

Research Article

The Orchestrating Role of Carbon Subsidies in a Capital-Constrained Supply Chain

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In this paper, we investigate the role of carbon subsidies in a capital-constrained supply chain. We analyze two green technology investment structures in such supply chains: one where the manufacturer determines the optimal carbon emission abatement level (MI-structure) and one where the retailer determines the optimal carbon emission abatement level (RI-structure). As the leader (the powerful participant or the first mover in a supply chain), the manufacturer may choose the investment structure that is most favorable to them. Our major findings are as follows: (1) carbon subsidies can improve the performance of a centralized green supply chain; (2) there exists a threshold value of carbon subsidy that determines the manufacturer's choice of the best carbon emission abatement investment structure, but the retailer always benefits from RI-structure; and (3) the traditional cost-sharing contract fails to achieve green supply chain coordination. However, as an orchestrator, the carbon subsidy plays a crucial role in achieving quantity coordination when implemented alongside traditional cost-sharing contracts. Furthermore, using a parameter of side-payment, we propose a new contract design that facilitates win-win coordination.

1. Introduction

In the past decade, the Earth has been experiencing critical and significant environmental challenges [1], and these serious environmental problems have drawn much attention in many countries [2]. Properly addressing environmental issues such as carbon emissions and the resulting climate change has become an urgent task for governments and industries. For example, the UK has launched a Carbon Reduction Commitment (CRC) to achieve carbon emissions goals [3]. The Chinese government clearly stated an emissions reduction goal at the Climate Change Conference held in Paris in 2015 [4] and has recently set an even more ambitious carbon reduction target. On September 22, 2020, in the 75th session of the UN General Assembly, the Chinese government promised to adopt more powerful policies and measures to achieve the targets of “carbon emission peak” and “carbon neutrality” (http://www.gov.cn/xinwen/2020-09/22/content_5546169.htm).

In addition to these declarations of governmental action, consumers' awareness of the necessity for environmental protection and of green products is becoming stronger. Many studies show that consumers' green awareness is a key factor driving markets, and an increasing number of consumers prefer to purchase pollution-free and environmentally friendly green products [5]. Recently, surveys conducted by the Carbon Trust indicate that approximately 20% of customers prefer to buy green products, even at a higher price [6]. In the first half of 2017, JD.com's green brand growth rate rose to 16.1% [7].

Several countries have launched legislation such as carbon tax, carbon subsidies, and cap-and-trade systems to attempt to address the greenhouse gas emission problem. As a powerful policy mechanism to curb carbon emissions, carbon taxes have been adopted by many countries such as France [8], Japan [9], and China [10]. Governments have also implemented many different forms of environmental subsidy policies, such as China's green credit mode [11] and

the Australian emissions reduction fund [1]. Meanwhile, many enterprises also consciously make an effort to produce and promote green products. For instance, MACALLINE, as one of the largest Chinese home furnishing sales enterprises, launched a program designed to make them the “leading brand of green home furniture” in 2013. In this program, MACALLINE collaborates with China Quality Certification Center (CQC) to select the most environmentally friendly furniture brands. Small- and medium-sized enterprises (SMEs) are also motivated to reduce carbon emissions in order to improve performance [12]. In an investigation of 202 SMEs, Meath et al. [13] find that adoption of energy-saving measures can improve companies’ financial performance as well as their competitiveness.

To address these pressing environmental issues, the cooperation of upstream and downstream firms is necessary and important. Thus, scholars propose concepts such as green supply chains and sustainability [14]. In a supply chain management process, cash-flow management is vital to the performance of the whole supply chain. Due to fierce market competition and low margin profits, many companies, even industry giants, face capital constraints. For example, Zhongneng Chemical, one of the top 50 producers of chemical fertilizer in China, is characterized by a short selling period and a long production lead time. To abate the great financial pressure caused by the high production cost, the manufacturer uses conventional bank loans and also resorts to other financial tools [15]. For SMEs, which lack collateral and have lower credit ratings, it is even harder to get financial access. For instance, as an SME, China’s Shenzhen Xiangkong Technology Co. Ltd. has to rely on self-raised funds to support its business before it is eligible for government support [3]. In this context, carbon emission abatement investments will definitely increase the burden on SMEs’ cash flow [16].

Generally, supply chain finance (SCF) can solve this problem. As an effective solution, SCF aims to alleviate financing distress and improve financial efficiency in a capital-constrained supply chain [17]. As a major financing source of SCF, bank credit finance plays an important role in relieving SMEs’ capital constraints. For example, Industrial and Commercial Bank of China has offered 100 billion yuan to help capital-constrained SMEs make carbon reduction investments [12].

In practice, both upstream and downstream companies in many industries can shoulder the task of carbon abatement. For example, say that in a triple-echelon supply chain in the power industry, a power generation company purchases thermal coal from a mine and sells electricity to a grid company. To reduce carbon emissions, the mine can invest in coal-washing technology, the power generation company can purchase waste gas treatment equipment, and the grid company can reduce line loss. Another example is the electronic industry. Some manufacturers such as Hewlett-Packard recycle used computers and peripherals from consumers directly, while other manufacturers such as Apple and Dell encourage consumers to return used products to retailers [18]. Researchers often assume that the manufacturer (the leader of the supply chain) takes the

responsibility for investing in carbon abatement technology (e.g., [11,12,14,19]). However, few papers pay attention to the impacts of different green investment options on the performance of supply chains. Although carbon subsidies are recognized as an important tool for improving environmental performance, few scholars investigate the role of these subsidies in supply chain coordination.

In this paper, we try to bridge this research gap by exploring the merits of different investment structures. We construct a carbon subsidized supply chain consisting of a manufacturer and a capital-constrained retailer to answer the following questions:

- (i) Q1: What are the optimal responses of the manufacturer and retailer in a subsidized and capital-constrained supply chain?
- (ii) Q2: Which investment option (MI-structure or RI-structure) is better in the supply chain?
- (iii) Q3: What is the role of carbon subsidies in green supply chain coordination?

