decision benefits > R&D incentive decision benefits > Nash noncooperative decision scenario. Thus, Figure 1b indicates the following two points: (1) Regardless of the existence of government subsidies, the alliance of enterprises with collaborative control can achieve sufficient information exchange and can maximize the benefits of the supply chain as a whole, which provides a reference for the joint emission reduction of manufacturing and retail enterprises. (2) Through government subsidies, the overall benefits of enterprises under R&D incentive-based decision making reach the overall benefits under fully collaborative decision making, which indicates that the government subsidy strategy changes the traditional relationships among the magnitudes of supply chain benefits under the three types of decision making.

Figure 1c reports the impact of the sensitivity coefficient of market demand to the green marketing of retail enterprises under three kinds of decision scenario on the overall revenue of enterprises. Under the same sensitivity coefficient, the overall revenue of enterprises with government-subsidized R&D incentives > cooperative decision revenue > R&D incentive revenue without government subsidies. With the increase in the effect of the sensitivity coefficient of market demand on the green marketing of retail enterprises, the overall revenue of enterprises increases accordingly, and R&D incentivization with government subsidies is most effective. This finding has several practical implications for enterprise management: formulating perfect marketing strategies for emission reduction products and creating a special sales model, such as an exclusive sales system for emission reduction and environmental protection products to increase consumers' preference for emission reduction, helps maximize the revenue of the whole commodity value.

