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Research on Decision-Making and Coordination of Closed-Loop Supply Chain Under Green and Low-Carbon Perspective

Jianhua Wang and Xinyan Cai *

School of Business, Jiangnan University, Wuxi 214126, China; wjh@jiangnan.edu.cn
* Correspondence: 6220910002@stu.jiangnan.edu.cn; Tel.: +86-18921102626

Abstract: This study explores low-carbon tech investment decisions in a closed-loop supply chain and their impact on supply chain optimization and relationships, using non-cooperative and cooperative game theories. This study examines the behavior patterns and potential gains of suppliers and manufacturers in independent vs. cooperative circumstances using model simulations. This study reveals that the following: (1) Optimal pricing, technology investment, profit, and cost-sharing ratios for low-carbon technologies can be determined under certain conditions to maximize stakeholder profits. (2) Suppliers and manufacturers can mutually benefit in supplier-driven markets. (3) Manufacturers have greater investment opportunities in low-carbon technology when suppliers have market power. (4) Provider utility decreases as consumer preference for low-carbon products rises. (5) The dominant market structure for low-carbon products evolves with the market stage. These findings provide strategic guidance for green supply chain management. The research presented in this paper offers a theoretical foundation and strategic direction for low-carbon technology investment in CLSCs.

Keywords: closed-loop supply chain; low-carbon technology investment decisions; non-cooperative–cooperative games; Starkelberg gaming

1. Introduction

1.1. Background and Significance

In the contemporary business environment, sustainability has emerged as a critical factor influencing corporate strategies and operational decisions. With the increasing awareness of environmental issues and the urgent need for mitigating climate change, businesses are being compelled to adopt green practices and integrate sustainability into their core operations. One area where this transformation is particularly evident is in the realm of supply chain management, leading to the emergence of the green closed-loop supply chain (GCLSC).

The significance of studying low-carbon technology investment decisions in GCLSCs lies in their potential to drive innovation and foster collaboration among supply chain partners. By adopting such technologies, companies can reduce their carbon emissions, enhance their environmental performance, and differentiate themselves in the marketplace. However, making these investments requires careful consideration of various factors, including pricing strategies, technology adoption costs, profit margins, and market dynamics.

This paper delves into the complex decision-making and coordination challenges faced by suppliers and manufacturers in GCLSCs when it comes to low-carbon technology investments. By utilizing non-cooperative and cooperative game theories, this study examines the behavior patterns and potential gains of these supply chain entities in independent versus cooperative scenarios. The objective is to provide insights into how optimal pricing, technology investment, profit, and cost-sharing ratios can be determined under different conditions to maximize stakeholder profits while minimizing environmental impacts.

The findings of this research hold significant strategic implications for green supply chain management. By providing a theoretical foundation and strategic direction for

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low-carbon technology investment in GCLSCs, this paper contributes to the advancement of sustainable supply chain practices. It offers practical guidance for companies seeking to optimize their supply chains, enhance their environmental performance, and achieve long-term profitability. Furthermore, this research underscores the importance of collaboration and coordination among supply chain partners in achieving sustainability goals, highlighting the potential for mutual benefits and shared value creation through strategic investment in low-carbon technologies.

1.2. Current Status of Research

In terms of research views, the current body of work on closed-loop supply chains domestically and internationally is rather substantial and diverse. The majority of them address closed-loop supply chain pricing and coordination, production decision-making, and product recovery in this manner. Liu et al. [1] investigated the best pricing, collection ratio, and profit distribution of each model in the modeling of closed-loop supply chains using a combination of the fuzzy cut-set method and the Stackelberg game. A portion of the literature focuses on pricing and coordination in closed-loop supply chains. By using Karush–Kuhn–Tucker conditions for limited optimization and solving a multilevel sequential move game under two ensemble models, Sumit and Shrey [2] found constraints on the occurrence of perfect Nash equilibria for subgames. The study demonstrated that if the retailer's dominance inequality aversion is sufficiently severe, a constant wholesale price contract can coordinate the fragmentation channel in a manufacturer-dominated CLSC. Cross-channel recovery rates and customer channel preferences, according to Zhao and Ye [3], have a direct and substantial influence on pricing strategies, including choices about profit sharing in closed-loop supply chains. Different pricing strategies and judgments are made by manufacturers and merchants based on the preferences of different channels. When cross-channel recovery rises and channel preferences remain constant, manufacturer pricing falls. Using the Stackelberg game, Zhao et al. [4] looked into the best pricing schemes for batteries used in electric vehicles with three distinct Chinese recycling channels that were supported by government funding. According to the findings, the government ought to push EV manufacturers to take on battery recycling duties and boost subsidies for reusing EV batteries. Centralized cooperation can result in the maximum overall profit for a closed-loop supply chain; therefore, in order to increase profits, communication between the supply chain's upstream and downstream parties needs to be strengthened. Liu et al. [5] focused on the current state of affairs in China, where it is challenging to recycle used mobile phones. They discovered that prompt promotion of environmental education and information channels is necessary to increase audience awareness and encourage recycling. Three competing options for manufacturer selection were examined by Wang et al. [6] Initially, the remanufacturer assumes full control of the recycling company while the manufacturer gives up on creating a fully closed-loop supply chain. In the second scenario, the manufacturer initiates the creation of its own recycling network and engages in competition with the remanufacturer in the recycling market. Third, the retailer competes with the remanufacturer in the recycling market once the manufacturer outsources the recycling to the retailer. A global enterprise-level EV-LIBs recycling supply chain network was built by Mu et al. [7] using sophisticated network theory and actual supply relationship data from significant players in the EV-LIBs recycling market. Pazoki and Zaccour [8] investigated ways to minimize the production's negative environmental effects or maximize product recovery by determining the appropriate values for subsidies and fines in a number of environmental regulations. With respect to a single manufacturer and a single traditional retailer, Pan and Liu [9] concentrated on the two-stage closed-loop supply chain pricing problem while taking cross-channel recovery and channel preference into account. In a two-stage CLSC system, the impacts of channel preference and cross-channel recovery rate on pricing and profitability were described. The findings indicate that when cross-channel recovery rate rises and channel preference remains constant, manufacturer pricing will decrease, and because it is less affected by

the cross-channel recovery rate, the retailer's pricing stays constant. Zulkaif Ahmed Saqib et al. [10] explored the moderating effects of product modularity and supply chain visibility on the sustainability and operational initiatives of small- and medium-sized manufacturing firms (SMEs) through empirical analyses, providing new perspectives on understanding how these firms can improve their operational and sustainability performances in the face of supply chain and technological pressures.

Scholars domestically and internationally have carried out extensive research on inter-firm competitiveness decision-making in supply chain emission reduction. At this point, academic research on supply chain emission reduction decision-making is more developed. The two primary categories of study subjects are manufacturers and retailers; for example, Zhou et al. [3] examined a secondary supply chain system made up of retailers and manufacturers, analyzing joint emission reduction strategies under advertisement cooperation as well as single and dual channels. Xia et al. [11] examined supply chain companies' dynamic low-carbon strategies and suggested a contract for cooperation between retailers and manufacturers. Scholars primarily concentrate on the tactics used by manufacturers to reduce emissions and by retailers to advertise, publicize, and promote their products. They also conduct research on the collaboration between manufacturers and retailers. Wang et al. [12] analyzed the effects of cost-sharing and wholesale price premium contracts on supply chain emission reduction decisions and took into account customers' low-carbon environmental awareness. An evolutionary game model between manufacturers and suppliers was established by Qiu-fang et al. [13] in order to research and determine supply chain emission reduction input techniques. In order to investigate the best emission reduction plans and profit margins for both game participants under market regulation, government involvement, and channel coordination, Zu et al. [14] built a differential game model between manufacturers and suppliers. The game issue of coordinated pricing for a second-tier supply chain with a manufacturer and several suppliers was examined by Ma et al. [15] in light of inventory and carbon tax limitations. In the framework of government incentives based on the pace at which businesses reduce their carbon emissions, Jian et al. [16] examined supply chain emission reduction decisions. Fair profit distribution is a key component in providing incentives for supply chain members, and fairness concerns can encourage and coordinate supply chain members to invest more in sustainable green technology innovation development in an equitable manner. Concerns about equity might encourage and help supply chain participants to allocate more funds to the development of innovative, sustainable green technologies under fair conditions. Game theory was employed by Yang et al. [17] to examine how green supply chain companies innovate in supply chain innovation, risk aversion, and the competitive environment to accomplish green pricing and decision-making innovations. Additionally, they analyzed various retailer sales models and discovered that green innovation models can boost manufacturer and retailer earnings. Meng et al.'s study [18] examined three scenarios for innovation subsidies and categorized consumers as either green or non-green. It revealed that when the government provides manufacturers with subsidies, this can encourage the entire supply chain to adopt green innovation by offering incentives along the way. This will have a positive impact on the environment, economic efficiency, and social welfare. Furthermore, the government's willingness to provide manufacturers with subsidies rises in tandem with the degree of government subsidies for green innovation and the percentage of green consumers, resulting in enhanced social welfare, economic benefits, and environmental advantages. Lai et al. [19] saw the management of low-carbon technology integration at the research center. They then concluded that modular design is a useful technique for quickly integrating low-carbon technologies from around the world to satisfy the market's constantly shifting demands by analyzing the state of green building-related indicators and creatively proposing an evaluation system on low-carbon technology integration and innovation. At the moment, the majority of research on the cost of low-carbon products focuses on how power structures, government regulations, business social responsibility, and customer behavior affect pricing. This research, in contrast to the literature men-