Our main findings are as follows. Compared to a traditional capital-constrained supply chain, a centralized supply chain has better performance with carbon subsidies. We find there exists a threshold value of carbon subsidy that will determine the manufacturer’s choice of carbon emission abatement investment options. When the total carbon subsidy is greater than this value, the manufacturer prefers the MI-structure. However, the retailer always benefits from the RI-structure. This study also shows that traditional cost-sharing contracts fail to achieve green supply chain coordination. However, as an orchestrator, a carbon subsidy can help a contract achieve quantity coordination. Furthermore, with a parameter of side-payment, we propose a new contract type that facilitates win-win coordination.

Our work contributes to the literature in three ways:

- (1) We provide insights into operation management from a supply chain perspective. Given a finance cost, we investigate the optimal decisions for the supply chain.
- (2) We distinguish the merits of MI-structure and RI-structure, and we identify the conditions for different participants’ supply chain preferences.
- (3) We explore the orchestrating role of carbon subsidies in supply chain coordination, and we derive the optimal parameters of a win-win contract.

The remainder of this paper is structured as follows. Section 2 reviews the related literature. Section 3 details the problems, notations, and assumptions. In Section 4, we analyze the optimal solutions of the model and propose a new contract to achieve win-win coordination. Section 6 concludes our key findings and proposes future research directions.

2. Literature Review

This study investigates the orchestrating role of carbon subsidy in a capital-constrained supply chain. Hence, this

work draws on and contributes to two strands of literature: finance strategy in a green supply chain and carbon subsidies.

2.1. Finance Strategy in a Green Supply Chain. In a seminal work on supply chain finance, Goyal [20] first researched the issue of delay-in-payment in an economic order quantity (EOQ) model. Since then, there has been growing interest among academics in exploring SCF functions in relation to promoting other supply chain capabilities [21] such as cost reduction [22], coordination condition [23], and efficiency improvement [24]. In this stream of literature, the potential for improving green supply chains also draws the attention of many scholars.

According to IFC (2017), green finance is defined as the “financing of investments that provide environmental benefits,” and the core is financing tools for coping with climate change and other sustainability issues [25]. Some papers investigate the mechanisms of green finance tools empirically [26, 27] or examine the green credit tool in China [28, 29].

In a supply chain, green finance refers to any finance tools for improving supply chain sustainability. Generally speaking, there are two major financing tools in SCF: bank credit financing and trade credit financing [17]. Tsao et al. [30] present newsvendor models that use carbon emission and trade credits and product recycling to determine the maximized total profit. Cao and Yu [16] consider the role of trade credit in an emission-dependent supply chain. Qin et al. [31] consider the mechanisms of green bank finance and cap-and-trade in a green supply chain. Similar research can be found in Cong et al. [19]. Some scholars also investigate the roles of different financing sources such as options in a supply chain [32], a combination of trade credit and partial credit guarantee [12], and green bank credit [3].

The coordination problem is another important issue in a capital-constrained green supply chain, since supply chain constituents must be aligned to act in a united manner under sustainability commitments [33]. In a highly competitive business environment, all participants in a supply chain should align the incentives to pull in the same direction in order to achieve channel coordination [34]. However, double marginalization often causes deviation from channel coordination; i.e., the summed profit of a decentralized supply chain is less than that of a centralized supply chain [35]. Aljazzar et al. [36] study the effects of trade credit in a two-echelon coordinated supply chain on environmental improvement and economic performance. Taking carbon emission permits as bank credit collateral, Cao and Yu [37] present some contracts to coordinate an emission-dependent supply chain. Dash Wu et al. [14] design a contract that combines cost-sharing and side-payment to achieve supply chain coordination. In a double distribution channel green supply chain, Yang et al. [38] establish a revenue sharing contract to coordinate profit allocation.

Consistent with Qin et al. [31] and Cong et al. [19], in this paper, we take bank credit as a green finance tool. We do this for two main reasons: (1) Many banks throughout the world

have launched green credit finance to support green investment and alleviate companies’ financial distress, such as BNP Paribas and China’s Huarong Xiangjiang Bank [3]. In China, green credit is a major green finance tool with a significant market share [19]. (2) Evidence from China shows that the adoption of fin-tech effectively facilitates the banking sector’s credit supply to SMEs [39]. Compared to bank credit, although trade credit finance has several merits in supply chain management and supply chain coordination, it is not easy to find a reference interest rate in practice. For example, in China, the yearly rate of private lending for mortgages in some areas has exceeded 30% in recent years [15]. Moreover, financing risks related to local state-owned enterprises have drawn much attention from China’s government (<http://www.sasac.gov.cn/n2588035/n2588320/n2588335/c11469566/content.html>).

2.2. Carbon Subsidies. Governments often choose to subsidize companies for conserving the environment and supporting socially responsible operations or impose environmental taxes to induce firms to lower their emissions [1]. In China, government subsidy is one of the common instruments to promote carbon abatement [40]. In this subsection, we recall some key studies of subsidy policies in green supply chains. In a newsvendor-like model, Cohen et al. [41] study a manufacturing industry’s response to the adoption of green technology with government subsidies, quantifying the impact of demand uncertainty on each player in the supply chain. Similarly, Chen et al. [42] investigate the impact of government subsidies on a supply chain’s sustainability innovation. For different products or channels, Hafezalkotob [43] develops competition and cooperation models for two green supply chains under government financial intervention. Considering a symmetric/asymmetric duopoly setting, Luo et al. [44] investigate the government’s optimal subsidy strategy for traditional and public interest products. Alizmir et al. [45] compare two government subsidy programs in the agriculture industry and provide guidelines to farmers for enrolling crops in the subsidy programs. Considering a dual-channel green supply chain, Meng et al. [46] find that government subsidies will be beneficial to the manufacturer, but this is not always true for the retailer.