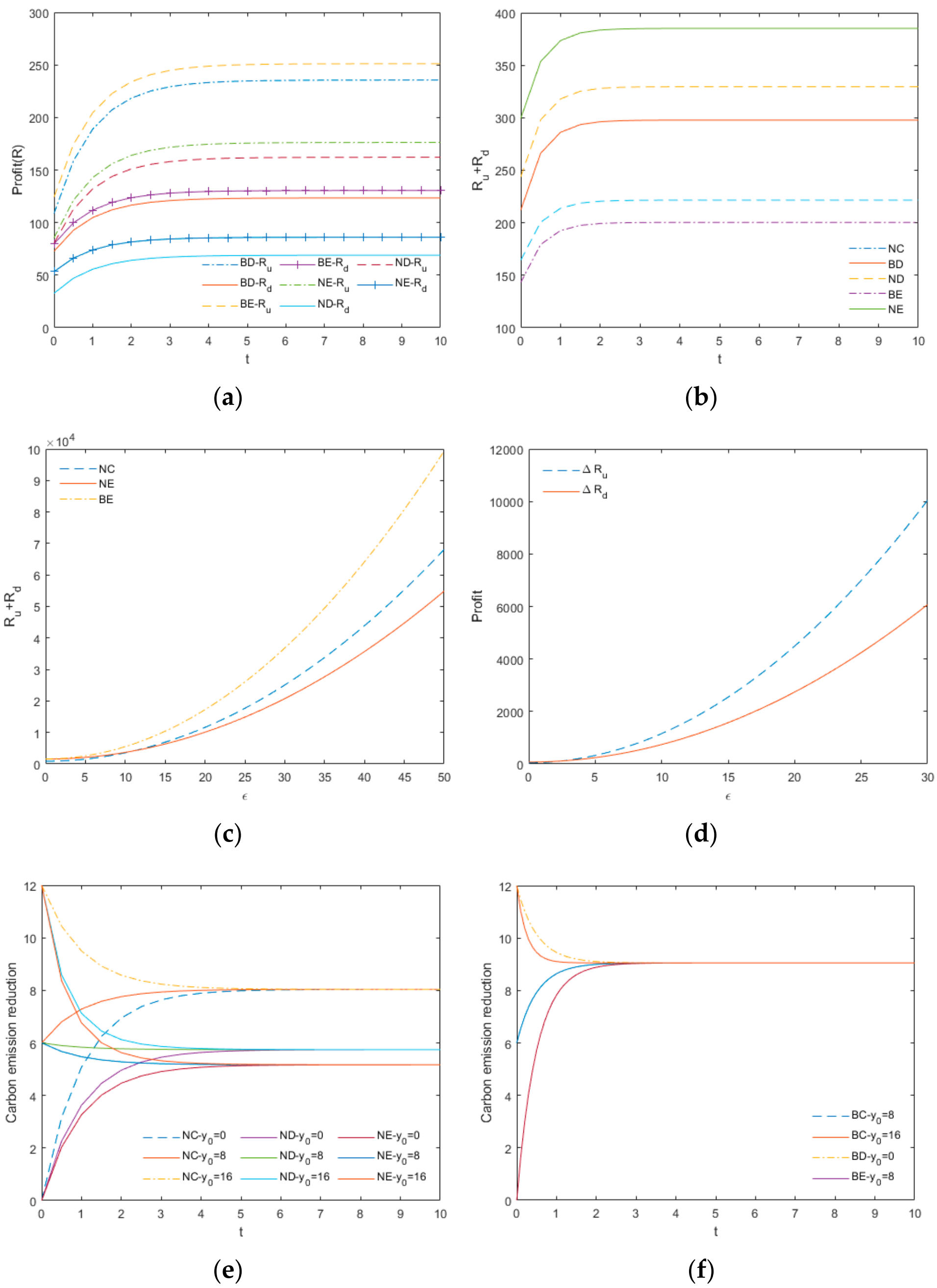

Figure 1. (**a**) Comparison of earnings of manufacturing and retail companies under government subsidies. (**b**) Comparison of the overall profitability of the company in six types of decision scenario. (**c**) The impact of ε on overall corporate earnings under three types of decision scenario. (**d**) Effect of parameter ε on incremental earnings of two firms. (**e**) Effect of different initial emission reductions with time on emission reductions without government subsidies. (**f**) Effect of different initial emission reductions under government subsidies on emission reductions over time.

Figure 1e reflects the situation without government subsidies and shows that the optimal trajectory has a decreasing trend when the initial emission reduction is greater than the stable value. When the initial emission reduction is less than the stable value, the optimal trajectory shows an increasing trend, i.e., the trend of commodity emission reduction over time is determined by the relative sizes of the stable and initial emission reductions. The size relationship of the optimal trajectory of emission reduction for the three decision scenarios is as follows: fully collaborative decision > Nash noncooperative decision > R&D incentive decision. Obviously, there is room for Pareto improvement in the emission reduction of commodities in this case. Figure 1f reports that the optimal trajectory of the emission reduction of commodities appears to vary with increasing and decreasing time as the initial emission reduction of the manufacturing enterprises changes, but eventually it converges to a stable value. Under the government subsidy strategy, the optimal emission reductions for different decision scenarios eventually converge to the same level. In Figure 1f, the emission reductions under the government subsidy strategy reach the emission reductions under the fully collaborative decision scenario without government subsidies, so the government subsidy strategy can effectively enhance the R&D enthusiasm of manufacturing enterprises for emission reduction technologies.

7. Conclusions

In this paper, we constructed a differential game model of cooperative emission reduction technology R&D, green marketing, and subsidies in infinite time for three game subjects: the government, manufacturing enterprises, and retail enterprises. Then, we explored the long-term dynamic equilibrium strategies of manufacturing and retail enterprises under different decision situations and reached the following conclusions.

(1) The equilibrium coefficients of government subsidies provided to manufacturing and retail enterprises are closely related to their marginal returns. When the government participates in the game, the returns of both enterprises under the R&D incentive decision increase compared to those under the Nash noncooperative decision scenario, and the government subsidy policy also changes the optimal inputs of both enterprises. In addition, the stronger the sensitivity coefficient of market demand to the inputs of both enterprises, the better the effect of the government subsidy strategy on the overall revenue enhancement of the enterprises under the Nash noncooperative and R&D incentive decision scenarios.

(2) Without government subsidies, the technological R&D investment, emission reduction, market demand, and overall corporate revenue of manufacturing enterprises are enhanced under retailer-led R&D incentive-based decision making, compared to the Nash noncooperative decision-making scenario, achieving a win–win situation for the supply chain and the environment. In addition, the relative size of the marginal revenue of manufacturing and retail enterprises has an important impact on their profits.

(3) The effect of commodity emission reduction is influenced by multiple factors, such as the effect of the sensitivity coefficient of market demand on emission reduction and initial emission reduction, and its optimal trajectory shows a diversified trend of change. Compared with the Nash noncooperative decision scenario, the overall benefits of enterprises under the fully collaborative decision and R&D incentive decision scenarios are enhanced, and the net present value of the benefits of each subject is influenced by the specific allocation agreement. Although a regional voluntary negotiation strategy is considered an effective way to obtain the benefits of environmental improvement, in reality, this strategy faces difficulty in terms of achieving full cooperation across regions due to the constraints of information, technology, and policies. The development of scientific and reasonable horizontal technology R&D incentive contracts to balance the interests among enterprises is of great practical significance for the long-term cooperative management of water resource intensification in supply chains.

(4) The government can develop differentiated subsidy programs based on different gaming strategies and benefit distribution agreements, combined with relevant parameters,

to help manufacturing enterprises accelerate their development of resource-intensive production methods, help the retail sector create a better green market atmosphere, and improve the consumer recognition of emission-reducing products to enhance the effect of supply chain emission reduction.

