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The Research on Decisions of Carbon Neutral Technology in A Retailer-led Green Supply Chain Based on Cost Reduction and Carbon Trading

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Abstract: *In this paper, based on the concept of green supply chain management, we construct a two-level supply chain game model consisting of an upstream manufacturer and a downstream retailer, where the downstream retailer is the leader and the upstream manufacturer is the follower. In addition, the upstream manufacturer in this model invests in carbon-neutral technology innovations that reduce production costs, lower carbon emissions, and increase market demand for their products. Based on this game model, the optimal equilibrium outcome of the supply chain is solved, and the influences of the carbon-neutral sensitivity coefficient, the investment coefficient for carbon-neutral technology innovation, carbon emission reduction efficiency, and the carbon-neutral technology cost reduction efficiency on the operation decision of supply chain firms are examined. The results show that (1) the consumer carbon neutrality sensitivity factor has a positive impact on the carbon neutral strategy, product ordering, and performance of supply chain firms. (2) The investment factor of carbon-neutral technology innovation hurts the carbon-neutral decision, product ordering, and performance of supply chain firms, while the pricing strategy also has a positive correlation impact with the carbon-neutral sensitivity factor of consumers as the carbon-neutral technology innovation investment factor increases. (3) The cost reduction efficiency of carbon-neutral technologies promotes carbon-neutral decisions, product ordering, and performance of supply chain firms. However, the pricing strategy is also closely related to market size and correlates negatively. (4) The carbon emission reduction efficiency per unit product is positively correlated with the carbon neutral decision, product ordering, and performance of supply chain firms, while the pricing strategy is also linked to market size and has a negative correlation.*

Keywords: *Green supply chain, Technological innovation of carbon neutrality, Carbon trade, Retailer Stackelberg game*

1. Introduction

China introduced a series of policies to promote green development, with the goal of "double carbon". The National Development and Reform Commission and the Ministry of Science and Technology jointly issued the "Implementation Plan on Further Improving the Market-Oriented Green Technology Innovation System (2023-2025)" in December 2022, proposing to fully exploit green technology innovation's critical role in supporting green and low-carbon development. At the same time, the Center for Global Environmental Information Research (CDP) reports that the carbon emissions created by a company's supply chain are often 5.5 times that of its business scope. As a result, how businesses can develop a green supply chain, increase green technological innovation to optimize the utilization of resources, and reduce carbon emissions has become a heated issue of discussion. In this context, many businesses are actively investigating the practice of standardizing and developing green supply chain management as an achievable choice to enhance brand reputation and practice corporate social responsibility. For example, SF has developed biodegradable plastic bags "Feng Xiaobao" and "Feng Dobao" recycling boxes to reduce energy consumption in packaging and thus reduce carbon emissions; BMW Group has announced that it will collaborate with suppliers such as Ningde Times and Shougang Group to achieve a 20% emission reduction target by 2030 in the upstream part of the supply chain.

Currently, an increasing number of academics are studying issues associated with green, low-carbon supply chain management. Habiba et al. (2022) investigated the influence of financial development, green technology innovation, and the usage of renewable energy on carbon emissions[1]. Roh et al. (2022)

investigated the influence of green activities such as green management and green marketing innovation on firm environmental performance[2]. Fu et al. (2019) investigated the influence of government subsidies on upstream and downstream firms in the green supply chain's game decisions[3]. Cheng et al. (2022) studied the green supply chain of green technology R&D using differential games with centralized and decentralized decision-making, respectively[4]. Wang et al. (2020) discussed the optimal decision-making and innovation performance of enterprises' green technology innovation under various regulatory and decision-making scenarios[5]. Guan et al. (2020) investigated the optimization of collaborative green innovation between manufacturers and suppliers, as well as the development of a two-way cost-sharing contract[6]. However, none of the previous research examined the influence of carbon-neutral technical innovation on green supply chain operating costs and carbon trading.