There are also some studies that explore the effects of different policy combinations. Cao et al. [47] investigate two policies (cap-and-trade and low-carbon subsidy) in a green supply chain. They find a crucial value of an environmental damage coefficient that can determine which policy should be implemented. Yi and Li [48] consider a manufacturer-retailer channel to examine how carbon taxes and energy-saving product subsidies affect enterprises’ operational decisions. Bian and Zhao [1] investigate the impact of an emission abatement subsidy and an emission tax on a supply chain. Introducing a dual regulation regime characterized by a deposit-refund policy and a minimum collection rate for used products, Liu et al. [49] examine the impact of dual regulation on supply chain operations.

These studies have made significant contributions to the understanding of subsidy policies in the field of sustainable operations management. However, the above-mentioned studies fail to consider the impact of cash flow on the performance of a supply chain given the high cost of green technology investment. In fact, few papers consider a subsidized green supply chain with capital constraints. In one study that does, Huang et al. [11] compare three green subsidy modes in a capital-constrained supply chain, and they describe green credit as a government subsidy mode offered to banks. In the three subsidy modes, they depict demand as a specific function. However, in reality, a supply chain always faces some uncertainty (yield and/or demand) and involves financial risk [19]. Cong et al. [19] also consider carbon subsidies in a green supply chain, but they fail to consider the impact of different investment structures.

In this paper, we fill these gaps by constructing a capital-constrained green supply chain with carbon subsidies. Our paper is distinguished from prior work as follows. (1) We deduce optimal decisions in a capital-constrained supply chain with carbon subsidies. (2) We investigate the impact of different green investment options (i.e., MI-structure and RI-structure) on the performance of a supply chain. (3) We propose new contracts to achieve two types of supply chain coordination, i.e., quantity coordination and win-win coordination.

3. Model Assumptions and Descriptions

Considering a carbon subsidized supply chain with a manufacturer and a capital-constrained retailer who can access regular bank credit, both the manufacturer and the retailer can abate carbon emissions related to the product. The carbon subsidy issued by the government will be offered to the participant who actually improves the carbon abatement level. This paper focuses on the influences of carbon subsidies on optimal decisions in a green supply chain. For this purpose, we set the following assumptions and symbols.

3.1. Model Assumptions

Assumption 1. For convenience, we assume that the initial working capital of the retailer is 0. This assumption is common in supply chain finance literature [34, 35, 50].

Assumption 2. Following the convention in the literature [14,51], we assume that the capital market is perfectly competitive and that all bank loans are priced at a risk-free interest rate $r_f = 0$. This assumption also confers the advantage of allowing us to ignore discounting [35].

Assumption 3. The market demand is uncertain. The expression of uncertain demand can be formulated in different forms, such as an inverse demand function with a uniform distribution parameter [52] or a demand function with definite mean and variance [53]. In this paper, we set the actual market demand as qX , where q denotes the retailer's

order quantity and X is a random variable with $E[X] = 1$ and $\text{Var}(X) = \sigma^2$ [19].

Assumption 4. The inverse demand function is given by $p(q) = A - \alpha qX + \lambda e$, where A is the total market demand, α is the price sensitivity to demand, λ ($\lambda > 0$) is a coefficient that describes the consumer's low-carbon preference, and e is the carbon emission abatement level. Many papers suppose that demand is related to carbon emissions and retail price and that consumers in various markets are willing to pay premiums for products with low-carbon emissions [19]. Similar assumptions can be found in Cao et al. [47] and Zhu and He [54].

Assumption 5. The cost of carbon emission abatement is $C(e) = \gamma e^2/2$, where $\gamma > 0$ indicates the pollution-abatement cost efficiency. Similar expressions have been widely adopted by authors such as Yi and Li [48] and Bian and Zhao [1]. Since the process of emission abatement is a one-time investment, γ is typically large [19].

Assumption 6. The carbon subsidy is se , where $s > 0$. We assume that the government should subsidize the one who processes the carbon emission abatement [1].

3.2. Model Description. We adopt a Stackelberg game in the supply chain. A Stackelberg game is usually adopted to derive optimal decisions in a sequential decision-making supply chain. In this paper, we assume that the manufacturer is a leader who first announces the wholesale price (and/or emission abatement level). Then, as a follower, the retailer decides order quantity (and/or emission abatement level). The government acts as an environmental performance supervisor who does not make any decisions in the supply chain. In addition, as a finance source, the bank is not a player in the game. The interactions are described by Figure 1.

As shown in Figure 1, in MI-structure (illustrated by the solid line), the manufacturer decides the wholesale price and carbon emission abatement level, and the retailer decides order quantity. Accordingly, the manufacturer gets the carbon subsidy. In RI-structure (illustrated by the dashed line), the retailer decides carbon emission abatement level and gets the carbon subsidy. The bank in a competitive capital market is always accessible to the capital-constrained retailer, Table 1.

4. Model Solutions

4.1. A Centralized Supply Chain with Bank Finance and Carbon Subsidies. In this subsection, we consider a centralized supply chain with bank finance and carbon subsidies as a benchmark, and we explore the role of carbon subsidies in the supply chain. We first consider a traditional centralized supply chain (i.e., without carbon subsidies and an emission abatement process, denoted by superscript t). The retailer orders q units of products with wholesale price w , and the loan principal is wq . The retail price is determined by

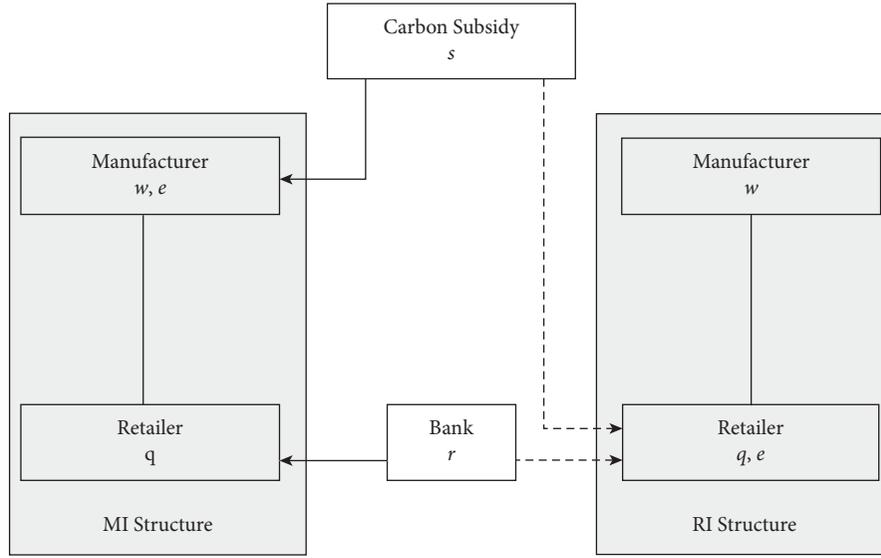


FIGURE 1: Illustration of different structures in the supply chain.