This paper focused on the impact of R&D investment in the emission reduction technologies of individual manufacturing enterprises and the green marketing investment of individual retail enterprises as well as government subsidies on supply chain cooperation in terms of emission reduction and corporate profits. The R&D incentive decision mechanism designed in this paper can lead to Pareto improvement in corporate earnings, but there are many forms of incentives among enterprises, and in addition to sharing R&D costs, other contractual mechanisms can be designed to achieve this effect in a fully collaborative decision-making scenario by means of co-built environmentally friendly industrial parks, which is a possible direction for future research.

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Appendix A

According to optimal control theory, for $\forall I_{u,d} > 0$, the optimal control problem of the supply chain system satisfies the following HJB equation:

$$\rho {V_T}^{NC} = \max_{I_u^{NC} \geq 0, I_d^{NC} \geq 0} \begin{array}{c} (\Pi_u + \Pi_d)E_a^* - \frac{w_u}{2}\left(I_u^{NC}\right)^2(t) - \frac{w_d}{2}\left(I_d^{NC}\right)^2(t) + \\ V'\left(y^{BC}\right)\left[\alpha \cdot I_u^{BC^*} - (\gamma - r)y(t)\right] \end{array} \tag{A1}$$

The Hessian matrix with respect to I_u^a, I_d^a is

$$H = \begin{bmatrix} -(1-\varphi_u)w_u & 0 \\ 0 & -(1-\varphi_d)w_d \end{bmatrix}$$

When the Hessian Matrix is negative definite, i.e., when $\rho F_T(E_a^*)$ is a concave function, the maximum can be found with respect to I_u^{NC} and I_d^{NC}, and the first-order partial derivatives of I_u^{NC} and I_d^{NC} are found for $F_T(y^a)$ and made to equal 0, respectively, to obtain the maximization condition.

$$I_u^{NC^*} = \frac{\alpha F'\left(y^{NC^*}\right)}{\left(1-\varphi_u^{NC^*}\right)w_u}, I_d^{NC^*} = \frac{(\Pi_u + \Pi_d)\varepsilon}{w_d\left(1-\varphi_d^{NC^*}\right)} \tag{A2}$$

Substituting (A2) into (A1), we obtain

$$\rho V_T\left(y^{NC}\right) = \frac{\alpha^2\left(F'\left(y^{NC^*}\right)\right)^2}{2(1-\varphi_u)w_u} + \frac{\varepsilon^2(\Pi_u+\Pi_d)^2}{2(1-\varphi_d)w_d} + (\Pi_u + \Pi_d)E_0 + \\ \left[(\Pi_u + \Pi_d)s - (\gamma - r)V'\left(y^{NC^*}\right)\right]y^{BC^*} \tag{A3}$$

According to the structure of (A3), it can be assumed that $V_T\left(y^{NC}\right)$ has the following linear structure.

$$V_T\left(y^{NC}\right) = k_1 y^{NC} + b_1$$

where k_1 and b_1 are constants, and substituting $F_T\left(y^{NC}\right)$ and $F'\left(y^{NC}\right)$ into Equation (A3), we solve for

$$V'\left(y^{NC}\right) = k_1 = \frac{(\Pi_u + \Pi_d)s}{\rho - \gamma} \tag{A4}$$

Combining (A2) and (A4), $I_u^{NC^*}$ can be found, and y^{NC} can be found from $I_u^{NC^*}$ and Equation (2).

Appendix B

Similarly, let $R_{u,d}^{ND}\left(y^{ND}\right) = \mathrm{e}^{-\rho t} V_{u,d}\left(y^{ND}\right)$. For $\forall y^{ND} \geq 0$, $V_{u,d}\left(y^{ND}\right)$, all satisfy the HJB equation, i.e.,

$$\rho V_u\left(y^{ND}\right) = \max_{I_u^{ND}}[\Pi_u \cdot E(t) - C_u(I_u) + F_u'(y^{ND})(\alpha \cdot I_u^{ND^*} - (\gamma - r)y^{ND^*}] \tag{A5}$$

$$\rho V_d\left(y^{ND}\right) = \max_{I_d^{ND}}[\Pi_d \cdot E(t) - C_d(I_d) + F_d'(y^{ND^*})(\alpha \cdot I_u^{ND^*} - (\gamma - r)y^{ND^*}] \tag{A6}$$

$\rho V_{u,d}\left(y^{b^*}\right)$ is a concave function on $I_{u,d}^{ND}$, and the first-order condition for the same reason is solved as follows:

$$I_u^{ND^*} = \frac{\alpha V_u'\left(y^{ND^*}\right)}{w_u}, I_d^{BD^*} = \frac{\varepsilon \Pi_d}{w_d} \tag{A7}$$