This paper investigates the optimal carbon-neutral strategy and supply chain performance of a secondary supply chain comprised of a single upstream manufacturer and a single downstream retailer under the assumption that carbon-neutral innovation in technology by the upstream manufacturer can not only improve market demand but also reduce production costs and carbon emissions. The effects of the consumer's carbon-neutral sensitivity coefficient, carbon-neutral technology innovation investment coefficient, carbon emission reduction efficiency per unit product, and carbon-neutral technology cost reduction efficiency are also investigated in supply chain enterprise operational decisions. This study not only theoretically compensates for the deficiency of previous research on carbon neutrality in the supply chain, but it also serves as a theoretical reference for future relevant research approaches. In reality, it also provides methodological direction to the government and supply chain firms on how to promote carbon neutrality.

2. Assumption

In this paper, we consider a two-level supply chain model consisting of a single upstream manufacturer M and a single downstream retailer R, where the retailer is the leader and the manufacturer is the follower. In the supply chain, the manufacturer's production cost is c , and the products are traded based on the wholesale price contract, that is, the manufacturer sells the products to the retailer at a wholesale price w , and then the retailer sells them to consumers at a market price p , where $c < w < p$. The remaining assumptions are as follows.

Assumption 1: According to Fan et al. (2020)[7], assume that the investment cost of carbon-neutral technology innovation is $k\theta^2/2$, where k denotes as the investment efficiency of carbon-neutral technology innovation and greater k means that the manufacturer needs to invest more in carbon-neutral technology. Therefore, the investment cost function of carbon neutrality is an increasing marginal cost function of the technological innovation level θ of carbon neutrality.

Assumption 2: Concerning Fan et al. (2017)[8] and Hong et al. (2023)[9], it is assumed that the market demand is $q = a - bp + \beta\theta$, where q is the market demand, a is the market size, b is the price sensitivity coefficient affecting market demand, and β is the carbon neutrality sensitivity coefficient affecting market demand. It is easy to observe how a drop in product sales price or an improvement in carbon-neutral technology innovation can raise market demand for products.

Assumption 3: Assuming that the manufacturer's unit production cost can be reduced when the carbon-neutral technology is improved. For example, Haier has made it possible to save about $1.35 million in annual electricity costs by building a smart building, which has greatly shortened the project payback period while improving carbon reduction. Therefore, it is assumed that when the manufacturer realizes carbon neutrality, the unit cost will be reduced by $c(1-\delta\theta)$, where δ is the cost-reducing efficiency, and $1-\delta\theta > 0$.

Assumption 4: It is assumed that improvements in carbon-neutral technology will effectively reduce product carbon emissions, thereby reducing the amount of carbon purchased. It is assumed that the amount of carbon that the manufacturer needs to buy per unit of product is e_0 and that the market transaction price is p_0 . As a result, as carbon-neutral technology improves, the amount of carbon that the manufacturer needs to buy will decrease, and the total cost of carbon transactions for the manufacturer at this time is $p_0(e_0 - \lambda\theta)$, where λ is the carbon emission reduction efficiency.

Assumption 5: Assume that supply chain firms form a Stackelberg game in which the retailer is the leader and the manufacturer is the follower and that the information between the manufacturer and the

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retailer is completely symmetrical.

Based on the above understanding, the profit functions of the supply chain are derived as follows:

$$\Pi_M = \left[w - c(1-\delta\theta)\right]q - p_0(e_0 - \lambda\theta)q - \frac{1}{2}k\theta^2$$

$$\Pi_R = (p - w)q$$

In the retailer-led Stackelberg game model, the retailer has greater channel power and acts as the leader of the Stackelberg game, with the manufacturer as the follower. The retailer decides the retail price of the product first, and then the manufacturer decides the wholesale price and the carbon-neutral technology innovation.