TABLE 1: List of notations.

Categories	Notations	Descriptions
Parameters	A	Initial market potential demand
	α	Price sensitivity to demand quantity
	X	Random variable, $E(X) = 1$ and $\text{var}(X) = \sigma^2$
	λ	Coefficient that describes the consumer's low-carbon preference
	γ	Carbon emission abatement cost
	s	Carbon subsidy per abatement unit
	r	Interest rate charged by the bank
	c	Unit product cost
	ϕ_i	$i = \text{MI, RI}$ carbon subsidy share
	φ_i	$i = \text{MI, RI}$ investment cost share
Decision variables	v	Bargaining power of manufacturer
	T	Side-payment
	Π_j^i	Profit of j in contract i
	w^f	Wholesale price in supply chain i
	q^i, e^i	Order quantity and carbon emission abatement level in supply chain i

$p(q) = A - \alpha qX$, which is a linear function of the order quantity.

Since the retailer has a bankruptcy risk resulting from the market demand uncertainty, the bank must charge a higher interest rate r ($r > 0$) for risk compensation. The interest rate r denotes the actual finance cost paid by the retailer. Following Kouvelis and Zhao [51], the decision of the bank is given by

$$wq = E[\min(pqX, wq(1+r))], \quad (1)$$

where in pqX is the retailer's sales revenue and $wq(1+r)$ is the bank loan payoff amount. Equation (1) means that the value of the bank loan principal and interest in a perfectly competitive market (risk-free interest rate) is the expected value of the retailer's repayment. Since a low sales revenue pqX may be less than $wq(1+r_f) = wq$, the bank has to charge an interest rate r ($r > r_f = 0$) to make a trade-off, as mentioned above.

The retailer's decision is given by

$$\Pi_{qR}^t = \max [Aq - wq - \alpha(1 + \sigma^2)q^2]. \quad (2)$$

In this paper, we assume the manufacturer is capital sufficient for the production process. Anticipating the retailer's response, the manufacturer's problem is

$$\Pi_{wM}^t = \max(w - c)q. \quad (3)$$

Then, the profit of the centralized supply chain (which has only one decision maker, as opposed to more than one decision maker as in a decentralized supply chain) is expressed as

$$\Pi_{qSC}^t = \max[(A - c)q - \alpha(1 + \sigma^2)q^2]. \quad (4)$$

Equation (4) denotes the total profit of the whole supply chain as the sum of (3) and (2). Then, the optimal decisions are $q^{t*} = (A - c)/[2\alpha(1 + \sigma^2)]$ and $\Pi_{q^{t*}SC}^{t*} = (A - c)^2/[4\alpha(1 + \sigma^2)]$.

We then consider a subsidized centralized supply chain with the process of emission abatement. If the retailer makes a decision to adjust their processes in order to reach emission abatement level e , the loan principal will be $(wq + \gamma e^2)/2$. If not, the retailer's loan principal is wq . Accordingly, the production cost to the manufacturer will be cq or $(cq + \gamma e^2)/2$. The retail price is determined by $p(q) = A - \alpha qX + \lambda e$, which means that low-carbon preference contributes to market demand. The profit of the centralized supply chain is $\Pi_{q,e_{SC}} = \max\{[(A - c + \lambda e)q - \alpha(1 + \sigma^2)q^2 - \gamma e^2/2] + se\}$. It should be noted that the profits of the centralized supply chain are the same in the two different investment structures.

The optimal decisions of the centralized supply chain are determined by Lemma 1.

Lemma 1. *In a subsidized and bank-financed centralized supply chain with the process of emission abatement, the optimal decisions are $q^{SC*} = (\gamma(A - c) + \lambda s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2)$ and $e^{SC*} = (\lambda(A - c) + 2\alpha(1 + \sigma^2)s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2)$.*

All the proofs can be found in Appendix A.

Lemma 1 implies that the order quantity produced in the subsidized centralized supply chain will be higher than that produced in a traditional supply chain ($q^{SC*} > q^*$). Although γ affects the supply chain negatively, the positive impacts of λ and s overwhelm this negative influence. It is also noted that demand uncertainty will reduce order quantity, which is also in line with the intuition.

Proposition 1. *The subsidized centralized supply chain achieves better performance than the traditional centralized supply chain.*

Together with low-carbon preference, carbon subsidy plays a value-added role in a centralized supply chain, as depicted in Proposition 1. This result is intuitive. Compared to the traditional supply chain, a subsidized supply chain has an extra profit (the government's subsidy) distributed into the system, which is beneficial for both participants in the supply chain. In addition, the greenness of the product will induce customers to buy more.

Next, we will explore the role of carbon subsidies in different investment structures.

4.2. A Decentralized Supply Chain with MI-Structure. In this subsection, we consider a decentralized supply chain in which the manufacturer invests in carbon emission abatement technology (denoted as MI-structure). As in Assumption 6, the manufacturer can get a carbon subsidy as compensation. Following the backward induction principle, we first consider the optimal decision of the retailer. The retailer's problem is $\Pi_{q_R}^{MI} = \max[Aq + \lambda eq - \alpha(1 + \sigma^2)q^2 - wq]$.