tioned above, focuses on the implementation of low-carbon product price decisions and low-carbon technological input between upstream and downstream enterprises. Secondly, instead of using the cost-sharing coefficient as a parameter to control the profitability of two or more parties, this study introduces it and uses it as a decision variable for downstream enterprises. Furthermore, few studies have examined the concept of competition and cooperation coexisting (i.e., a non-cooperative–cooperative two-type game). The literature currently in publication analyzes low-carbon technology investment behavior and product pricing from the perspective of a single non-cooperative or cooperative game. The pricing of low-carbon products by upstream and downstream enterprises is, in fact, determined by their collaborative low-carbon technology investment behavior (e.g., manufacturers and suppliers); that is, their tactical decisions are carried out in accordance with their strategic decisions that deal with cooperation and competition amongst businesses. The biform game was introduced by Brandenburger and Stuar [20] in 2007. Since then, supply chain management-related topics such as inventory competition, investment incentive [21], technical innovation, network creation [22], and blockchain consensus reaching [23] have been studied using this analytical framework. In fact, Feess and Thun [22] even used the concept of the biform game to analyze the problems of surplus distribution and investment incentive in supply chains. However, they modeled the decision to invest made by supply chain participants as a non-cooperative game, and in the cooperative game portion, they also assumed, quite directly and unquestioningly, that the alliance profit formed among various members is a particular constant, without determining how the alliance profit is formed in cooperative games.

The literature at this stage focuses more on emphasizing the importance of sustainable green R&D technologies in the supply chain. Masanta et al. [24] investigated the impact of the learning effect on a multi-echelon CLSC. The demand was modeled as a function of some factors, which were green innovation, promotional efforts, and retail price. Du et al.'s research [25] demonstrated that sustainable green technology innovation is critical at all stages of supply chain development, and supply chain members at each stage need to invest in sustainable green technology innovation research and development. Based on the resource-based theory, Zulkaif Ahmed Saqib et al. [26] provided insights into how supply chain visibility moderates the impact of sustainable practices on the sustainable performance of small- and medium-sized manufacturing enterprises (SMEs), providing new insights into understanding the role of supply chain visibility in promoting sustainable business development. The findings show that supply chain visibility plays a significant moderating role between sustainable practices and sustainable performance, emphasizing the importance of information sharing for SMEs to enhance their sustainable performance and filling a research gap in this area. Leila et al. [27] presented a mathematical model for a closed-loop green supply chain under uncertain conditions, emphasizing the importance of CLSC management in reducing risks by coordinating processes within modern organizations. In contrast to previous research, this paper builds a non-cooperative–cooperative two-type game model of a low-carbon closed-loop supply chain with a manufacturer and a supplier. It then thoroughly examines the issues surrounding low-carbon technology investment decisions and product pricing under the simultaneous decision-making models of the two parties, the manufacturer-dominated model and the supplier-dominated model.

2. Design of a Green Supply Chain Program Considering Low-Carbon Technology Inputs

2.1. Description of the Problem

This study examines a two-tier low-carbon supply chain comprising a manufacturer (S) and a supplier (R). Within this supply chain, the primary responsibility of the producer is to produce and recycle remanufactured low-carbon items, which have a unit production cost denoted as c. The manufacturer sells the product to the supplier at a wholesale price denoted as w, and the supplier then sells it to the end customer at a market price denoted as p. Figure 1 displays the supply chain framework of this article.

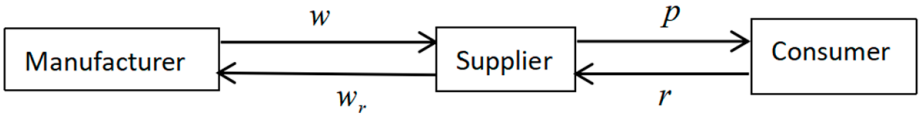


Figure 1. Low-carbon closed-loop supply chain structure.

This paper posits that manufacturers and suppliers are engaged in a collaborative endeavor known as Low Carbon Technology Development and Application (LCTDA). This project focuses on the implementation of carbon capture, utilization, and sequestration (CUSC) technologies, with the objective of enhancing the low-carbon content of products and optimizing the overall efficiency of the supply chain. This paper utilizes the theoretical framework of the non-cooperative–cooperative two-type game to thoroughly analyze three distinct decision-making models: a joint decision-making model involving both the manufacturer and supplier (Model 1), a decision-making model dominated by the supplier (Model 2), and a decision-making model dominated by the manufacturer (Model 3). The focus of the analysis is on addressing the issue of product pricing and the decision-making process for investing in low-carbon technologies. In this scenario, the cooperative game simulates the joint investment decision of a manufacturer and supplier in low-carbon technology for a product, while the non-cooperative game examines the pricing decision for the same product. Below is a given model of a non-cooperative–cooperative two-type game in a closed-loop supply chain, along with its basic foundation.

During the non-cooperative phase of the game, the manufacturer and the supplier independently determine their wholesale pricing (w) and marginal profit (m), which is similar to setting the supplier's selling price ($p = w + m$). The pricing in the cooperative phase of the game is affected by investment choices in low-carbon technology. As a result, it is not possible to estimate the exact wholesale costs and selling prices beforehand. This scenario gives rise to a distinct strategic situation among the participants in the collaborative aspect of the game. Clearly, the strategy variables of marginal profit (m) and wholesale pricing (w) in the low-carbon closed-loop supply chain model are of a continuous nature. This results in the formulation of a continuous non-cooperative–cooperative two-type game model. After evaluating their respective probable pricing, the manufacturer and supplier will design a strategy situation for the cooperative game component (m, w). However, the payment functions of manufacturers and suppliers in these situations are not directly revealed. This is because the payment function of suppliers depends on their own share of the cost of investment in low-carbon technologies, denoted as η, as well as the manufacturer's level of low-carbon technology, denoted as s. These parameters need to be determined in a cooperative game. This point also exemplifies a fundamental trait of the non-cooperative–cooperative two-type game.

In the cooperative game component, manufacturers and suppliers must collaboratively determine the cost-sharing ratio η for low-carbon technology investments and the level of low-carbon technology s, based on the established strategy situation or combination of strategies (m, w), in order to maximize their individual benefits. Furthermore, Shapley values are employed to compute and allocate the earnings of both entities, therefore establishing the precise payment function in the present strategic scenario (m, w).

Figure 2 illustrates the sequential process of the non-cooperative–cooperative two-type game model for a closed-loop supply chain with low-carbon characteristics.

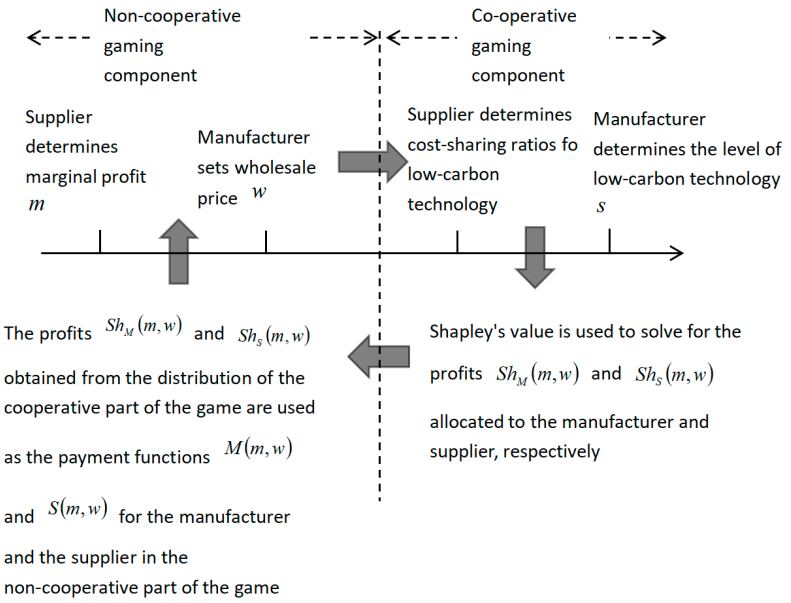


Figure 2. Low-carbon closed-loop supply chain non-cooperative–cooperative two-type game framework.