Substituting (A7) into (A5) and (A6), we obtain

$$\rho V_u\left(y^{ND^*}\right) = \left(\Pi_u s - (\gamma - r)V_u'\left(y^{ND^*}\right)\right)y^{b^*} + \Pi_u E_0 + \frac{\alpha^2\left(V_u'\left(y^{ND^*}\right)\right)^2}{2w_u} + \frac{\varepsilon^2 \Pi_u \Pi_d}{w_d} \tag{A8}$$

$$\rho V_d\left(y^{ND^*}\right) = \left(\Pi_d s - (\gamma - r)V_d'\left(y^{ND^*}\right)\right)y^{b^*} + \Pi_d E_0 + \frac{\varepsilon^2 {\Pi_d}^2}{2w_d} + \frac{\alpha^2 V_d'\left(y^{ND^*}\right)V_u'\left(y^{ND^*}\right)}{w_u} \tag{A9}$$

Suppose the linear structures of $\rho V_u\left(y^{ND}\right)$ and $\rho V_d\left(y^{ND}\right)$ are $V_u\left(y^{ND}\right) = k_2 y^{b^*} + b_2$ and $V_d\left(y^{ND}\right) = k_3 y^{b^*} + b_3$, respectively. Obviously, $V_u'\left(y^{ND}\right) = k_2$ and $V_d'\left(y^{ND}\right) = k_3$. By substituting k_2, b_2, k_3, b_3 into (A8) and (A9), we obtain ${k_2}^*$, ${k_3}^*, {b_2}^*$, and ${b_3}^*$. Substituting ${k_2}^*$ into $I_u^{ND^*}$, we can obtain $I_u^{BD^{**}}$, and substituting $I_u^{ND^{**}}$ into (2), we can obtain y^{b^*}. Furthermore, E^{b^*} can be obtained, ${k_2}^*, {k_3}^*, {b_2}^*, {b_3}^*$ are substituted into $V_u\left(y^{ND}\right)$, $V_d\left(y^{ND}\right)$, and $F_u\left(y^{ND}\right)^*$, $F_d\left(y^{ND}\right)^*$ can be collated.

Appendix C

Similarly, let $R_{u,d}^{NE}\left(y^{NE}\right) = \mathrm{e}^{-\rho t} V_{u,d}\left(y^{NE}\right)$; for $\forall y^{NE} \geq 0$, $V_{u,d}\left(y^{NE}\right)$, all satisfy the HJB equation, i.e.,

$$\begin{aligned} \rho V_u\left(y^{NE}\right) = \ & \max_{I_u^{NE}}[\Pi_u \cdot E(t) - (1-\theta)C_u(I_u) \\ & + F_u'\left(y^{NE}\right)(\alpha \cdot I_u^{NE^*} - (\gamma - r)y^{NE^*}] \end{aligned} \tag{A10}$$

$$\rho V_d\left(y^{NE}\right) = \max_{I_d^{NE}}\left[\Pi_d \cdot E(t) - C_d(I_d) - \theta C_u(I_u) + F_d'(y^{NE^*})(\alpha \cdot I_u^{NE^*} - (\gamma - r)y^{NE^*}\right] \tag{A11}$$

$\rho V_{u,d}\left(y^{b^*}\right)$ is a concave function with respect to $I_{u,d}^{NE}$, θ. The first-order condition for the same reason is solved as follows:

$$I_u^{NE^*} = \frac{\alpha V_u'\left(y^{NE^*}\right)}{w_u(1-\theta)}, I_d^{BE^*} = \frac{\varepsilon \Pi_d}{w_d}, \theta = \frac{2V_d'\left(y^{NE^*}\right) - V_u'\left(y^{NE^*}\right)}{2V_d'(y^{NE^*}) + V_u'(y^{NE^*})} \tag{A12}$$

Substituting (A12) into (A10) and (A11), we obtain

$$\begin{gathered}\rho V_u\left(y^{NE^*}\right) = \left(\Pi_u s - (\gamma - r)V_u'\left(y^{NE^*}\right)\right)y^{b^*} + \Pi_u E_0 + \\ \frac{\alpha^2 V_u'\left(y^{NE^*}\right)\left(V_u'\left(y^{NE^*}\right)+2V_d'\left(y^{NE^*}\right)\right)}{4w_u} + \frac{\varepsilon^2 \Pi_u \Pi_d}{w_d}\end{gathered} \tag{A13}$$

$$\begin{gathered}\rho V_d\left(y^{NE^*}\right) = \left(\Pi_d s - (\gamma - r)V_d'\left(y^{NE^*}\right)\right)y^{b^*} + \Pi_d E_0 + \frac{\varepsilon^2 {\Pi_d}^2}{2w_d} + \\ \frac{\alpha^2\left(2V_d'\left(y^{NE^*}\right)+V_u'\left(y^{NE^*}\right)\right)^2}{8w_u}\end{gathered} \tag{A14}$$