The optimal order quantity is $q^{MI} = (A - w + \lambda e)/2\alpha(1 + \sigma^2)$. Anticipating the retailer's response, the manufacturer's problem is $\Pi_{w,e}^{MI} = \max\{((w - c)q + se - \gamma e^2)/2\}$.

The optimal decisions in this supply chain are summarized in Lemma 2.

Lemma 2. *In a manufacturer-invested decentralized supply chain, the optimal decisions are $w^{MI*} = ((2\alpha(1 + \sigma^2)(\gamma(A + c) + \lambda s) - \lambda^2 c)/h_2)$, $e^{MI*} = ((4\alpha(1 + \sigma^2)s + \lambda(A - c))/h_2)$, and $q^{MI*} = ((\gamma(A - c) + \lambda s)/h_2)$, where $h_2 = 4\alpha\gamma(1 + \sigma^2) - \lambda^2$.*

In MI-structure, there exists the phenomenon of double marginalization, since the optimal order quantity and carbon abatement level are both less than their values in a centralized supply chain. Proposition 2 shows the conclusion of MI-structure supply chain coordination.

Proposition 2. *The manufacturer-invested decentralized supply chain fails to coordinate.*

Because of double marginalization, neither the decentralized traditional supply chain nor the decentralized green supply chain will be coordinated. Since both participants try to maximize their own profit in the ordering decisions and green investment, the performance of the supply chain fails to reach the optimal solution.

4.3. A Decentralized Supply Chain with RI-Structure. In this subsection, we consider a decentralized supply chain in which the retailer invests carbon emission abatement technology (denoted as RI-structure). The retailer's problem is

$$\Pi_{q,e_R}^{RI} = \max\left[\frac{(Aq + \lambda eq - \alpha(1 + \sigma^2)q^2 - wq + se - \gamma e^2)}{2}\right]. \quad (5)$$

The optimal order quantity is $q^{RI} = ((A - w)\gamma + \lambda s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2)$, $e^{RI} = ((A - w)\lambda + 2\alpha(1 + \sigma^2)s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2)$. Anticipating the retailer's response, the manufacturer's problem is $\Pi_{w,M}^{RI} = \max\{(w - c)q^{RI}\}$.

The optimal decisions in this supply chain are summarized in Lemma 3.

Lemma 3. *In a retailer-invested decentralized supply chain, the optimal decisions are $w^{RI*} = (\gamma(A + c) + \lambda s)/2\gamma$, $e^{RI*} = ((4\alpha(1 + \sigma^2)s + \lambda(A - c) - \lambda^2 s)/\gamma)/2h_1$, and $q^{RI*} = (\gamma(A - c) + \lambda s)/2h_1$, where $h_1 = 2\alpha\gamma(1 + \sigma^2) - \lambda^2$.*

The conclusion of retailer-invested decentralized supply chain coordination is shown in Proposition 3.

Proposition 3. *The retailer-invested decentralized supply chain fails to coordinate.*

Due to double marginalization, the order quantity in the RI-structure decentralized supply chain is half that found in a centralized supply chain, i.e., $q^{RI*} = (q^{SC*}/2)$. Meanwhile, the environmental performance of a centralized supply chain is also better than the performance of a decentralized one.

We summarize and compare the optimal decisions in different supply chains in Table 2.

4.4. The Participants' Preferences in a Decentralized Supply Chain. We have discussed the optimal decisions, in a decentralized supply chain, regarding two different carbon abatement investment structures. The question that arises is, which structure is more beneficial to the agents in the supply

TABLE 2: Summary and comparison.

Type	Scenario	q	e	Comparison
Centralized supply chain	Traditional	$q^{f*} = ((A - c)/2\alpha(1 + \sigma^2))$	$e^{SC*} = ((\lambda(A - c) + 2\alpha(1 + \sigma^2)s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2))$	(1) $q^{f*} < q^{SC*}$
	Subsidized	$q^{SC*} = (\gamma(A - c) + \lambda s)/(2\alpha\gamma(1 + \sigma^2) - \lambda^2)$	$e^{MI*} = (4\alpha(1 + \sigma^2)s + \lambda(A - c))/h_2$	(2) $q^{MI*} < q^{SC*}$, $e^{MI*} < e^{SC*}$
Decentralized supply chain	Subsidized MI	$q^{MI*} = (\gamma(A - c) + \lambda s)/h_2$	$e^{RI*} = ((4\alpha(1 + \sigma^2)s + \lambda(A - c) - \lambda^2 s)/\gamma)/2h_1$	(3) $q^{RI*} = (q^{SC*}/2)$, $e^{RI*} < e^{SC*}$
	Subsidized RI	$q^{RI*} = (\gamma(A - c) + \lambda s)/2h_1$		

chain? In other words, as the leader of the supply chain, how should the manufacturer make a favorable choice between the two structures?

Proposition 4. *In a decentralized supply chain:*

- (a) *The manufacturer will prefer the RI-structure if $s \in [0, \lambda\gamma(A-c)/(\sqrt{h_2(h_2-\lambda^2)} - \lambda^2)]$, and they will prefer the MI-structure otherwise.*
- (b) *The retailer will always benefit from RI-structure.*

Proposition 4 illustrates that there exists a threshold value of carbon subsidy in a decentralized supply chain. If the government subsidy is quite high, $s > ((\lambda\gamma(A-c))/(\sqrt{h_2(h_2-\lambda^2)} - \lambda^2))$, the manufacturer will process the carbon emission abatement. If the subsidy is lower than the threshold value, the manufacturer will tend to adopt RI-structure. However, the subsidy and the extra market demand will always benefit the retailer in a decentralized supply chain with RI-structure.

From Proposition 4, we also conclude that the opportunity cost for green investment is much higher for the manufacturer than for the retailer. If only low compensation is offered by the government, there is no motivation for the manufacturer to invest in green technology. However, such green investment can attract a larger market share for the retailer, and thus for the retailer, the carbon subsidy is more effective leverage.