2.2. Non-Cooperative and Cooperative Two-Type Game Model Assumptions and Symbolic Description

Relevant Assumptions

Assumption 1. *Manufacturers primarily focus on producing low-carbon products in order to enhance their products to low-carbon standards and decrease carbon emissions. This necessitates substantial investment in research and development and the implementation of new low-carbon technologies or enhancements to current low-carbon production methods. It is presumed that the manufacturer's level of low-carbon technology is s ($s \geq 0$). A value of $s = 0$ signifies that manufacturers are abstaining from investing in low-carbon technologies, whereas a value of $s > 0$ indicates that manufacturers have indeed made investments in low-carbon technologies. As the level of low-carbon technology s increases, so does the corresponding investment cost. Therefore, the cost of a manufacturer's investment in low-carbon technology can be represented as $\frac{ks^2}{2}$, where k represents the elasticity coefficient of a manufacturer's low-carbon investment costs in relation to changes in the level of low-carbon technology. This coefficient is known as the low-carbon technology investment cost coefficient. Higher values of the coefficient k imply that manufacturers face higher costs when investing in low-carbon technologies, whereas lower values suggest lower costs.*

Manufacturers can lower their unit production costs by investing in low-carbon technologies, enhancing their current production processes, adopting advanced manufacturing techniques and other technologies, optimizing material utilization and production efficiency, and reducing labor expenses. In order to measure the impact of low-carbon technologies on productivity enhancements, a factor called "low-carbon technology cost reduction efficiency" is proposed as b. A linear function is employed to represent the influence of low-carbon technology on unit manufacturing costs ($c - bs$). The linear function can demonstrate the correlation between the rise in productivity and the increase in low-carbon technological inputs, resulting in a decrease in the unit cost of production. As investments in low-carbon technologies persist, productivity will not continue to rise indefinitely, nor will the unit cost of production keep decreasing indefinitely. Instead, they will approach a stable value that will either remain constant or change only slightly. This is in accordance with the law of diminishing marginal utility, which implies that further investments in low-carbon technologies will not lead to any significant reduction in unit production costs. It aligns with the current production of the firm. Additionally, the delineation of linear functions not only streamlines the process of finding solutions but also aids in the examination of outcomes and the uncovering of concealed implications in

management. $0 \leq c < w < p$ suggests that manufacturers will venture into the market for environmentally friendly items; $b \in [0,1]$ quantifies the effectiveness of implementing low-carbon technology upgrades in decreasing the costs of producing each unit.

Assumption 2. *The supplier primarily specializes in the sale of low-carbon products, which are its major commodities. Suppliers contribute to the financial burden of manufacturers' low-carbon technology investments to develop enduring and mutually beneficial supply and demand partnerships. The supplier is expected to contribute to the manufacturer's investment in low-carbon technologies in a ratio of* η *(*$\eta \in [0,1]$*).* $\eta = 0$ *denotes that suppliers bear no shared burden of investment expenses for low-carbon technologies;* $\eta \in (0,1)$ *denotes that suppliers bear a fraction of the financial burden associated with the implementation of low-carbon technologies; and* $\eta = 1$ *signifies that the financial burden of investing in low-carbon technologies is solely shouldered by the suppliers of manufacturers.*

Assumption 3. *Given that customers have a preference for products with low-carbon emissions and are ready to pay a premium for such products, a rise in the availability of low-carbon products leads to a corresponding increase in consumer preference and ultimately boosts sales of low-carbon products. As a result, consumer demand for low-carbon items is q depending on the market price of low-carbon products p (which is* $p = w + m$*). The demand function for a manufacturer's low-carbon technology level is described as linear, denoted by* $q = A + \alpha s - (w + m)$*. In that,* $m = p - w$ *represents the supplier's marginal profit on the sale of one unit of low-carbon product and* $A > w + m$*.* α *indicates consumer sensitivity to low carbon levels, which is also named consumer low-carbon preferences. The larger* α *is, the higher the consumer demand for low-carbon products, and the greater the market demand accordingly. For ease of calculation, we assume the potential market size A to be 1.*

Assumption 4. *Used products recovered by suppliers from consumers are carefully screened and all meet the criteria for remanufacturing. These new products, produced by reprocessing the used products obtained through recycling, are identical in quality and functionality to new products produced directly from new materials and are therefore sold on the market at the same price.*

Assumption 5. *The vendor recovery rate can be expressed as* $r = \sqrt{I/h}$*. I indicates the effective recovery investment of the recycling enterprise (supplier) and h indicates the coefficient of difficulty for recycling enterprises to recover used products. Therefore, the supplier's effective recovery investment cost function is* $I = hr^2$*.*

The related symbols and meanings are shown in Table 1.

Table 1. Relevant symbols and meanings.

Symbols	Meanings
c	Unit production costs of manufacturers of low-carbon products
w	Wholesale price at which manufacturers sell their products to suppliers
w_r	Price at which suppliers sell recovered used products to manufacturers
p	Price sold by suppliers to consumers
m	Supplier's marginal profit per unit of product sold
r	Recycling rate of used products recovered by suppliers
I	Investment cost for suppliers to recycle used products
h	Difficulty factor for suppliers to recycle used products
c_0	Manufacturer's unit cost of remanufacturing new products from used products
A	Potential market size
q	Demand for low-carbon products
s	Low-carbon technology levels of manufacturers
k	Investment cost factor for low-carbon technologies
α	Consumer low-carbon preferences
b	Cost reduction efficiency factor for low-carbon technology levels
η	Supplier cost-sharing ratio for low-carbon technology investments
$S_i (i = 1,2,3)$	Profits earned by suppliers in Models 1, 2, and 3
$M_i (i = 1,2,3)$	Profits earned by manufacturers in Models 1, 2, and 3
$SM_i (i = 1,2,3)$	Profits earned by the supply chain system in models 1, 2, and 3

2.3. Construction of Green Supply Chain Model Considering Low-Carbon Technology Inputs

2.3.1. Construction of Non-Cooperative–Cooperative Two-Type Game Model

Combining the above assumptions, the profit functions of the manufacturer and supplier, respectively, can be obtained as follows:

$$M = -\frac{1}{2}k(1-\eta)s^2 + (1-m+\alpha s-w)(-c+bs+w) - r(1-m+\alpha s-w)(c_0+w_r) \quad (1)$$

$$S = -hr^2 - \frac{1}{2}k\eta s^2 - m(-1+m-\alpha s+w) \quad (2)$$

Low-Carbon Technology Investment and Cost-Sharing Ratios

In the non-cooperative–cooperative game model of a low-carbon closed-loop supply chain, the payoff functions of the non-cooperative part of the game are not directly or specifically given in advance as in a traditional non-cooperative game. Instead, these payoff functions are determined by the cooperative part of the game. Therefore, in order to construct a non-cooperative–cooperative game model for such a low-carbon closed-loop supply chain, it is necessary to create cooperative games for all possible strategic situations of manufacturers and suppliers in the cooperative game section and to determine the profit-sharing values of the parties involved (i.e., manufacturers and suppliers) in each cooperative game.

In the cooperative game component, the alliance profit is determined based on the supplier's cost-sharing ratio of low-carbon technology investment η and the supplier's low-carbon technology level s. For any strategy situation (m, w), which consists of two strategies (or decision variables), i.e., the supplier's marginal profit m and the manufacturer's wholesale price w, a cooperative game $V(m, w)$ is formed. In the cooperative part of the game, suppliers and manufacturers need to consider their respective returns on investment and make a decision on the optimal level of low-carbon technology and the optimal cost-sharing ratio of low-carbon technology investment. Under any strategy situation (m, w), four coalitions can be formed, namely $\{\varnothing\}$, $\{S\}$ and $\{M\}$, and $\{S, M\}$, using the von Neumann coalition characteristic function determination method. The coalition characteristic function of the cooperative game, i.e., the coalition profit function $V(m, w)$, can be constructed as follows:

(1) Empty alliance's affiliate profit is $V(m, w)(\varnothing) = 0$;
(2) The alliance profits of a single innings alliance (i.e., supplier or manufacturer) are, respectively, as follows:

$$V(m,w)(M)* = \frac{-\frac{1}{2}k(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r)^2-(2\alpha b-k)r(c_0+w_r)((2\alpha b-k)(1-m-w)+\alpha(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r))}{(2\alpha b-k)^2}$$
$$+\frac{((2\alpha b-k)(1-m-w)+\alpha(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r))((2\alpha b-k)(-c+w)+b(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r))}{(2\alpha b-k)^2}$$
$$\mathrm{V(m,w)(S)^*} = -\mathrm{hr^2} + \mathrm{m(1-m-w)}$$

(3) The alliance profit of a grand alliance (i.e., consisting of a supplier and a manufacturer) is as follows:

$$V(m,w)(M,S)* = \frac{1}{(2\alpha b-k)^2}(-h(2\alpha b-k)^2 r^2 - \frac{1}{2}k(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r)^2 + (2\alpha b-k)(m-r(c_0+w_r))((2\alpha b-k)(1-m-w)$$
$$+\alpha(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r)) + ((2\alpha b-k)(1-m-w)+\alpha(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r))((2\alpha b-k)(-c+w)$$
$$+b(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha r w_r)))$$

From the coalition characteristic function $V(m,w)$ of the cooperative game between two people, the supplier and the manufacturer, it can be determined that the cooperative game satisfies convexity, and the coalition characteristic value satisfies the following conditions:

$$V(m,w)(A) + V(m,w)(T) \leq V(m,w)(A \cup T) + V(m,w)(A \cap T)$$

It can be seen that the two-player cooperative game between the supplier and the manufacturer is convex, and the Shapley assignment values are core and unique. Therefore, in this paper, the Shapley value is used to allocate the profit of the cooperative game.