3. Equilibrium

The Stackelberg model is solved by backward induction. Let $m = p - w$ be the retailer's retail margin, and substitute $m = p - w$ into the profit functions of the manufacturer and the retailer, we can obtain the following:

$$\Pi_M = [w - c(1-\delta\theta)]\left[a - b(w+m) + \beta\theta\right] - p_0(e_0 - \lambda\theta)\left[a - b(w+m) + \beta\theta\right] - \frac{1}{2}k\theta^2$$

$$\Pi_R = m\left[a - b(w+m) + \beta\theta\right]$$

In the second stage, the manufacturer decides the optimal w and θ to maximize its profit. The first-order conditions of Π_M with respect to w and θ are obtained as follows:

$$\begin{cases} \dfrac{\partial \Pi_M}{\partial \theta} = -k\theta + c\delta\left[a - b(m+w) + \beta\theta\right] + \beta\left[w - c(1-\delta\theta)\right] + p_0\lambda\left[a - b(w+m) + \beta\theta\right] - p_0\beta(e_0 - \lambda\theta) \\ \dfrac{\partial \Pi_M}{\partial w} = a - b(m+w) + \beta\theta - b\left[w - c(1-\delta\theta)\right] + bp_0(e_0 - \theta\lambda) \end{cases}$$

When $k > \dfrac{[\beta + b(c\delta + p_0\lambda)]^2}{2b}$ is satisfied, the Hessian Matrix of Π_M is negative, and the manufacturer's profit Π_M is a concave function of (w,θ). Let $\dfrac{\partial \Pi_M}{\partial \theta} = 0$ and $\dfrac{\partial \Pi_M}{\partial w} = 0$, the optimal carbon-neutral technology innovation and the product sales price can be obtained as:

$$\theta = \frac{\begin{Bmatrix} ak - \beta^2(c + e_0p_0) + b^2m(c\delta + p_0\lambda) - a(c\delta + p_0\lambda)(\beta + bc\delta + bp_0\lambda) \\ -b(c - m + e_0p_0)(\beta c\delta + \beta p_0\lambda - k) \end{Bmatrix}}{2bk - \left[\beta + b\left(c\delta + p_0\lambda\right)\right]^2}$$

$$w = \frac{a - b(c - m + e_0p_0)(\beta + bc\delta + bp_0\lambda)}{2bk - \left[\beta + b\left(c\delta + p_0\lambda\right)\right]^2}$$

Substituting w and θ into the retailer's profit function Π_R results in the following:

$$\Pi_R = \frac{bkm\left[b(c + m + e_0p_0) - a\right]}{\left[\beta + b\left(c\delta + p_0\lambda\right)\right]^2 - 2bk}$$

The first-order condition of Π_R with respect to m is obtained as follows:

$$\frac{\partial \Pi_R}{\partial m} = \frac{bk\left[b(c + 2m + e_0p_0) - a\right]}{\left[\beta + b\left(c\delta + p_0\lambda\right)\right]^2 - 2bk}$$

Because of $\dfrac{\partial^2 \Pi_R}{\partial m^2} = \dfrac{2b^2k}{\left[\beta + b\left(c\delta + p_0\lambda\right)\right]^2 - 2bk} < 0$, we know that the retailer's profit function Π_R is concave in m .Then let $\dfrac{\partial \Pi_R}{\partial m} = 0$, the optimal market price m is obtained as follows:

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$$m^* = \frac{a - b(c + e_0 p_0)}{2b}$$

Thus, substituting m^* into w and θ gives the following:

$$w^* = \frac{\begin{Bmatrix} a\left[k - (c\delta + p_0\lambda)(\beta + bc\delta + bp_0\lambda)\right] \\ +(c + e_0 p_0)\left[3bk - 2\beta^2 - b(c\delta + p_0\lambda)(3\beta + bc\delta + bp_0\lambda)\right] \end{Bmatrix}}{2\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

$$\theta^* = \frac{\left[a - b(c + e_0 p_0)\right](\beta + bc\delta + bp_0\lambda)}{2\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

Then, $p = w + m$ can be obtained as

$$p^* = \frac{\begin{Bmatrix} b(c + e_0 p_0)\left[b(k - c\beta\delta - p_0\beta\lambda) - \beta^2\right] \\ +a\left[3bk - \beta^2 - b(c\delta + p_0\lambda)(3\beta + 2bc\delta + 2bp_0\lambda)\right] \end{Bmatrix}}{2b\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

In addition, to ensure that $1 - \delta\theta > 0$ and all decision variables are positive, the conditions $k > \frac{\left[\beta + b(c\delta + p_0\lambda)\right]\left\{2\beta + \delta\left[a + b(c - e_0 p_0)\right]\right\}}{4b}$, $a > b(c + e_0 p_0)$, and $\beta > b\left[p_0\lambda - \delta(c + 2e_0 p_0)\right]$ need to be met, so Proposition 1 can be obtained as follows.