5. Supply Chain Coordination

We have analyzed the optimal decisions in a centralized supply chain as well as in a decentralized supply chain with two different investment structures. In this section, we explore the impact of carbon subsidies on system coordination based on a traditional wholesale pricing contract. For more information on supply chain coordination contracts, please refer to Cachon [55].

5.1. MI-Structure Supply Chain. We set $(1 - \phi_{MI})$ ($0 \leq \phi_{MI} \leq 1$) as the subsidy share that goes to the retailer from the manufacturer and $(1 - \varphi_{MI})$ ($0 \leq \varphi_{MI} \leq 1$) as the carbon emission abatement cost shared from the manufacturer to the retailer. We first show that, in this context, the traditional cost-sharing contract fails to coordinate the supply chain.

Proposition 5. *The traditional cost-sharing contract with parameters (w, φ_{MI}) fails to coordinate the MI-structure supply chain.*

From Proposition 5, we find that the cost-sharing contract fails to achieve quantity coordination or supply chain coordination. The reason is that the supply chain cannot achieve coordination by manipulating one parameter, φ_{MI} .

Proposition 6 therefore proposes a contract that does achieve quantity coordination (please refer to Choi and Guo [56] for the definition of supply chain coordination), and this contract shows the orchestrating role of carbon subsidies.

Proposition 6. *In a decentralized supply chain with MI-structure, quantity coordination can be achieved by setting a contract with parameters $(w, \varphi_{MI}, \phi_{MI})$.*

According to the definition of supply chain coordination in Choi and Guo [56], a contract (w, φ, ϕ) can only achieve quantity coordination. To ensure win-win coordination that leaves participants' profits better off than they would be without quantity coordination, an improved contract should be considered. Since the bargaining power has a major influence on the leadership in a supply chain, and since the Nash bargaining model is the most common in the literature for deriving bargaining outcomes [57], we follow Shi et al. [58] and Choi and Guo [56] and employ a similar Nash bargaining model. We assume that the fixed bargaining powers of manufacturer and retailer are v and $1 - v$, respectively. We also denote a contract WW with parameters $(w, \varphi_{MI}, \phi_{MI}, T)$, where T is the side-payment from the manufacturer to the retailer in MI-structure. The Nash bargaining model is

$$\begin{aligned} \max \theta^{WW} &= E(\Pi_M^{MI-WW})^v (\Pi_R^{MI-WW})^{1-v}, \\ \text{s.t. } &E(\Pi_M^{MI-WW}) + E(\Pi_R^{MI-WW}) \leq E(\Pi_{SC}). \end{aligned} \quad (6)$$

From this model, we get the optimal solutions $E(\Pi_M^{MI-WW}) = vE(\Pi_{SC})$ and $E(\Pi_R^{MI-WW}) = (1 - v)E(\Pi_{SC})$.

Proposition 7 (win-win coordination contract). *In a decentralized supply chain with MI-structure, win-win coordination can be achieved by setting a contract with parameters $(w, \varphi_{MI}, \phi_{MI}, T)$, where T is the side-payment from the manufacturer to the retailer.*

In Proposition 7, we show a supply chain coordination contract. A green supply chain can be coordinated by manipulating parameters φ_{MI} , ϕ_{MI} , and T . This means that when the manufacturer and the retailer share the subsidy and investment cost, a side-payment will play an important role in supply chain coordination. The management insight lies in the fact that a simple side-payment transfer with a traditional cost-sharing contract can improve the performance of the whole supply chain, while the subsidy plays an orchestrating role in supply chain coordination.

5.2. RI-Structure Supply Chain. Similarly, we set ϕ_{RI} ($0 \leq \phi_{RI} \leq 1$) as the subsidy share that goes to the manufacturer from the retailer and φ_{RI} ($0 \leq \varphi_{RI} \leq 1$) as the abatement cost shared from the retailer to the manufacturer in the RI-structure supply chain. Our conclusions are similar to those in MI-structure supply chain coordination, as illustrated in Propositions 8 and 10.

Proposition 8. *The traditional cost-sharing contract with parameters (w, φ_{RI}) fails to coordinate the RI-structure supply chain.*

Proposition 9. *In a decentralized supply chain with RI-structure, quantity coordination can be achieved by setting a contract with parameters $(w, \varphi_{RI}, \phi_{RI})$.*

In fact, from the expected profit expressions of the manufacturer and the retailer under the two quantity

coordination contracts, it is easy to find that $\varphi_{MI} = \phi_{MI} = \varphi_{RI} = \phi_{RI} = 1/2$. Then, the expected profits of the retailer (manufacturer) are the same under the two investment structures. The managerial implication is that despite the investment structure, the optimal responses such as order quantity and emission abatement level are unique in this supply chain, as are the share of carbon subsidy and investment cost.

Proposition 10. *In a decentralized supply chain with MI-structure, win-win coordination can be achieved by setting a contract with parameters $(\omega, \varphi_{RI}, \phi_{RI}, T)$, where T is the side-payment from the manufacturer to the retailer.*

Similarly, the results of Proposition 10 are the same as the results of Proposition 7, since the win-win coordination is unique.

6. Conclusions and Policy Implications

Considering the challenges of environmental protection and the growing consumer awareness of green products, governments and industries are forced to pursue green economics and sustainable development in order to balance environmental needs and production activity. In this paper, we explore the effects of carbon subsidy on a capital-constrained supply chain. We model a supply chain with a manufacturer and a capital-constrained retailer who can access bank credit at a risk-free interest rate. Specifically, we assume two different carbon emission abatement investment options (i.e., MI-structure and RI-structure) in the supply chain.

The main findings are as follows:

- (1) Comparing a centralized supply chain to a traditional capital-constrained supply chain and factoring in consumers' low-carbon preference, we find that carbon subsidies always have a positive impact on the profit of a centralized supply chain, in addition to having environmental benefits.
- (2) Previous papers often assume that the leader of the supply chain should take the responsibility for investing in carbon abatement technology. However, in this paper, we find that the preferred investment structure for the manufacturer (the leader in the supply chain) depends on the carbon subsidy amount. There exists a crucial value of carbon subsidy that will determine the manufacturer's choice of investment structure, while the retailer will always benefit from RI-structure.
- (3) The carbon subsidy plays an orchestrating role in supply chain coordination. Moreover, we propose two different contracts to achieve quantity coordination and win-win coordination, respectively.