According to the Shapley value solution formula, the profit shared by the supplier and manufacturer in the cooperative game part under strategy situation (m,w) can be obtained as follows:

$$Sh_S(m,w) = \frac{3\alpha bm + \alpha^2 cm - 2km - \frac{\alpha^2 m^2}{2} - 3\alpha bm^2 + 2km^2 + \alpha^2 c_0 mr - 4\alpha bhr^2 + 2hkr^2 - \alpha^2 mw - 3\alpha bmw + 2kmw + \alpha^2 mrw_r}{4\alpha b - 2k} \tag{3}$$

$$\begin{aligned} Sh_M(m,w) = {} & \tfrac{1}{(2\alpha b-k)^2}\left(-\tfrac{1}{2}h(2\alpha b-k)^2 r^2 + \tfrac{1}{2}(2\alpha b-k)^2(hr^2 + m(-1+m+w)) - \tfrac{1}{4}k(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r)^2\right. \\ & -\tfrac{1}{4}k(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r)^2 - \tfrac{1}{2}(2\alpha b-k)r(c_0+w_r)(-((2\alpha b-k)(-1+m+w)) + \alpha(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r)) \\ & +\tfrac{1}{2}(-((2\alpha b-k)(-1+m+w)) + \alpha(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r))(-((2\alpha b-k)(c-w)) + b(-b+\alpha c+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r)) \\ & +\tfrac{1}{2}(2\alpha b-k)(m-r(c_0+w_r))(-((2\alpha b-k)(-1+m+w)) + \alpha(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r)) \\ & \left.+\tfrac{1}{2}(-((2\alpha b-k)(-1+m+w)) + \alpha(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r))(-((2\alpha b-k)(c-w)) + b(-b+\alpha c-\alpha m+bm+\alpha c_0 r-\alpha w+bw+\alpha rw_r))\right) \end{aligned} \tag{4}$$

Pricing of Low-Carbon Products

According to Equations (3) and (4), the payment functions of the supplier and the manufacturer in the non-cooperative part of the game, i.e., the profits $Sh_S(m,w)$ and $Sh_M(m,w)$ obtained by the supplier and the manufacturer in the cooperative part of the game after the allocation of Shapley's value, are obtained, denoted as $S(m,w) = Sh_S(m,w)$, and $M(m,w) = Sh_M(m,w)$. In the pricing phase of the non-cooperative part of the game, we consider the impact of three different power structures on product pricing with simultaneous decision-making by the supplier and manufacturer (Model 1), supplier-dominated decision-making (Model 2), and manufacturer-dominated decision-making (Model 3).

(1) Simultaneous decision-making model for suppliers and manufacturers (i.e., Model 1)

The decision sequence in Model 1 is that the supplier and the manufacturer determine the marginal profit m and the wholesale price w simultaneously, respectively. According to Equations (3) and (4), the profits of the supplier and the manufacturer in model 1 can be obtained, respectively, as follows:

$$S_1(m_1,w_1) = \frac{4k\left(hr^2 + m_1(-1+m_1+w_1)\right) - 2\alpha b\left(4hr^2 + 3m_1(-1+m_1+w_1)\right) + \alpha^2 m_1(2c - m_1 - 2w_1 + 2r(c_0+w_r))}{8\alpha b - 4k} \tag{5}$$

$$\begin{aligned} M_1(m_1,w_1) = {} & -\tfrac{1}{8\alpha b-4k}\left(2b^2(-1+m_1+w_1)^2 + 4k(-1+m_1+w_1)(c-w_1+r(c_0+w_r)) - 2\alpha b(-1+m_1+w_1)(2c+m_1-2w_1+2r(c_0+w_r))\right. \\ & \left.+\alpha^2\left(2c^2 + {m_1}^2 - 2c(m_1+2w_1-2r(c_0+w_r)) + 2m_1(w_1-r(c_0+w_r)) + 2(w_1-r(c_0+w_r))^2\right)\right) \end{aligned} \tag{6}$$

To find the first order derivatives of $S_1(m_1,w_1)$ and $M_1(m_1,w_1)$ with respect to m_1 and w_1, respectively, and making them equal to 0, we have

$$\frac{dS_1(m_1,w_1)}{dm_1} = \frac{\alpha b(3-6m_1-3w_1) + k(-2+4m_1+2w_1) + \alpha^2(c-m_1-w_1+r(c_0+w_r))}{4\alpha b - 2k}$$

$$\begin{aligned} \tfrac{dM_1(m_1,w_1)}{dw_1} = {} & \tfrac{1}{(2\alpha b-k)^2}\left(k^2 + ck^2 - k^2 m_1 + c_0 k^2 r - 2k^2 w_1 + b^2 k(-1+m_1+w_1) + k^2 rw_r + \alpha^3 b(2c - m_1 + 2c_0 r - 2w_1 + 2rw_r)\right. \\ & +\alpha b\left(b^2(2-2m_1-2w_1) + k(-3-3c+2.5m_1-3c_0 r+6w_1-3rw_r)\right) + \alpha^2(k(-c+0.5m_1-c_0 r+w_1-rw_r) \\ & \left.+b^2(2+2c-m_1+2c_0 r-4w_1+2rw_r))\right) \end{aligned}$$

Solving this system of equations gives

$$m_1^* = \frac{36\left(b^2+\alpha^2(c+r(c_0+w_r))+\alpha b(1+c+r(c_0+w_r))-k(1+c+r(c_0+w_r))\right)}{18\alpha^2+18\alpha b+36b^2-36k}$$

$$w_1^* = \frac{\alpha^3 b(1-13c-13c_0r-13rw_r)+\alpha^4(-c-c_0r-rw_r)+k\left(4b^2+k(-4-8c-8c_0r-8rw_r)\right)}{\alpha^4+4\alpha^3 b+5\alpha^2b^2+6\alpha b^3-4\alpha^2k-8\alpha bk-4b^2k+4k^2}$$
$$+\frac{\alpha^2\left(b^2(-11-10c-10c_0r-10rw_r)+k(8c+8c_0r+8rw_r)\right)+\alpha b\left(-6b^2+k(12+20c+20c_0r+20rw_r)\right)}{\alpha^4+4\alpha^3 b+5\alpha^2b^2+6\alpha b^3-4\alpha^2k-8\alpha bk-4b^2k+4k^2}$$

To find the second order derivatives of $S_1(m_1, w_1)$ and $M_1(m_1, w_1)$ with respect to m_1 and w_1, respectively, we have

$$\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} = \frac{-\alpha^2-6\alpha b+4k}{4\alpha b-2k}$$

$$\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} = -2+\frac{\alpha^2-2\alpha b+b^2}{-2\alpha b+k}$$

Analyses are available:

(1) When $k > \frac{\alpha^2+2\alpha b+b^2}{2}$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

(2) When $0 < 2b < \alpha$ and $0 < k < 2\alpha b$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

(3) When $0 < \alpha < 2b$ and $0 < k < \frac{\alpha^2+6\alpha b}{4}$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

At this point, the right-hand side functions of Equations (5) and (6) are convex functions with respect to marginal profit and wholesale price, respectively, and there exists a point of extreme value, i.e., there exists a unique marginal profit m_1^* and wholesale price w_1^* that makes the supplier's and manufacturer's profits maximal, respectively.

Substituting m_1^* and w_1^* into (5) and (6), respectively, the optimal profits for the manufacturer and supplier can be obtained as

$$S_1^* = \frac{4k\left(hr^2+m_1^*(-1+m_1^*+w_1^*)\right)-2\alpha b\left(4hr^2+3m_1^*(-1+m_1^*+w_1^*)\right)+\alpha^2m_1^*(2c-m_1^*-2w_1^*+2r(c_0+w_r))}{8\alpha b-4k}$$

$$M_1^* = -\frac{1}{8\alpha b-4k}\left(2b^2(-1+m_1^*+w_1^*)^2+4k(-1+m_1^*+w_1^*)(c-w_1^*+r(c_0+w_r))-2\alpha b(-1+m_1^*+w_1^*)(2c+m_1^*-2w_1^*+2r(c_0+w_r))\right.$$
$$\left.+\alpha^2\left(2c^2+m_1^{*2}-2c(m_1^*+2w_1^*-2r(c_0+w_r))+2m_1^*(w_1^*-r(c_0+w_r))+2(w_1^*-r(c_0+w_r))^2\right)\right)$$

Substitute m_1^*, w_1^*, S_1^*, M_2^* into (1) and (2) to find η_1^* and s_1^*.

(2) Supplier-led decision-making model (i.e., Model 2)

Decision sequence in Model 2 is that the supplier first determines the marginal profit m_2 of the low-carbon product, and subsequently, the manufacturer determines the wholesale price w_2 of the low-carbon product. According to Equations (3) and (4), the profit functions of suppliers and manufacturers in model 2 can be obtained as

$$S_2(m_2,w_2) = \frac{4k(hr^2+m_2(-1+m_2+w_2))-2\alpha b(4hr^2+3m_2(-1+m_2+w_2))+\alpha^2m_2(2c-m_2-2w_2+2r(c_0+w_r))}{8\alpha b-4k} \quad (7)$$

$$M_2(m_2,w_2) = -\frac{1}{8\alpha b-4k}\left(2b^2(-1+m_2+w_2)^2+4k(-1+m_2+w_2)(c-w_2+r(c_0+w_r))-2\alpha b(-1+m_2+w_2)(2c+m_2-2w_2+2r(c_0+w_r))\right.$$
$$\left.+\alpha^2\left(2c^2+m_2{}^2-2c(m_2+2w_2-2r(c_0+w_r))+2m_2(w_2-r(c_0+w_r))+2(w_2-r(c_0+w_r))^2\right)\right) \quad (8)$$

According to inverse induction, first find the first order derivative of $M_2(m_2, w_2)$ with respect to w_2 and make it equal to 0. There is

$$\frac{dM_2(m_2,w_2)}{dw_2} = \frac{1}{(2\alpha b-k)^2}(k^2+ck^2-k^2m_2+c_0k^2r-2k^2w_2+b^2k(-1+m_2+w_2)+k^2rwr+\alpha^3b(2c-m_2+2c_0r-2w_2+2rw_r)$$
$$+\alpha b\left(b^2(2-2m_2-2w_2)+k(-3-3c+2.5m_2-3c_0r+6w_2-3rw_r)\right)+\alpha^2(k(-c+0.5m_2-c_0r+w_2-rw_r)$$
$$+b^2(2+2c-m_2+2c_0r-4w_2+2rw_r)))$$