Suppose the linear structures of $\rho V_u\left(y^{NE}\right)$ and $\rho V_d\left(y^{NE}\right)$ are $V_u\left(y^{NE}\right) = k_4 y^{b^*} + b_4$ and $V_d\left(y^{NE}\right) = k_5 y^{b^*} + b_5$, respectively. Obviously $V_u'\left(y^{NE}\right) = k_4$, $V_d'\left(y^{NE}\right) = k_5$. Substituting k_4, b_4, k_5, b_5 into (A13) and (A14), we obtain ${k_4}^*$, ${k_5}^*$, ${b_4}^*$, ${b_5}^*$. Substituting ${k_4}^*$ into $I_u^{NE^*}$, we obtain $I_u^{NE^{**}}$. Substituting $I_u^{NE^{**}}$ into (2), we obtain y^{b^*}. Furthermore, E^{b^*} can be obtained, ${k_4}^*$, ${k_5}^*$, ${b_4}^*$, ${b_5}^*$, are substituted into $V_u\left(y^{NE}\right)$, $V_d\left(y^{NE}\right)$, and $F_u\left(y^{NE}\right)^*$, $F_d\left(y^{NE}\right)^*$ can be collated.

Appendix D

R_T satisfies the HJB equation for any $I_{u,d}^{BC} \geq 0$.

$$\rho {V_T}^{BC} = \max_{I_u^{BC}\geq 0, I_d^{BC}\geq 0} \begin{gathered}(\Pi_u + \Pi_d)E_a^* - (1-\varphi_u)\frac{w_u}{2}\left(I_u^{BC}\right)^2(t) - (1-\varphi_d)\frac{w_d}{2}\left(I_d^{BC}\right)^2(t) + \\ V'\left(y^{BC}\right)\left[\alpha \cdot I_u^{BC^*} - (\gamma - r)y(t)\right]\end{gathered} \tag{A15}$$

The Hessian matrix with respect to I_u^{BC}, I_d^{BC} is

$$H = \begin{bmatrix} -(1-\varphi_u)w_u & 0 \\ 0 & -(1-\varphi_d)w_d \end{bmatrix} \tag{A16}$$

Substituting (A16) into (A15) and organizing, we obtain

$$\begin{gathered}\rho V_T\left(y^{BC}\right) = \frac{\alpha^2\left(F'\left(y^{BC^*}\right)\right)^2}{2(1-\varphi_u)w_u} + \frac{\varepsilon^2(\Pi_u+\Pi_d)^2}{2(1-\varphi_d)w_d} + (\Pi_u + \Pi_d)E_0 + \\ \left[(\Pi_u + \Pi_d)s - (\gamma - r)V'\left(y^{BC^*}\right)\right]y^{BC^*}\end{gathered} \tag{A17}$$

According to the structure of (A17), it can be assumed that $V_T\left(y^{BC}\right)$ has the following linear structure.

$$V_T\left(y^{BC}\right) = k_1 y^{BC} + b_1$$

where k_1 and b_1 are constants. Substituting $F_T\left(y^{BC}\right)$ and $F'\left(y^{BC}\right)$ into Equation (12), we solve for

$$V'\left(y^{BC}\right) = k_1 = \frac{(\Pi_u + \Pi_d)s}{\rho - \gamma} \tag{A18}$$

Combining (A16) and (A18), we can find $I_u^{BC^*}$, and from $I_u^{BC^*}$ and (2), we can find y^{BC}. From Equation (5), the objective function of the government, R_g satisfies the HJB equation for $\forall \varphi_{u,d} \geq 0$.

$$\rho {V_g}^{BC} = \max_{\varphi_{u,d} \geq 0} \mathrm{e}^{-\rho t} \left\{ \begin{array}{c} (\Pi_u + \Pi_d)(sy + \varepsilon I_d + E_0) - \frac{w_u}{2}\left(I_u^{BC}\right)^2 - \frac{w_d}{2}\left(I_d^{BC}\right)^2 + \\ V'\left(y^{BC}\right)\left[\alpha \cdot I_u^{BC} - (\gamma - r)y\right] \end{array} \right\} \tag{A19}$$

Substituting I_u^{BC}, I_d^{BC} into (10), the first-order extremum condition, we obtain

$$-w_u I_u^{BC} \frac{\partial I_u^{BC}}{\partial \varphi_u} + F'\left(y^{BC}\right)\alpha \frac{\partial I_u^{BC}}{\partial \varphi_u} = 0, \Pi_d \varepsilon \frac{\partial I_d^{BC}}{\partial \varphi_d} - w_d I_d^{BC} \frac{\partial I_d^{BC}}{\partial \varphi_d} = 0 \tag{A20}$$

Solving Equation (A20), we obtain $\varphi_u^{BC^*} = 0, \varphi_d^{BC^*} = 0$. Substituting $\varphi_u^{BC^*}$ and $\varphi_d^{BC^*}$ into (13), we can obtain $I_u^{BC^*}$, $I_d^{BC^*}$ and other equilibrium results.