To avoid trivial situations and keep the calculation simple, we employ a linear expression of price and order quantity. The novelty of this research lies in three aspects: the merits of different green investment structures, the orchestrating role of carbon subsidies in supply chain

coordination, and a win-win contract design. The managerial insights are as follows.

- (1) Traditionally, practitioners in industry and academia tend to believe that manufacturers rather than retailers should undertake the task of reducing carbon emissions. In a subsidized supply chain, we find that the retailer is willing to invest in green technology, while the manufacturer should consider the scale of the carbon subsidy. Although a loan for green technology investment may lay an extra burden on the capital-constrained retailer, the carbon subsidy will obtain more benefit for the retailer when combined with consumers' green preference. For the manufacturer, however, as the supply chain leader, the first-move advantage may not ensure a favorable profit if the scale of carbon subsidy is small.
- (2) Generally speaking, supply chain coordination is important for all participants, since coordination means Pareto optimality. The orchestrating role of carbon subsidies implies that the government can improve supply chain performance by manipulating the allocation of carbon subsidies. From the government perspective, there exist three policy implications. First, since subsidy policies have positive effects on supply chain performance as well as environmental benefits, the government may choose to prioritize the implementation of subsidy policies. Specifically, such subsidy policies may guide subsequent green technology investment. Second, supply chain contracts can be designed to achieve win-win coordination, which will stimulate investment in carbon emission abatement technology, and in these contracts carbon subsidies play a vital role. Third, the government should also set a proper threshold for carbon subsidies in manufacturer-led supply chains.
- (3) We also find that traditional cost-sharing contracts fail to coordinate the supply chain, while our proposed contract can achieve win-win coordination. Although quantity coordination is good for the whole supply chain, it is not always good for all the participants. In win-win coordination, the participants can achieve better profits through bargaining.

This paper's main contribution is its exploration of the role of carbon subsidy in a capital-constrained supply chain. However, there are still some limitations to our research. First, within the broader concept of green finance, we focus on bank credit, but there are various financing tools in green finance such as green insurance, green securities, and trade credits with carbon emission limitations. An interesting direction for expanding our research would be to model the benefits of these green finance tools in a sustainable supply chain. Second, in practice, a precise prediction of market demand is impossible. Exploring a stochastic demand (such as newsvendor model) supply chain subject to other environmental policies (such as carbon tax or cap-and-trade) may be another research direction that would contribute to the existing literature. Third, considering the leadership in

the supply chain, future research could design different financing schemes for capital-constrained manufactures and retailers. Furthermore, since government policies could focus on maximizing social welfare, examining effective implementation of these policies is an open avenue for future research.

Appendix

Proof of Lemma 1. By taking the first-order and second-order partial derivatives of Π_{SC} with respect to q , it follows that $(\partial\Pi_{q,eSC}/\partial q) = A - c + \lambda e - 2\alpha(1 + \sigma^2)q$, and $(\partial^2\Pi_{q,eSC}/\partial q^2) = -2\alpha(1 + \sigma^2) < 0$.

Similarly, we get $(\partial\Pi_{q,eSC}/\partial e) = \lambda q - \gamma e + s$ and $(\partial^2\Pi_{q,eSC}/\partial e^2) = -\gamma < 0$. The determinant of the Hessian matrix can be expressed as $|H| = 2\alpha\gamma(1 + \sigma^2) - \lambda^2 > 0$ (see Assumption 5). Hence, Π_{SC} is concave with respect to q and e .

The optimal order quantity and carbon abatement level can be given by $(\partial\Pi_{q,eSC}/\partial q) = 0$ and $(\partial\Pi_{q,eSC}/\partial e) = 0$. \square

Proof of Proposition 1. From Lemma 1, we get the profit of the subsidized centralized supply chain $\Pi_{q^{sc*},e^{sc*},SC}^* = (\gamma(A - c)^2 + \lambda s(A - c))/2h_1$, where $h_1 = 2\alpha\gamma(1 + \sigma^2) - \lambda^2$. The difference of the two supply chains' profits is $\Delta\Pi = \Pi_{q^{sc*},e^{sc*},SC}^* - \Pi_{q^{MI*},SC}^* > 0$. \square

Proof of Lemma 2. Substituting q^{MI} into the expression of $\Pi_{w,eM}^{MI}$, we get

$$\Pi_{w,eM}^{MI} = (w - c) \frac{A - w + \lambda e}{2\alpha(1 + \sigma^2)} + se - \frac{\gamma e^2}{2}. \quad (A.1)$$

Taking the first-order and second-order partial derivative of $\Pi_{w,eM}^{MI}$ with respect to w and e , we get the determinant of the Hessian matrix $|H| = (4\alpha\gamma(1 + \sigma^2) - \lambda^2)/4\alpha(1 + \sigma^2) > 0$. The optimal wholesale price and carbon abatement level can be given by $(\partial\Pi_{w,eM}^{MI}/\partial w) = 0$ and $(\partial\Pi_{w,eM}^{MI}/\partial e) = 0$. \square

Proof of Proposition 2. From Lemmas 1 and 2, it is easy to verify that $q^{SC*} > q^{MI*}$; then, the supply chain fails to coordinate. \square

Proof of Lemma 3. The proof is similar to that of Lemma 2, so we omit it. \square

Proof of Proposition 3. The proof is similar to that of Proposition 3, so we omit it. \square