Solving the above equation gives

$$w_2^* = \frac{b^2(1-m_2)+k(-1-c+m_2-c_0r-rw_r)+\alpha^2(c-0.5m_2+r(c_0+w_r))+\alpha b(1+c-0.5m_2+r(c_0+w_r))}{\alpha^2+2\alpha b+b^2-2k} \quad (9)$$

Substituting w_2^* into Equation (7) to find the first order derivative of $S_2(m_2, w_2)$ with respect to m_2 and making it equal to 0, we have

$$m_2^* = \frac{\alpha^2(0.5-0.5c-0.5c_0r-0.5rw_r)+\alpha b(0.5-0.5c-0.5c_0r-0.5rw_r)+k(-1+c+c_0r+rw_r)}{\alpha^2+2\alpha b-2k}$$

To find the second order derivatives of the supplier's and manufacturer's profit functions with respect to the marginal profit m_2 and the wholesale price w_2, respectively, we have

$$\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} = \frac{-\alpha^2-6\alpha b+4k}{4\alpha b-2k}$$

$$\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} = -2+\frac{\alpha^2-2\alpha b+b^2}{-2\alpha b+k}$$

Analyses are available:

(1) When $k > \frac{\alpha^2+2\alpha b+b^2}{2}$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

(2) When $0 < 2b < \alpha$ and $0 < k < 2\alpha b$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

(3) When $0 < \alpha < 2b$ and $0 < k < \frac{\alpha^2+6\alpha b}{4}$, there are $\frac{d^2S_1(m_1,w_1)}{dm_1{}^2} < 0$ and $\frac{d^2M_1(m_1,w_1)}{dw_1{}^2} < 0$.

At this point, the right-hand side functions of Equations (5) and (6) are convex functions with respect to marginal profit and wholesale price, respectively, and there exists a point of great magnitude, i.e., there exists a unique marginal profit m_1^* and wholesale price w_1^* that makes the supplier's and manufacturer's profits maximal, respectively.

(3) Manufacturer-led decision-making model (i.e., Model 3)

The decision sequence in Model 3 is that the manufacturer first determines the wholesale price w of the low-carbon product, and subsequently, the supplier determines the marginal profit m of the low-carbon product. The results from solving Model 3 are similar to those of Model 2, so the solution procedure will not be repeated below. The optimal marginal profit, the optimal share of the cost of investment in low-carbon technology, and the optimal wholesale price for the supplier and the manufacturer are, respectively, as follows.

$$m_3^* = \frac{\alpha b(3-3w_3)+k(-2+2w_3)+\alpha^2(c-w_3+r(c_0+w_r))}{\alpha^2+6\alpha b-4k}$$

$$w_3^* = \frac{\alpha^5(c+c_0r)+bk^2(4-8c-8c_0r-8rw_r)+\alpha^4b(3-4c-4c_0r-4rw_r)+\alpha^2b\left(k(-2+14c+14c_0r)+b^2(6-12c-12c_0r-16rw_r)\right)}{\alpha^5+2\alpha^4b-10\alpha^3b^2-16bk^2+\alpha^2(-48b^3+12bk)+\alpha\left(8b^4+56b^2k-4k^2\right)}$$
$$+\frac{\alpha^3\left(b^2(4-14c-14c_0r)+k(-2+2c+2c_0r+2rw_r)\right)+\alpha\left(-4b^4+k^2(-4c-4c_0r)+b^2k(-10+24c+24c_0r+24rw_r)\right)}{\alpha^5+2\alpha^4b-10\alpha^3b^2-16bk^2+\alpha^2(-48b^3+12bk)+\alpha\left(8b^4+56b^2k-4k^2\right)}$$

Combining the above results, it can be concluded that when the following conditions are satisfied,

(1) $k > \frac{\alpha^2+2\alpha b+b^2}{2}$

(2) $0 < 2b < \alpha$ and $0 < k < 2\alpha b$

(3) $0 < \alpha < 2b$ and $0 < k < \frac{\alpha^2+6\alpha b}{4}$

$m_i^*, \eta_i^*, w_i^*, s_i^*$ are the unique marginal profit, the unique low-carbon technology investment cost-sharing ratio, the unique wholesale price, and the unique low-carbon technology level that maximize the profits of suppliers and manufacturers in Models 1, 2, and 3.

When cost factors become dominant, manufacturers and suppliers will be faced with the challenge of investing in and sharing the costs of low-carbon technologies. This is mainly due to the significant low-carbon technology investment costs that manufacturers need to incur in upgrading their low-carbon products. Increased costs can significantly reduce the incentive for manufacturers to invest in low-carbon technologies, and unless external financial or technical support is available (e.g., help from suppliers), manufacturers may not make any investments. In this case, if suppliers step in and are willing to share the cost of low-carbon technologies with manufacturers, while providing some technical support, then the willingness of manufacturers to implement low-carbon technologies will gradually increase. This kind of cooperation is a common practice in real-life situations and helps to drive the industry as a whole in a more environmentally friendly direction. For example, in 2019, Apple, faced with low supplier demand and financial pressures that made it difficult to reach a power deal on its own, used the strength of its platform to bring together multiple buyers. Such an initiative led to the successful contracting of a 75-megawatt wind power project in Texas, through a collective purchasing contract that significantly increased suppliers' incentives to use cleaner power as an alternative to conventional power. If a manufacturer is financially strong and able to bear a significant portion of the investment costs of low-carbon technologies on its own with little impact on its production operations or financial chain, then there is no need for suppliers to share the investment costs of low-carbon technologies, and the issue of co-investment and profit-sharing will not be involved.

The proportionality between consumers' low-carbon preferences and the efficiency coefficients of low-carbon technologies in reducing unit costs has a significant impact on manufacturers' cost-input sensitivity to low-carbon technologies. As market demand expands and the unit cost of the production of low-carbon products falls rapidly, both suppliers and manufacturers are able to benefit from the market for low-carbon products beyond the cost of investment in low-carbon technologies by increasing the price of low-carbon products, which further reduces the sensitivity of suppliers to the cost of investment in low-carbon technologies. In this scenario, manufacturers may already be well versed in the application of various low-carbon technologies, or they may be incentivized to actively engage in low-carbon production by increasing their technical or financial support to manufacturers in order to quickly capture market share and maximize profits after suppliers see the huge market potential for low-carbon products.

2.3.2. Analysis of Model Results

Based on the equilibrium results of the three models, the following theorem is obtained.

Theorem 1. *Under condition 1,* $k > \frac{\alpha^2+2\alpha b+b^2}{2}$*, then the manufacturer's optimal wholesale price has the following relationship in the three models.*

(1) When $k > \frac{\alpha^2+3\alpha b}{2}$ *or* $\alpha \leq b$*, there is* $w_3^* > w_1^* > w_2^*$.

(2) When $b < \alpha$ *and* $k < \frac{\alpha^2+3\alpha b}{2}$*, there are* $w_2^* > w_1^* > w_3^*$.

The conclusion in Theorem 1 implies that if manufacturers are very responsive to the costs associated with low-carbon technology, they may opt to increase wholesale prices as a means of safeguarding their own interests. In a manufacturer-dominated business, the manufacturer holds a position of power and can address its capital requirements by decreasing the profit margins of its suppliers. Consequently, in a manufacturer-driven situation, wholesale costs are generally higher compared with a model where decisions are made through mutual agreement or led by the supplier. This approach enables firms to adapt their financial standing, albeit potentially jeopardizing the enduring stability of

supply chain partnerships. Conclusion (2) in Theorem 1 implies that wholesale prices will be higher in mutual decision-making compared with manufacturer-led and supplier-led decision-making models, but only if consumers are more sensitive to low-carbon technologies than the efficiency of these technologies in reducing production costs per unit. Additionally, this will also depend on the manufacturer's level of sensitivity to the cost of inputs for low-carbon technologies. This indicates that in situations where consumers highly value low-carbon attributes and these attributes have a significant impact on market demand, the additional expenses related to investing in low-carbon technologies can be offset by higher product prices. This is especially true when manufacturers and suppliers collaborate in making decisions.

Theorem 2. *Under condition 1, the supplier's optimal marginal profit has the following relationship in the three models:*

(1) When $\alpha \leq b$ *and* $k > \frac{\alpha^2+2\alpha b+b^2}{2}$, *or* $\alpha > b$ *and* $k > \frac{\alpha^2+3\alpha b}{2}$, *there is* $m_2^* > m_1^* > m_3^*$.

(2) When $\alpha < b$ *and* $k < \frac{\alpha^2+3\alpha b}{2}$, *there are* $m_1^* > m_2^* > m_3^*$.

(3) When $\alpha < b$ *and* $k < \frac{\alpha^2+2\alpha b+b^2}{2}$, *there are* $m_1^* > m_3^* > m_2^*$.

(4) When $b < \alpha < 1$ *and* $\frac{(\alpha+b)^2}{2} < k < \frac{\alpha^2+3\alpha b}{2}$, *there are* $m_3^* > m_1^* > m_2^*$.