Appendix E

Let $R_{u,d}^{BD}\left(y^{BD}\right) = \mathrm{e}^{-\rho t} V_{u,d}\left(y^{BD}\right)$. For $\forall y^{BD} \geq 0$, $V_{u,d}\left(y^{BD}\right)$, all satisfy the HJB equation, i.e.,

$$\begin{aligned} \rho F_u\left(y^{BD}\right) = \quad & \max_{I_u^{BD}} [\Pi_u \cdot E(t) - (1 - \varphi_u) C_u(I_u) \\ & + F_u'\left(y^{BD}\right)(\alpha \cdot I_u^{BD^*} - (\gamma - r) y^{BD^*}] \end{aligned} \tag{A21}$$

$$\begin{aligned} \rho V_d\left(y^{BD^*}\right) = \quad & \max_{I_d^{BD}} [\Pi_d \cdot E(t) - (1 - \varphi_d) C_d(I_d) \\ & + F_d'(y^{BD^*})(\alpha \cdot I_u^{BD^*} - (\gamma - r) y^{BD^*}] \end{aligned} \tag{A22}$$

$\rho V_{u,d}\left(y^{b^*}\right)$ is a concave function on $I_{u,d}^{BD}$ and, similarly, is solved by the first-order condition to obtain

$$I_u^{BD^*} = \frac{\alpha V_u'\left(y^{BD^*}\right)}{(1 - \varphi_u^{BD}) w_u}, I_d^{BD^*} = \frac{\varepsilon \Pi_d}{w_d\left(1 - \varphi_d^{BD^*}\right)} \tag{A23}$$

Substituting (A23) into (A21) and (A22), we obtain

$$\rho V_u\left(y^{BD^*}\right) = \left(\Pi_u s - (\gamma - r) V_u'\left(y^{BD^*}\right)\right) y^{b^*} + \Pi_u E_0 + \frac{\alpha^2 \left(V_u'\left(y^{BD^*}\right)\right)^2}{2(1 - \varphi_u) w_u} + \frac{\varepsilon^2 \Pi_u \Pi_d}{(1 - \varphi_d) w_d} \tag{A24}$$

$$\rho V_d\left(y^{BD^*}\right) = \left(\Pi_d s - (\gamma - r) V_d'\left(y^{BD^*}\right)\right) y^{b^*} + \Pi_d E_0 + \frac{\varepsilon^2 {\Pi_d}^2}{2(1 - \varphi_d) w_d} + \frac{\alpha^2 V_d'\left(y^{BD^*}\right) V_u'\left(y^{BD^*}\right)}{(1 - \varphi_u) w_u} \tag{A25}$$

Suppose the linear structures of $\rho V_u\left(y^{BD}\right)$ and $\rho V_d\left(y^{BD}\right)$ are $V_u\left(y^{BD}\right) = k_2 y^{b^*} + b_2$ and $V_d\left(y^{BD}\right) = k_3 y^{b^*} + b_3$, respectively; it is obvious that $V_u'\left(y^{BD}\right) = k_2$ and $V_d'\left(y^{BD}\right) = k_3$. Substituting k_2, b_2, k_3, b_3 into (A24) and (A25), we obtain ${k_2}^*, {k_3}^*, {b_2}^*, {b_3}^*$. Substituting ${k_2}^*$ into $I_u^{BD^*}$, we can obtain $I_u^{BD^{**}}$. Substituting $I_u^{BD^{**}}$ into (2), we can obtain y^{BD^*}. Furthermore, we can obtain E^{BD^*}. Substituting ${k_2}^*, {k_3}^*, {b_2}^*, {b_3}^*$ into $V_u\left(y^{BD}\right)$, $V_d\left(y^{BD}\right)$ and collating, we can obtain $F_u\left(y^{BD}\right)^*$, $F_d\left(y^{BD}\right)^*$.