Proposition 1: When $k > \frac{\left[\beta + b(c\delta + p_0\lambda)\right]\left\{2\beta + \delta\left[a + b(c - e_0 p_0)\right]\right\}}{4b}$, $a > b(c + e_0 p_0)$, and $\beta > b\left[p_0\lambda - \delta(c + 2e_0 p_0)\right]$, the equilibrium results of the supply chain are as follows:

$$\theta^* = \frac{\left[a - b(c + e_0 p_0)\right](\beta + bc\delta + bp_0\lambda)}{2\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}, \qquad q^* = \frac{bk\left[a - b(c + e_0 p_0)\right]}{2\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

$$w^* = \frac{\left\{k\left[a + 3b(c + e_0 p_0)\right] - (\beta + bc\delta + bp_0\lambda)\begin{Bmatrix} 2\beta(c + e_0 p_0) \\ +\left[a + 3b(c + e_0 p_0)\right]\left[c\delta + p_0\lambda\right] \end{Bmatrix}\right\}}{2\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

$$p^* = \frac{\left\{kb\left[3a + b(c + e_0 p_0)\right] - (\beta + bc\delta + bp_0\lambda)\begin{Bmatrix} b\beta(c + e_0 p_0) \\ +a\left[\beta + 2b(c\delta + p_0\lambda)\right] \end{Bmatrix}\right\}}{2b\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

$$\Pi_M^* = \frac{k\left[a - b(c + e_0 p_0)\right]^2}{8\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}, \qquad \Pi_R^* = \frac{k\left[a - b(c + e_0 p_0)\right]^2}{4\left\{2bk - \left[\beta + b(c\delta + p_0\lambda)\right]^2\right\}}$$

4. Equilibrium analysis

Proposition 2: As the consumer carbon-neutral sensitivity coefficient β increases, the following results are obtained: (1) $\frac{d\theta^*}{d\beta} > 0$, $\frac{dq^*}{d\beta} > 0$, $\frac{d\Pi_M^*}{d\beta} > 0$, and $\frac{d\Pi_R^*}{d\beta} > 0$; (2) $\frac{dw^*}{d\beta} > (\leq) 0$ and $\frac{dp^*}{d\beta} > (\leq) 0$ if $a > (\leq) a^\#$, where $a^\# = \frac{2\left[b^2(c\delta + p_0\lambda)^2 - \beta^2\right] + b(c + e_0 p_0)}{\beta\delta}$.

Proposition 2 investigates the effect of the customer carbon-neutral sensitivity coefficient on the equilibrium outcome of the supply chain. The results show that as the customer carbon-neutral sensitivity coefficient increases, the level of carbon-neutral technology innovation, product sales, and profits of supply chain firms increase. It is easy to understand that the greater the customer carbon-neutral sensitivity coefficient, the stronger the willingness of upstream enterprises to engage in carbon-neutral technology innovation, which leads to an increase in market demand and ultimately leads to higher profits for supply chain firms. However, it is clear from Proposition 2(2) that the pricing strategy of supply chain firms is closely related to market size. When the market size is large enough, it means that there is a greater demand for the product in the market. At this point, as the customer carbon-neutral sensitivity coefficient increases, consumers tend to purchase products with higher carbon neutrality levels, which has a double impact. As a result, supply chain firms choose to maximize their profits by deciding on a higher price. When the market size is small enough, with the increase of customer carbon-neutral sensitivity coefficient, the supply chain companies all choose to make a lower price decision to further stimulate the market demand. This reveals that the pricing strategy of supply chain firms is a process of flexible decision-making with the elastic size of the market, and its main objective is to increase the sales volume of the product and thus maximize the profit level of the supply chain firms.