Theorem 2 demonstrates that varying ranges of investment cost coefficients for low-carbon technologies have an impact on suppliers' marginal profits from selling individual products. This leads to differences in marginal profits based on different power structures, particularly when consumer preferences for low-carbon technologies are more important than their efficiency in reducing unit production costs. This instance also demonstrates changes in the sequence of suppliers' incremental profits across different power arrangements. Both Conclusion (2) and Conclusion (3) indicate that wholesale prices reach their peak when decisions are made simultaneously. Ultimately, when consumers choose low-carbon technologies more than cost efficiency in decreasing production expenses, the wholesale prices for simultaneous decisions are lower than in the supplier-led scenario but higher than in the manufacturer-led scenario. This indicates that the wholesale prices for simultaneous decision-making were effective given the conditions. When consumer preferences for low-carbon technologies are lower than their efficiency in reducing production costs, the cost of investment coefficients for low-carbon technologies can vary. This can lead to either the highest marginal profits for the supplier or the manufacturer, depending on which party is more responsive to changes in the inputs to the low-carbon technology. In this scenario, the marginal profit of making decisions simultaneously typically falls between the outcomes where one party dominates. This reflects the fact that the dominant participant has more decision-making power and can therefore attain a better outcome.

Theorem 3. *The optimal profits of suppliers and manufacturers under condition 1 are related under the three models as follows.*

(1) When $\alpha \leq b$ *and* $k \neq \frac{(\alpha+b)^2}{2}$, *or* $\alpha > b$ *and* $k > \frac{\alpha^2+3\alpha b}{2}$, *there is* $S_2^* > S_1^* > S_3^*$.

(2) When $\alpha > b$ *and* $k < \frac{\alpha^2+3\alpha b}{2}$, *there is* $S_2^* > S_3^* > S_1^*$

(3) When $\alpha \leq b$ *and* $k > \frac{(\alpha+b)^2}{2}$, *there is* $M_3^* > M_1^* > M_2^*$

(4) When $\alpha < b$, *there is* $M_2^* > M_3^* > M_1^*$.

Theorem 3 asserts that (1) when customer demand for low-carbon products increases and manufacturers become more aware of the costs associated with investing in low-carbon technology, both suppliers and manufacturers are inclined to take on leadership roles within the supply chain. This market structure enables each participant to exert greater control over supply chain decisions in order to optimize their personal profit maximization. (2) Manufacturers choose a market system where suppliers have more control when customer desires are not high and the cost coefficient of investing in low-

carbon technologies is low. The reason for this preference is that when the supplier takes the lead position, they may assist in reducing the risks and cost pressures that the manufacturer is facing. (3) Suppliers and manufacturers prefer a market structure where suppliers have more control when consumer preferences grow at a slower rate than the drop in unit production costs and when firms are not very concerned about the expense of investing in low-carbon technologies. In this arrangement, the supply chain can achieve a greater level of stability, as suppliers can more efficiently handle and spread out the risks related to low-carbon production.

Theorem 4. *Under condition 1, the overall profit of the supply chain system has the following relationship in the three models:*

(1) When $\alpha < b$ *and* $k > \frac{(\alpha+b)^2}{2}$, *or* $b < \alpha < 1$ *and* $k > \frac{\alpha^2+3\alpha b}{2}$, *there is* $SM_1^* > SM_2^* > SM_3^*$.

(2) When $\alpha < b$ *and* $k > \frac{(\alpha+b)^2}{2}$, *there is* $SM_2^* > SM_1^* > SM_3^*$.

(3) When $\alpha > b$ *and* $k < \frac{\alpha^2+3\alpha b}{2}$, *there is* $SM_2^* > SM_3^* > SM_1^*$.

The total profit of the supply chain system is typically maximized under a two-party joint decision-making model when manufacturers can reduce their unit production costs through low-carbon technologies more efficiently than consumers' low-carbon preferences are growing. This is especially true if manufacturers are not highly concerned about the cost of investing in low-carbon technologies. This is because in the shared decision-making paradigm, suppliers and manufacturers have equal power, preventing one side from using its dominating position to exploit the other for financial gain. Conversely, in situations where there are disparities in power, such as when manufacturers have a dominating position, they may exploit their advantage by raising wholesale prices and boosting their own profits at the expense of suppliers. This, in turn, diminishes suppliers' motivation to invest in low-carbon technologies. In a market structure where suppliers have significant control, manufacturers may face limitations in raising wholesale prices. Consequently, manufacturers may opt to enhance their profitability by augmenting their investment in low-carbon technologies, thereby stimulating market demand for their products.

Furthermore, a market structure where suppliers have dominant control maximizes the overall profitability of the supply chain system under the condition that consumer demand for low-carbon products grows at a slower rate than the manufacturers' ability to reduce production costs through low-carbon technologies. This is also true when manufacturers have a moderate level of concern regarding the cost of investing in low-carbon technologies. Supplier dominance in this scenario enhances the utilization of market resources, hence optimizing the advantages for the whole supply chain.

3. Numerical Example and Analysis

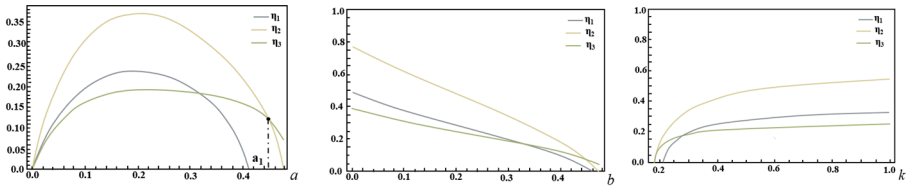
In the following, we will utilize Mathematica to conduct numerical analyses in order to visually demonstrate the impact of different factors on the ideal wholesale price, optimal marginal profit, optimal degree of low-carbon technology, and its profitability for manufacturers and suppliers. We will analyze the effects of consumers' preferences for low-carbon products, the efficiency of cost reduction in low-carbon technologies, and the cost of investing in low-carbon technologies on the optimal level of low-carbon technologies, the optimal cost-sharing ratio for investing in low-carbon technologies, and the optimal profits of manufacturers and suppliers. Table 2 gives assigned values of the related parameters.

Table 2. Assigned values of the related parameters.

Parametric	α	b	k	c
Assign a value	(0, 0.475)	0.2	0.2	0.1
	0.2	(0, 0.475)	0.2	0.1
	0.2	0.2	(0.18, 1)	0.1
	0.2	0.2	0.2	(0, 1)

(1) Variation in the suppliers' share of the cost of investment in low-carbon technologies by parameter.

Figure 3 shows the evolution of the supplier's optimal cost share of investment in low-carbon technologies with parameters a, b, and k. Figure 3a shows that the cost-sharing ratios for optimal low-carbon technology investments by suppliers do not always increase or decrease in a consistent manner as consumers' low-carbon preferences increase. Instead, these ratios reach their maximum value at a specific threshold of low-carbon preference. This implies that suppliers' answers to consumers' low-carbon choices become less effective as the desires increase.



(**a**) (**b**) (**c**)

Figure 3. (**a**) Trends in cost-sharing ratios for investment in low-carbon technologies with parameters a (consumer low-carbon preferences) in Models 1, 2, and 3. (**b**) Trends in cost-sharing ratios for investment in low-carbon technologies with parameters b (cost reduction efficiency factor for low-carbon technology levels) in Models 1, 2, and 3. (**c**) Trends in cost-sharing ratios for investment in low-carbon technologies with parameters k (investment cost factor for low-carbon technologies) in Models 1, 2, and 3.

From Figure 3a, we can see that when the level of consumer preference for low-carbon products is below α_1, the manufacturer's ideal cost-sharing ratio for low-carbon technology investment is consistently higher in the manufacturer-dominated model compared with Models 2 and 3. When α_1 is surpassed, it signifies a significant consumer inclination towards low-carbon products. At this point, the proportion of investment costs allocated to low-carbon technologies is maximized for suppliers operating under the manufacturer-led model. In actuality, these situations are infrequent. Firstly, maintaining a strong consumer inclination towards low-carbon products is often challenging, potentially because of the difficulty in accurately gauging consumer awareness of low-carbon options. Secondly, disparities in the quality of service offered by companies to their customers can lead individuals with a strong preference for low-carbon products to either shift to a group with lower preferences or cease purchasing low-carbon items altogether.

From Figure 3b, we can see that manufacturers have effectively decreased the cost of producing low-carbon products and boosted their incremental profits by investing in low-carbon technologies. This has enabled them to accumulate more capital to offset the expenses associated with low-carbon technology investments. Suppliers that witness this activity may opt to decrease their cost-sharing ratios in order to enhance their earnings.

From Figure 3c, we can see that manufacturers who are very responsive to the expenses associated with adopting low-carbon technology may alter their investment choices and actions in response to even minor cost fluctuations. Suppliers may opt to raise their contribution towards the cost of investing in low-carbon technologies when they notice this behavior. This is done to encourage manufacturers to adopt low-carbon practices, which in turn reduces the financial burden on manufacturers and increases their motivation to invest in carbon reduction. In a supplier-led strategy, suppliers are motivated to encourage manufacturers to invest in low-carbon technology, improve existing low-carbon technologies, and decrease overall carbon emissions. This approach promotes the adoption of low-carbon practices throughout the whole supply chain.

(2) Changes in the level of low-carbon technology of manufacturers with each parameter.