Let the government's objective function $R_g^{BD} = \mathrm{e}^{-\rho t} V_g\left(y^{BD}\right)$, where $V_g\left(y^{BD}\right)$ satisfies the HJB equation:

$$\rho V_g\left(y^{BD}\right) = \max_{I_u^{BD}} \left[(\Pi_u + \Pi_d) E(t) - \frac{w_u}{2} I_u^2(t) - \frac{w_d}{2} I_d^2 + V_g'(y^{BD})(\alpha \cdot I_u^{BD^*} - (\gamma - r) y^{BD^*}\right] \tag{A26}$$

I_u^{BD} and I_d^{BD} are substituted into (A26) by solving the first-order condition:

$$\varphi_u^{BD} = 1 - \frac{\Pi_u s}{V_g'(y^{BD})(\rho + \gamma - r)}, \varphi_d^{BD} = \frac{\Pi_u}{\Pi_u + \Pi_d} \quad \text{(A27)}$$

Substituting (A27) into (A26), simplified and sorted, we can obtain

$$\begin{aligned} \rho V_g\left(y^{BD}\right) = \; & [(\Pi_u + \Pi_d)s - (\gamma - r)V_g'(y^{BD})]y^{BD} + (\Pi_u + \Pi_d)E_0 + \frac{\alpha^2\left(V_g'\left(y^{BD*}\right)\right)^2}{2w_u} \\ & + \frac{\varepsilon^2(\Pi_u + \Pi_d)^2}{2w_d} \end{aligned} \quad \text{(A28)}$$

By analyzing the order characteristics of (A28), it can be assumed that $V_g\left(y^{BD}\right) = c_1 y^{BD} + c_2$, where c_1 and c_2 are both constants. It is easy to determine that $V_g'\left(y^{BD}\right) = c_1$. Set $V_g\left(y^{BD}\right)$ and its first-order partial derivative are substituted into Equation (A28), and $c_1{}^*$ and $c_2{}^*$ can be obtained. By substituting $c_1{}^*$ into Equation (A27), the optimal subsidy rate provided by the government to manufacturers and retailers can be obtained as φ_u^{BD*} and φ_d^{BD*}. By adding φ_u^{BD*} and φ_d^{BD*} and substituting * into $I_u^{BD^*}$, $I_d^{BD^*}$, y^{BD}, sorting can obtain $I_u^{BD^{**}}$, $I_d^{BD^{**}}$, y^{BD^*}.

Appendix F

Similarly, let $R_{u,d}^{BE}\left(y^{BE}\right) = \mathrm{e}^{-\rho t} V_{u,d}\left(y^{BE}\right)$. For $\forall y^{BE} \geq 0$, $V_{u,d}\left(y^{BE}\right)$, all satisfy the HJB equation, i.e.,

$$\begin{aligned} \rho V_u\left(y^{BE}\right) = \; & \max_{I_u^{BE}} [\Pi_u \cdot E(t) - (1 - \varphi_u^{BE} - \theta)C_u(I_u) \\ & + F_u'(y^{BE})(\alpha \cdot I_u^{BE^*} - (\gamma - r)y^{BE^*}] \end{aligned} \quad \text{(A29)}$$

$$\begin{aligned} \rho V_d\left(y^{BE}\right) = \; & \max_{I_d^{NE}} [\Pi_d \cdot E(t) - \left(1 - \varphi_d^{BE}\right)C_d(I_d) - \theta C_u(I_u) \\ & + F_d'(y^{BE^*})(\alpha \cdot I_u^{BE^*} - (\gamma - r)y^{BE^*}] \end{aligned} \quad \text{(A30)}$$

$\rho V_{u,d}\left(y^{b^*}\right)$ is a concave function with respect to $I_{u,d}^{BE}$, θ. The first-order condition for the same reason is solved as follows:

$$I_u^{BE^*} = \frac{\alpha V_u'\left(y^{BE^*}\right)}{w_u(1 - \theta - \varphi_u^{BE})}, I_d^{BE^*} = \frac{\varepsilon \Pi_d}{w_d\left(1 - \varphi_d^{BE}\right)}, \theta = \frac{2V_d'\left(y^{BE^*}\right) - V_u'\left(y^{BE^*}\right)}{2V_d'(y^{BE^*}) + V_u'(y^{BE^*})} \quad \text{(A31)}$$