Proof of Proposition 4. From Lemmas 2 and 3, we get that

$$\begin{aligned} \Pi_M^{MI*} - \Pi_M^{RI*} &= \frac{\gamma(h_2 - \lambda^2)(4\alpha(1 + \sigma^2)s^2 + \gamma(A - c)^2 + 2\lambda s(A - c)) - h_2(\gamma(A - c) + \lambda s)^2}{4\gamma h_1 h_2} \\ &= \frac{h_2^2 s^2 - h_2 s^2 \lambda^2 - \lambda^2(\gamma(A - c) + \lambda s)^2}{4\gamma h_1 h_2} = \frac{2h_1 h_2 s^2 - \lambda^2(\gamma(A - c) + \lambda s)^2}{4\gamma h_1 h_2}. \end{aligned} \quad (A.2)$$

Let $P = 2h_1 h_2 s^2 - \lambda^2(\gamma(A - c) + \lambda s)^2$. If $P > 0$, i.e., $s > (\lambda\gamma(A - c)/(\sqrt{h_2(h_2 - \lambda^2)} - \lambda^2))$, the manufacturer will prefer MI-structure. If $P \leq 0$, the manufacturer will prefer RI-structure. Since $s \geq 0$, then $s \in [0, (\lambda\gamma(A - c)/(\sqrt{h_2(h_2 - \lambda^2)} - \lambda^2))]$.

Let $b = \gamma(A - c) + \lambda s$, then $\Pi_R^{MI*} - \Pi_R^{RI*} = (\alpha(1 + \sigma^2)b^2/h_2^2) - ((4s^2 h_1 + b^2)/8\gamma h_1)$. Since $2h_1 = h_2 - \lambda^2$ and $4\alpha\gamma(1 + \sigma^2) = h_2 + \lambda^2$, we get $\Pi_R^{MI*} - \Pi_R^{RI*} = (((h_2^2 - \lambda^4 - h_2^2)b^2 - 4s^2 h_1 h_2^2)/8\gamma h_1 h_2^2) < 0$. \square

Proof of Proposition 5. With the contract parameters (w, ϕ_{MI}) , the retailer's decision problem is $\Pi_{qR}^{MI-CS} = \max[(Aq + \lambda e q - \alpha(1 + \sigma^2)q^2 - wq - (1 - \phi_{MI})\gamma e^2)/2]$ and the manufacturer's decision problem is $\Pi_{w,eM}^{MI-CS} = \max[((w - c)q + se - \phi_{MI}\gamma e^2)/2]$. The optimal order quantity and carbon emission abatement level are expressed as $e^{MI-CS*} = (\lambda(A - c) + 4\alpha(1 + \sigma^2)s)/(4\alpha\gamma(1 + \sigma^2)\phi_{MI} - \lambda^2)$ and $q^{MI-CS*} = ((A - c) + \lambda e^{MI-CS*})/4\alpha(1 + \sigma^2)$, respectively. In a centralized supply chain, the optimal solutions are $e^{SC*} = (\lambda(A - c) + 2\alpha(1 + \sigma^2)s)/$

$((2\alpha\gamma(1 + \sigma^2) - \lambda^2)(1/2))$ and $q^{SC*} = ((A - c) + \lambda e^{SC*})/4\alpha(1 + \sigma^2)$; then, we cannot get $e^{SC*} = e^{MI-CS*}$ and $q^{SC*} = q^{MI-CS*}$ by manipulating ϕ_{MI} . \square

Proof of Proposition 6. With the contract parameters $(w, \phi_{MI}, \phi_{MI})$, the retailer's expected profit can be expressed as $\Pi_{qR}^{MI-QC} = \max[(Aq + \lambda e q - \alpha(1 + \sigma^2)q^2 - wq + (1 - \phi_{MI})se - (1 - \phi_{MI})\gamma e^2)/2]$, and the manufacturer's expected profit is expressed as $\Pi_{w,eM}^{MI-QC} = \max[((w - c)q + \phi_{MI}se - \phi_{MI}\gamma e^2)/2]$. The optimal order quantity and carbon abatement emission level are expressed as $e^{MI-QC*} = (\lambda(A - c) + 4\alpha(1 + \sigma^2)\phi_{MI}s)/(4\alpha\gamma(1 + \sigma^2)\phi_{MI} - \lambda^2)$ and $q^{MI-QC*} = ((A - c) + \lambda e^{MI-QC*})/4\alpha(1 + \sigma^2)$, respectively. Let $\phi_{MI} = \phi_{MI} = 1/2$, and then we get $e^{SC*} = e^{MI-QC*}$ and $q^{SC*} = q^{MI-QC*}$. Thus, quantity coordination can be achieved. \square

Proof of Proposition 7. In contract WW, as shown in Proposition 6, let $\phi_{MI} = \phi_{MI} = 1/2$, and then quantity coordination can be achieved. To achieve win-win coordination, we should set the retailer's expected profit equal to

$(1 - v)$ of the expected profit of the centralized supply chain. We have

$$\begin{aligned}
 E\left(\Pi_{qR}^{\text{MI-WW}}\right) &= Aq^{\text{SC}*} + \lambda e^{\text{SC}*} q^{\text{SC}*} - \alpha(1 + \sigma^2)q^{\text{SC}*2} - wq^{\text{SC}*} \\
 &\quad + \frac{(1 - \phi_{\text{MI}})se^{\text{SC}*} - (1 - \varphi_{\text{MI}})\gamma e^{\text{SC}*2}}{2} + T \\
 &= (1 - v)E(\Pi_{\text{SC}}).
 \end{aligned}
 \tag{A.3}$$

Solving this equation yields

$$\begin{aligned}
 T &= T^{\text{MI-WW}*} = \left(\frac{1}{2} - v\right)(A - c + \lambda e^{\text{SC}*})q^{\text{SC}*} \\
 &\quad - \alpha v(1 + \sigma^2)q^{\text{SC}*2} \\
 &\quad + \frac{((1/2) - v)se^{\text{SC}*} - ((1/2) - v)\gamma e^{\text{SC}*2}}{2}.
 \end{aligned}
 \tag{A.4}$$

□

Proof of Proposition 8. The proof is similar to that of Proposition 5, so we omit it. □

Proof of Proposition 9. The proof is similar to that of Proposition 6, so we omit it. □

Proof of Proposition 10. The proof is similar to that of Proposition 7, so we omit it. □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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