Proposition 3: As the carbon-neutral technology innovation investment coefficient k increases, there are (1) $\frac{d\theta^*}{dk}<0$, $\frac{dq^*}{dk}<0$, $\frac{d\prod_M^*}{dk}<0$, and $\frac{d\prod_R^*}{dk}<0$; (2) if $\beta>(\le)b(c\delta+p_0\lambda)$, $\frac{dw^*}{dk}<(\ge)0$ and $\frac{dp^*}{dk}<(\ge)0$.

Proposition 3 investigates the impact of the carbon-neutral technological innovation investment coefficient on the equilibrium outcomes of the supply chain. The results show that the level of carbon-neutral technology innovation, product sales, and supply chain firms' profits decrease as the carbon-neutral technological innovation investment coefficient increases. Obviously, the larger the carbon-neutral technological innovation investment coefficient, the less efficient the investment in carbon-neutral technology innovation, and therefore, the less incentive for the upstream manufacturer to promote carbon-neutral technology innovation, thus making the market demand for the product also decrease, which eventually leads to a decrease of profits of supply chain firms. However, it is known from Proposition 3(2) that the pricing strategy of supply chain firms is closely related to the consumer carbon-neutral sensitivity coefficient. When the consumer carbon-neutral sensitivity coefficient is large enough, it signifies that consumers are preferred to purchase products with higher carbon neutrality levels. Therefore, with the growth of the carbon-neutral technology innovation investment coefficient, the efficiency of carbon-neutral technology innovation investment decreases, the incentive of the upstream manufacturer to promote carbon-neutral technology innovation will be weakened, and the carbon-neutral technology innovation level of products will decrease when the supply chain firms will all agree to lower prices to stimulate the demand of products. On the contrary, when the consumer carbon-neutral sensitivity coefficient is small enough, the increase in the investment coefficient of carbon-neutral technology innovation will lead to an increase in the cost of upstream supply chain firms, so the supply chain firms will make higher pricing strategies to solve the problem of cost increase, so as to maximize profits.

Proposition 4: As the cost-reduction efficiency of carbon-neutral technology δ increases, there are (1) $\frac{d\theta^*}{d\delta}>0$, $\frac{dq^{N*}}{d\delta}>0$, $\frac{d\prod_M^*}{d\delta}>0$, and $\frac{d\prod_R^*}{d\delta}>0$; (2) $\frac{dw^*}{d\delta}<(\ge)0$ and $\frac{dp^*}{d\delta}<(\ge)0$ if $a>(\le)a^{\#\#}$, where $a^{\#\#}=\frac{2\beta^2-b^2(c\delta+p_0\lambda)\left[2p_0\lambda+\delta(c-e_0p_0)\right]}{b\delta(c\delta+p_0\lambda)}$.

Proposition 4 studies the influence of the cost-reduction efficiency of carbon-neutral technology on the equilibrium results of supply chain firms. The results show that with the increase of the cost-reduction efficiency of carbon-neutral technology, the level of carbon-neutral technology innovation, product sales, and profits of the supply chain all increase. It is not difficult to observe that the greater the cost-reduction efficiency of carbon-neutral technology, the stronger the willingness of the upstream enterprise to promote carbon-neutral technology innovation, which leads to increased market demand and ultimately increases the profits of supply chain firms. Moreover, from Proposition 4(2), the pricing strategy of supply chain firms is closely related to market size. When the market size is large enough, meaning that the market demand for the product is high, the more cost-reduction efficiency of carbon-neutral technology is, the less the upstream manufacturer has to invest in the production cost of the product. The cost reduction causes the supply chain firms to agree to lower prices to further stimulate market demand for the product, thus maximizing profits. When the market size is small enough, as the cost-reduction efficiency of carbon-neutral technology increases, the upstream manufacturer's production cost will subsequently decrease, and therefore supply chain firms will choose to make decisions about higher prices to maximize profits.