Substituting (A31) into (A29) and (A30), we obtain

$$\begin{aligned} \rho V_u\left(y^{BE^*}\right) = & \left(\Pi_u s - (\gamma - r)V_u'\left(y^{BE^*}\right)\right)y^{b^*} + \Pi_u E_0 + \\ & \frac{\alpha^2 V_u'\left(y^{BE^*}\right)\left(V_u'\left(y^{BE^*}\right) + 2V_d'\left(y^{BE^*}\right)\right)}{4w_u\left(1 - \varphi_u^{BE}\right)} + \frac{\varepsilon^2 \Pi_u \Pi_d}{w_d\left(1 - \varphi_d^{BE}\right)} \end{aligned} \quad \text{(A32)}$$

$$\begin{aligned} \rho V_d\left(y^{BE^*}\right) = & \left(\Pi_d s - (\gamma - r)V_d'\left(y^{BE^*}\right)\right)y^{b^*} + \Pi_d E_0 + \frac{\varepsilon^2 \Pi_d{}^2}{2w_d\left(1 - \varphi_d^{BE}\right)} + \\ & \frac{\alpha^2\left(2V_d'\left(y^{BE^*}\right) + V_u'\left(y^{BE^*}\right)\right)^2}{8w_u\left(1 - \varphi_u^{BE}\right)} \end{aligned} \quad \text{(A33)}$$

Suppose the linear structures of $\rho V_u\left(y^{BE}\right)$ and $\rho V_d\left(y^{NE}\right)$ are $V_u\left(y^{BE}\right) = k_4 y^{BE} + b_4$ and $V_d\left(y^{BE}\right) = k_5 y^{BE} + b_5$, respectively. Obviously, $V_u'\left(y^{BE}\right) = k_4$ and $V_d'\left(y^{BE}\right) = k_5$. Substituting k_4, b_4, k_5, b_5 into (A32) and (A33), we obtain $k_4{}^*, k_5{}^*, b_4{}^*, b_5{}^*$. Substituting $k_4{}^*$

into $I_u^{BE^*}$, we can obtain $I_u^{NE^{**}}$. Substituting $I_u^{BE^{**}}$ into (2), we can obtain y^{BE^*}. Furthermore, we can obtain E^{BE^*}. Substituting $k_4{}^*$, $k_5{}^*$, $b_4{}^*$, $b_5{}^*$ into $V_u\left(y^{BE}\right)$, $V_d\left(y^{BE}\right)$ and collating, we can obtain $F_u\left(y^{BE}\right)^*$, $F_d\left(y^{BE}\right)^*$.

Let the government's objective function $R_g^{BE} = \mathrm{e}^{-\rho t} V_g\left(y^{BE}\right)$, where $V_g\left(y^{BE}\right)$ satisfies the HJB equation:

$$\begin{aligned} \rho V_g\left(y^{BE}\right) = & \max_{\varphi_u^{BE}, \varphi_d^{BE}} \left[(\Pi_u + \Pi_d) E(t) - \tfrac{w_u}{2} I_u^2(t) - \tfrac{w_d}{2} I_d^2 \right. \\ & \left. + V_g'\left(y^{BE}\right)\left(\alpha \cdot I_u^{BE^*} - (\gamma - r) y^{BE^*}\right) \right] \end{aligned} \tag{A34}$$

I_u^{BE} and I_d^{BE} are substituted into (A34) by solving the first-order condition:

$$\varphi_u^{BE} = 1 - \frac{(2\Pi_d + \Pi_u)s}{2V_g'(y^{BE})(\rho + \gamma - r)}, \varphi_d^{BE} = \frac{\Pi_u}{\Pi_u + \Pi_d} \tag{A35}$$

Substituting (A35) into (A34), simplified and sorted, we can obtain

$$\begin{aligned} \rho V_g\left(y^{BE}\right) = & \left[(\Pi_u + \Pi_d)s - (\gamma - r) V_g'\left(y^{BE}\right) \right] y^{BE} + (\Pi_u + \Pi_d) E_0 \\ & + \tfrac{\alpha^2 \left(V_g'\left(y^{BE^*}\right) \right)^2}{2w_u} + \tfrac{\varepsilon^2 (\Pi_u + \Pi_d)^2}{2w_d} \end{aligned} \tag{A36}$$

By analyzing the order characteristics of (A36), it can be assumed that $V_g\left(y^{BE}\right) = c_3 y^{BE} + c_4$, where c_3 and c_4 are both constants. It is easy to determine that $V_g'\left(y^{BE}\right) = c_3$. Set $V_g\left(y^{BE}\right)$ and its first-order partial derivative are substituted into Equation (A36), and $c_3{}^*$ and $c_4{}^*$ can be obtained. By substituting $c_3{}^*$ into Equation (A35), the optimal subsidy rate provided by the government to manufacturers and retailers can be obtained as φ_u^{BE*} and φ_d^{BE*}. By adding φ_u^{BE*} and φ_d^{BE*} and substituting * into $I_u^{BE^*}$, $I_d^{BE^*}$, y^{BE}, sorting can obtain $I_u^{BE^{**}}$, $I_d^{BE^{**}}$, y^{BE^*}.

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