Figure 4 gives the trend in the manufacturer's optimal low-carbon technology level with parameters a, b, and k. In Models 2 and 3, the manufacturer's ideal level of low-carbon

technology is directly related to the consumer's preference for low-carbon options and the efficiency coefficient of low-carbon technology in reducing costs. However, it is inversely related to the investment cost coefficient of low-carbon technology. Contrarily, in Model 1, which is a market structure characterized by mutual decision-making, the manufacturer's ideal level of low-carbon technology initially increases as consumer preference for low-carbon products increases, but then starts to decrease. Additionally, the manufacturer's ideal level of low-carbon technology increases as the efficiency of cost reduction in low-carbon technology improves and decreases as the cost of investing in low-carbon technology decreases.

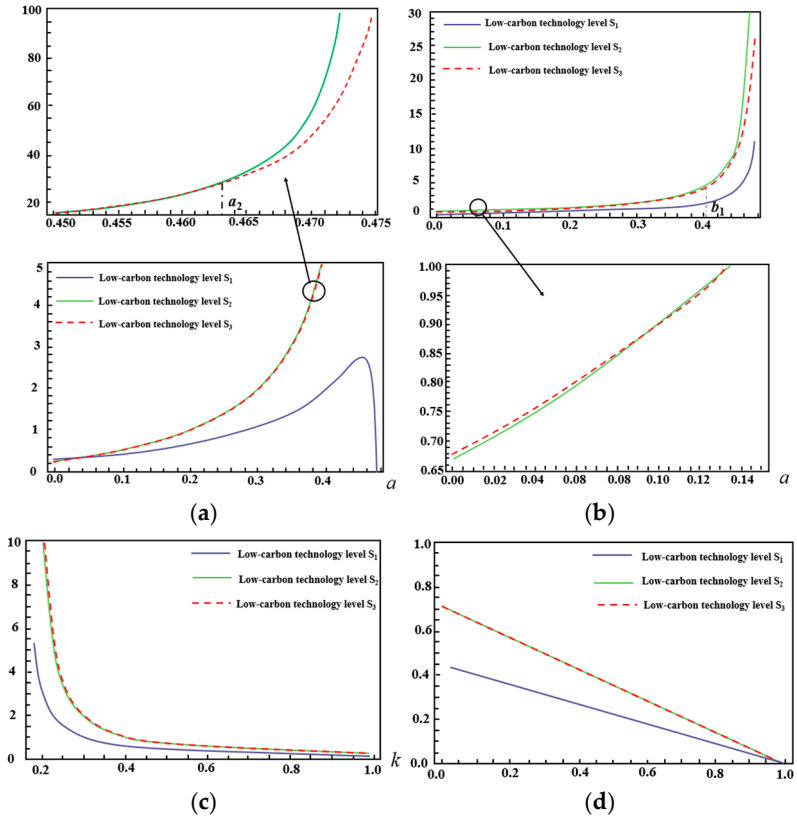


Figure 4. (**a**) Variation in low-carbon technology level with parameters α (consumer low-carbon preferences) in Models 1, 2, and 3. (**b**) Variation in low-carbon technology level with parameters b (cost reduction efficiency factor for low-carbon technology levels) in Models 1, 2, and 3. (**c**,**d**) Variation in low-carbon technology level with parameters k (investment cost factor for low-carbon technologies) in Models 1, 2, and 3.

Figure 4a indicates that in a market framework where consumers and manufacturers make joint decisions, when customers have a low demand for low-carbon products, manufacturers tend to have higher levels of low-carbon technology. When customers have a moderate demand for low-carbon products, the level of low-carbon technology used by manufacturers is similar in both supplier-led and manufacturer-led market structures. However, when customer preferences for low-carbon products surpass a specific threshold (e.g., $\alpha = \alpha_2$), the presence of low-carbon technology among manufacturers in a market structure dominated by suppliers reaches its peak. Furthermore, this level increases rapidly as consumer preferences for low-carbon products continue to climb.

It is shown in Figure 4b that the impact of the efficiency factor in reducing the cost of low-carbon technology on manufacturers' adoption of low-carbon technology is comparable to the influence of consumer demand for low-carbon products. Nevertheless, if the unit cost of producing low-carbon items is low (e.g., $b > b_1$), the pace at which manufac-

turers adopt low-carbon technology due to the cost-efficiency coefficient is less significant compared with the impact of consumer preferences.

From Figure 4c, we can see that the cost element of investing in low-carbon technology is typically at its lowest when suppliers and manufacturers collaborate to make decisions. This implies that manufacturers lack strong motivation in their investment behavior towards low-carbon technologies and may require additional incentives or regulatory support to enhance their readiness to invest in such technologies.

(3) Variation in suppliers' and manufacturers' profits with each parameter.

Figure 5 indicates that the profits of the supplier and manufacturer are directly related to the coefficients of consumers' preferences for low-carbon products and the efficiency coefficients of cost reductions in low-carbon technology. On the other hand, the profits are inversely related to the coefficients of the costs associated with investing in low-carbon technologies. From the supplier's standpoint, they have a preference for assuming the role of the leader within the supply chain, since it grants them greater leverage in negotiations. Suppliers can optimize their gains by reducing their wholesale costs and promoting manufacturers to invest in low-carbon technologies to stimulate market demand. Suppliers will alternate between Model 1 and Model 2 within a specific range (e.g., $\alpha_3 < \alpha < \alpha_4$), but overall, they generate more profits in Model 2. From the manufacturer's standpoint, they want a market structure where they are the leader of the supply chain, as long as certain conditions are met (e.g., $\alpha < \alpha_4$ or $b < b_2$). Manufacturers can raise wholesale pricing to address the financial challenges of investing in low-carbon technology and to maximize their profits, thanks to their extensive market reach.

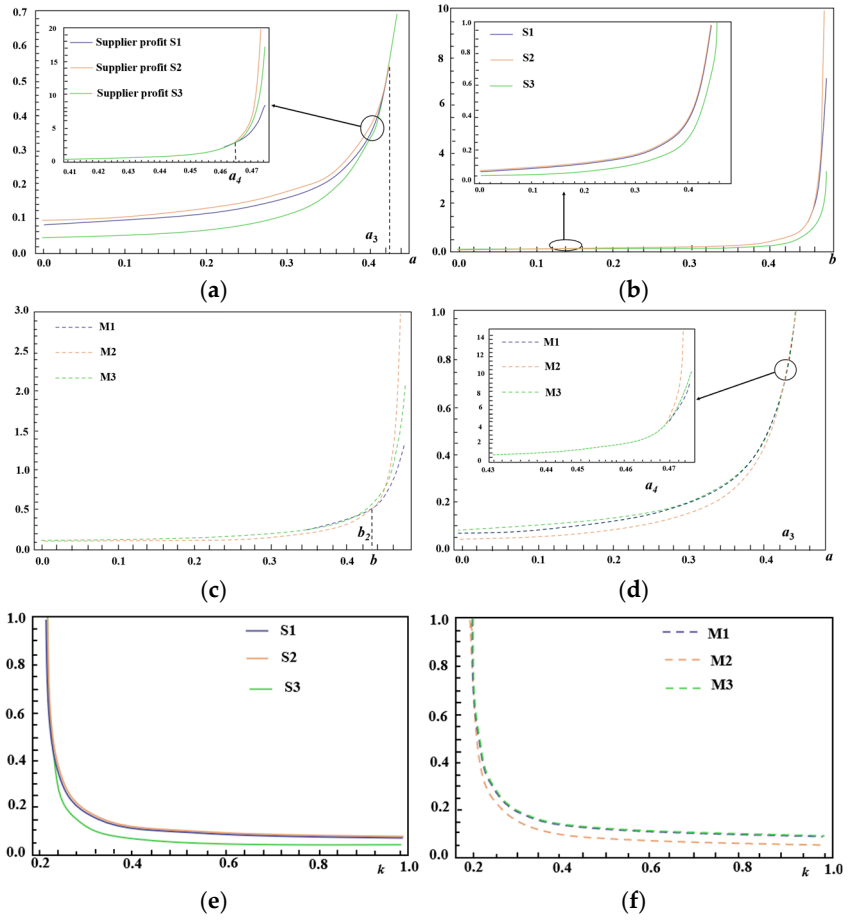


Figure 5. (**a**–**c**) The trend in the supplier's profits with parameters a, b, and k in Models 1, 2, and 3. (**d**–**f**) The trend in the manufacturer's profits with parameters a, b, and k in Models 1, 2, and 3.

Manufacturers can maximize their earnings in market structures where suppliers have a dominant position when consumer preferences keep growing or the production costs for low-carbon products keep decreasing. The significant increase in low-carbon capacity can be attributed to the manufacturers' expertise in implementing low-carbon technologies and the successful completion of the initial break-in period for low-carbon technology equipment. If a manufacturer heavily depends on a supplier's distribution channels, they will need to rely on the supplier's purchasing data for market intelligence on low-carbon products, as the supplier has the advantage of having knowledge of market demand.

Moreover, from Figure 5a,d, we can see that as consumers' demand for low-carbon products grows, they are ready to pay a premium for these products. This motivates manufacturers to invest more in low-carbon technologies to improve their ability to reduce carbon emissions. Due to this alteration, suppliers modify their portion of the investment cost in low-carbon technology based on consumer preferences. Simultaneously, as the implementation of low-carbon technology decreases the costs of producing each unit, manufacturers will lower wholesale prices and increase production capacity in order to quickly obtain a larger portion of the market, therefore boosting their own profits. Although the decrease in wholesale costs for manufacturers has resulted in higher profit margins for suppliers, suppliers are also inclined to lower the prices of low-carbon products to fulfill market demand and improve their competitiveness, therefore increasing their profits through higher sales.