Proposition 5: As the efficiency of carbon emission reduction per unit of product λ increases, there are (1) $\frac{d\theta^*}{d\lambda} > 0$, $\frac{dq^*}{d\lambda} > 0$, $\frac{d\prod_M^*}{d\lambda} > 0$, and $\frac{d\prod_R^*}{d\lambda} > 0$; (2) $\frac{dw^*}{d\lambda} < (\geq) 0$ and $\frac{dp^*}{d\lambda} < (\geq) 0$ if $a > (\leq) a^{\#\#}$, where $a^{\#\#} = \frac{2\beta^2 - b^2(c\delta + p_0\lambda)\left[2p_0\lambda + \delta(c - e_0 p_0)\right]}{b\delta(c\delta + p_0\lambda)}$.

Proposition 5 investigates the impact of carbon emission reduction efficiency on equilibrium outcomes of the supply chain. The results show that the level of investment in carbon-neutral technology innovation, the volume of product sales, and the profits of supply chain firms increase as the efficiency of carbon emission reduction per unit of product increases. Apparently, the more efficient the reduction in carbon emissions per unit of product, the fewer carbon credits the upstream manufacturer needs to purchase from the outside, which brings some profit to the firm. As a result, the upstream manufacturer has a more motivating incentive to engage in carbon-neutral technology innovation, which leads to increased market demand for their products and ultimately improves the performance of the supply chain. In addition, Proposition 5(2) shows that the pricing strategy of supply chain firms is tightly related to the market size. And when the market size is larger, it means that the market demand for the product is larger. At this stage, in order to further incentivize the market demand for the product, the supply chain firms instead decide on a lower price, thus maximizing their profits. When the market size is small enough, as the efficiency of carbon emission reduction per unit of product increases, the upstream manufacturer needs to purchase fewer carbon credits, and the operating costs of supply chain firms are reduced, and the cost reduction makes supply chain firms agree to raise prices to maximize profits.

5. Conclusions

This paper constructs a green supply chain game model in which the retailer leads and the manufacturer follows and considers that the manufacturer's investment in carbon-neutral technology innovation can not only improve the market demand for products but also reduce the production cost of products and influence carbon trading. Based on this model, the optimal carbon neutral strategy, pricing strategy, and supply chain firm performance are obtained by applying the backward induction method to the solution. With equilibrium results, the influences of the parameters, such as consumer carbon-neutral sensitivity coefficient, carbon-neutral technology innovation investment coefficient, carbon emission reduction efficiency, and carbon-neutral technology cost reduction efficiency, on the optimal operation decisions of supply chain firms are considered. The main conclusions are as follows: (1) The carbon-neutral strategy, product order quantity, and the performance of supply chain firms increase with the increase of the consumer carbon-neutral sensitivity coefficient. The pricing strategy of products is also related to the market size. With the increase of the consumer carbon-neutral sensitivity coefficient, when the market size is large enough, the pricing strategy of products will increase. Conversely, the pricing strategy of the product is then reduced. (2) The carbon-neutral technology innovation investment coefficient is negatively associated with carbon-neutral decision-making, product ordering, and performance of supply chain firms. On the other hand, pricing strategy is positively related to the consumer carbon-neutral sensitivity coefficient. As the investment factor of carbon-neutral technology innovation increases, the pricing strategy of the product shrinks when the consumer carbon-neutral sensitivity coefficient is large enough, and conversely, the pricing strategy of the product increases. (3) The cost-reduction efficiency of carbon-neutral technology is positively related to the carbon-neutral decision, product order quantity, and performance of supply chain firms, while the pricing strategy of products is strongly and negatively related to the market size. When the market size is large enough, the pricing strategy of the product decreases as the cost-reduction efficiency of carbon-neutral technology increases, and conversely, the pricing strategy of the product increases. (4) The efficiency of carbon emission reduction per unit of product is positively correlated with the carbon neutral decision, product order quantity, and performance of supply chain companies, while the pricing strategy of the product is strongly and negatively linked to the market size.

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