(4) Variation in supply chain system profit with each parameter.

Figure 6 gives the trend in the supply chain system profit with parameters a, b, k, and c under the three models. The profitability of the supply chain system is directly correlated with the consumer's preference for low-carbon products and the efficiency of reducing the cost of low-carbon technology. Conversely, it is inversely correlated with the cost of investing in low-carbon technology and the cost of unit production. Considering the arrangement of the market: (1) The low-carbon products market can be classified as being in the growth phase when customer preferences are at a moderate level. The current market system, where suppliers and producers make decisions together, results in increased profitability. Upon witnessing this behavior, it is advisable for the government to diminish the dominant control of monopolies in the market by enacting policies such as anti-trust laws. This will foster a completely competitive market environment, hence enhancing the overall efficiency of the supply chain. (2) The low-carbon product market is currently experiencing a phase of stabilization, characterized by customer preferences being at a moderate level. In this scenario, the profits generated by suppliers and manufacturers operating under their individual market structures are typically greater than the profits generated when they make choices together. Hence, it is imperative for the government to incentivize suppliers and manufacturers to fully utilize their individual market advantages and facilitate the coexistence of diverse market structures, hence fostering the robust growth of the market. (3) When customer preferences reach a high level, the market for low-carbon products might be deemed to be experiencing rapid growth. During this phase, the market structure driven by suppliers can provide higher profits for the supply chain system and demonstrate a significant growth trajectory. The government should strive to incentivize suppliers to assume the role of market leaders in order to drive the advancement of the low-carbon market, enhance low-carbon technology, and efficiently decrease carbon emissions across the supply chain. In general, the relationship between the decrease in cost and increase in efficiency of low-carbon technology and the profitability of the supply chain system is comparable to the impact of consumer preferences for low-carbon products. Both factors have a substantial influence on the benefits and options of market structure.

The aforementioned analyses indicate that the market for low-carbon products must be governed by distinct market structures during various stages of development and does not remain static within a fixed market structure. This is mostly due to the fact that in actual manufacturing operations, the initial costs of investing in low-carbon technologies are typically considerable, while the profits gained are relatively modest. As a result, manu-

facturers often require technical or financial assistance from suppliers in order to maintain market demand. With the market becoming more stable, manufacturers are advancing their low-carbon technologies and making substantial progress, as well as establishing a presence in the market. In this context, the government permits the coexistence of various market structures and encourages the rapid growth of the low-carbon market through market competition, in order to sustain its vitality.

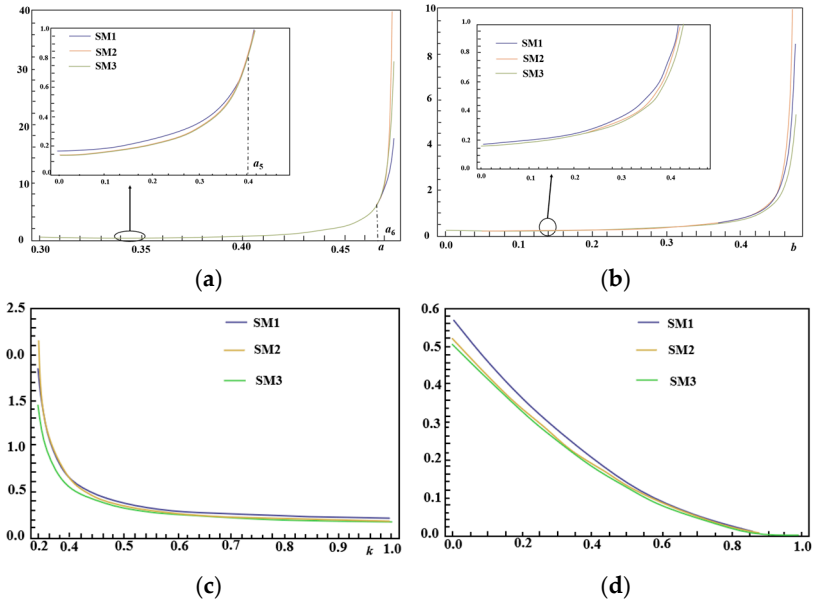


Figure 6. (**a**) The trend in the supply chain system profit with α in Models 1, 2, and 3. (**b**) The trend in the supply chain system profit with b in Models 1, 2, and 3. (**c**) The trend in the supply chain system profit with k in Models 1, 2, and 3. (**d**) The trend in the supply chain system profit with c in Models 1, 2, and 3.

In general, low-carbon products generate greater value for the entire supply chain system, resulting in an increasing trajectory in overall profitability. To assist the sustainable development of the low-carbon market, the government and firms can enhance consumers' understanding of low carbon and environmental protection by effectively disseminating information on environmentally friendly products.

4. Conclusions and Outlook

4.1. Conclusions

This research meticulously scrutinizes the intricate challenges involved in financing low-carbon technologies and establishing pricing strategies within a closed-loop supply chain framework aimed at fostering sustainable practices. It innovatively constructs a hybrid model that integrates non-cooperative and cooperative game theory within a closed-loop supply chain context, featuring a solitary producer and a solitary supplier. The study's contribution lies in providing profound insights into the collaborative dynamics between manufacturers and suppliers concerning investments in low-carbon technologies and their subsequent influence on product pricing. Specifically, the research delves into three distinct power structures: a simultaneous decision-making scenario, a manufacturer-dominated model, and a supplier-led model. In this setting, the collaborative facet of the game model is embodied by the joint investments in low-carbon technologies by both suppliers and manufacturers, whereas the independent aspect is reflected in product pricing decisions. The study initially pinpoints the most efficacious strategies for suppliers and manufacturers across these three models. Furthermore, it rigorously examines the ramifications of consumers' preferences for low-carbon products, the efficacy of low-carbon technology in curbing production costs, and the investment cost coefficient of such

technology on various optimal parameters. These parameters encompass the optimal adoption level of low-carbon technology, the optimal cost-sharing ratio for investment, the optimal wholesale price, the optimal marginal profit, and the optimal overall profit within each of the three examined models. Ultimately, the study validates the precision of its theoretical findings through rigorous numerical analysis.

The key findings indicate that the following: (1) It is possible to determine a single, optimal wholesale price, an optimal level of low-carbon technology, an optimal marginal profit, and an optimal cost-sharing ratio for investing in low-carbon technology. These determinations aim to maximize the profits of manufacturers and suppliers under the three models, provided that specific conditions are satisfied. This suggests that companies can use these insights to optimize their pricing strategies and investment decisions in low-carbon technologies. (2) In a supplier-driven market structure, suppliers and manufacturers have the potential to mutually benefit under specific circumstances. This finding highlights the importance of collaboration and coordination between these two parties in promoting the adoption of low-carbon technologies. (3) Within a market framework where suppliers hold significant power, manufacturers have more opportunities to enhance their investment in low-carbon technology. This suggests that manufacturers should prioritize partnerships with powerful suppliers to leverage their influence and increase investment in low-carbon technologies. (4) As consumers' preferences for low-carbon products increase, providers experience diminishing marginal utility in terms of the cost-sharing ratio for investing in low-carbon technologies. This finding implies that companies should be cautious about the level of investment in low-carbon technologies, as increasing consumer preference may not necessarily lead to increased profits. (5) From a supply chain system standpoint, various stages of expansion in the low-carbon product market necessitate distinct dominant market structures. This demand fluctuates with the market stage rather than remains constant. This suggests that companies and policymakers should adapt their strategies to accommodate the evolving market dynamics of low-carbon products.

4.2. Implications

4.2.1. Practical Implications

Businesses can use the insights from this study to optimize their pricing strategies and investment decisions in low-carbon technologies, thereby enhancing their profitability and sustainability.

Policymakers can leverage these findings to develop targeted incentives and regulations that promote the adoption of low-carbon technologies among businesses.

4.2.2. Theoretical Implications

This study contributes to the existing literature on closed-loop supply chains and low-carbon technology investment by providing a theoretical framework that incorporates game-theoretic models.

The findings of this study offer new insights into the optimal pricing, investment, and cost-sharing strategies for low-carbon technologies in different market structures.

4.2.3. Recommendations for Policymakers

(1) Develop incentives and subsidies for businesses to invest in low-carbon technologies.
(2) Implement regulations that encourage collaboration and coordination between suppliers and manufacturers in promoting the adoption of low-carbon technologies.
(3) Monitor and adapt policies to accommodate the evolving market dynamics of low-carbon products.

4.3. Limitations

This research examines the collaboration between manufacturers and suppliers in investing in low-carbon technologies and devising pricing strategies for low-carbon products. This research has several limitations that warrant attention. Firstly, it does not explicitly

investigate the direct causal effect of investments in low-carbon technologies on carbon emissions reduction. Instead, it relies on an implicit acknowledgment of the potential contribution of these technologies to lowering emissions. Secondly, while acknowledging the providers' capability to monitor or foresee consumer demand for low-carbon products and manufacturers' comprehensive understanding of their technological proficiency, the study assumes a perfect information scenario where all parties have equal access to relevant information. This idealized setting overlooks the complexities and realities of information asymmetry that may influence decision-making processes in practice. Lastly, the study does not explore how suppliers and manufacturers might navigate the complexities of pricing and investment decisions in scenarios where information is unevenly distributed, leaving this as an area for future research.

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