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Research Article

Energy Performance Contracting in a Supply Chain under Cap-and-Trade Regulation and Carbon Tax Policy

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Energy performance contracting (EPC) is a new tool for supply chain members to cooperate in emission reduction. This paper investigates a two-tier supply chain composed of a supplier and a capital-constricted manufacturer with carbon reduction demand under different low-carbon policies (Cap-and-Trade Regulation and Carbon Tax Policy, respectively). The manufacturer is motivated to cooperate with the supplier to reduce carbon emissions through EPC services. Different from other research, the emission reduction decision maker of EPC services in this paper could be any supply chain member. The results show that cap-and-trade regulation and carbon tax policy have the same impact on the optimal pricing and emission reduction decisions in the monopoly supply chain, but the manufacturer's profit is higher under cap-and-trade regulation. And when the cost-sharing coefficient is within a low range, the emission reduction targets decided by the manufacturer are lower. Otherwise, the targets decided by the supplier are lower. Moreover, supply chain members can obtain higher profits when the reduction targets are determined by themselves, and supply chain coordination under different decision models could be realized through revenue sharing contracts. Considering the total profit of the supply chain, when the cost-sharing rate is within a low range, the supply chain can achieve a Pareto improvement if the supplier determines the emission reduction targets. Otherwise, the reduction targets decided by the manufacturer can realize a Pareto improvement.

1. Introduction

Chinese government proposed that carbon dioxide emissions should strive to achieve "carbon peak" in 2030 and "carbon neutrality" in 2060 on the 75th UN General Assembly. Cap-and-trade regulation and carbon tax policy are two effective low-carbon policies widely adopted by governments. Under the "double carbon" goal and low-carbon policies, to achieve both economic and environmental benefits, more and more manufacturing enterprises have increased their investment in carbon emission reduction. However, small and medium-sized enterprises may not be able to afford the high investment cost and can only choose to reduce production scales which damages the overall economic benefits of supply chain. Therefore, supply chain members are motivated to help manufacturing enterprises to realize low-carbon production. Energy performance contracting (EPC) can be used as a financing mode to solve the above problem. For example, Siemens provides various modes of EPC services for its downstream manufacturers with limited funds and emission reduction needs to achieve environmental benefits [1]. Therefore, how to design an EPC project among supply chain members under the "double carbon" goal is very important.

At present, part of the research on EPC analyzes its implementation in the field of manufacturing [2], and is relatively rare in the context of supply chain [1]. On the other hand, the decider of the emission reduction targets in existing research on EPC is almost all the Energy Service Companies (ESCOs) which are the main investor of EPC services [1–3]. However, under low-carbon policies, EPC clients with emission reduction demand have a better understanding of their own emission reduction needs and are closer to consumers with low-carbon preference. Therefore, it is also necessary to consider the clients to be the decision maker of EPC reduction targets in the context of low-carbon supply chain.

Based on the above discussion, this study establishes a two-echelon supply chain composed of a single supplier and a capital-constricted manufacturer with carbon reduction demand to explore the optimal emission reduction strategies and pricing decisions. Supply chain members are motivated to cooperate to reduction emissions through EPC services. The impact of different decision makers of EPC reduction targets and low-carbon policies are studied in this paper.

The main contributions of this work are as follows. Firstly, we consider the EPC implementation in the context of low-carbon supply chain which is rarely considered in existing research. Second, to the best of our knowledge, this is the first study to consider the manufacturer to be the decision maker of the reduction targets of EPC services. Finally, both cap-and-trade regulation and carbon tax policy are considered in this paper, and our study states the optimal decision maker of EPC reduction targets and the optimal reduction strategies and pricing decision under different circumstances.

The rest of this paper is organized as follows. Section 2 is the literature review. Section 3 describes the model and basic assumptions. Section 4 and section 5 discuss and obtain the equilibrium solutions when the reduction targets are decided respectively by the supplier and the manufacturer. Then, section 6 analyzes and compares the equilibrium results under different decision models. Moreover, it discusses the revenue sharing contracts to realize a Pareto improvement in the supply chain. And section 7 concludes this paper and proposes future research.

2. Literature Review

The research related to this study is mainly the research on low-carbon policies and EPC services. The research on low-carbon policies mainly focuses on the decision of supply chain emission reduction strategies under carbon trading regulation and carbon tax policy [4]. As an indirect mandatory measure, carbon trading regulation has an important impact on supply chain members' emission reduction decisions and supply chain operation decisions. Wang et al. [5] investigated the carbon reduction strategies and product recycle decisions under cap-and-trade regulation in a closed-loop supply chain. An et al. [6] developed a model composed of a finance-constrained manufacturer and a well-funded supplier and concluded the manufacturer's selection towards green credit financing and trade credit financing under different carbon caps. As for the carbon tax policy. Zhang et al. [7] considered that two manufacturers collaborated in core components' provision and competed in the final product market, and they need to decide to produce normal or low-carbon products. There are also many studies comparing the above two carbon constraints. Zakeri et al. [8] analyzed the actual data from an Australian company to investigate the emission reduction decision and operation planning under these two policy schemes. Anand and Giraud-Carrier [9] developed an integrated production-pollution-abatement model of oligopolistic firms respectively under carbon trading and carbon tax policies and identified that these two low-carbon policies can replace each other to some extent. However, none of the above research has studied cooperative carbon reduction in the context of EPC projects.

The research on EPC mainly focuses on the implementation risks and obstacles [10–13], profit distribution [14] and building energy efficiency improvement [15, 16]. Liu et al. [3] explored the EPC contract design of building reconstruction under decentralized and centralized decision making, that is, the decisions on the distribution of EPC saving, contract term and project investment. Zhang et al. [2] compared the equilibrium solutions with or without EPC and with or without carbon trading respectively and found that the interaction between EPC and carbon trading regulation can reduce carbon emissions and increase corporate profits. Xu et al. [1] considered a two-echelon supply chain composed of a single supplier and two manufacturers with asymmetric funds and discussed the impact of the revenue sharing rates and variable cost coefficients on suppliers' profits, as well as which kind of manufacturers the supplier preferred to provide EPC services. However, the above literature does not consider that the manufacturer can also decide EPC's reduction targets, and only Xu et al. [1] considers the EPC service into a supply chain context.

The above literature studies the carbon reduction strategies of supply chain members and the design and implementation of EPC contracts from multiple perspectives. However, in the existing studies, few studies have considered EPC in a low-carbon supply chain and mostly consider the well-funded supplier as the decision maker of EPC reduction targets. However, the emission reduction targets decided by the manufacturer with emission reduction demand may be conducive to their collaborative management of carbon reduction and production. Hence, it is also necessary to consider that the manufacturer could be the decider of the EPC reduction target. This study considers the reduction targets can be decided by any supply chain member respectively under carbon trading regulation and carbon tax policy, discusses the impact of different low-carbon policies and different decision makers of reduction targets on the optimal pricing and reduction decision.

3. The Basic Model and Assumptions

This paper considers a two-echelon supply chain composed of a single supplier and a capital-constricted manufacturer with carbon reduction demand. The supplier is a Stackelberg leader and provides row materials to the manufacturer who produces and sells the final products to consumers. Besides, the supplier can also provide EPC services to the manufacturer as an ESCO to realize low-carbon production referring to the example of Siemens [1]. Facing various low-carbon policies, the capital-constrained manufacturer is also motivated to cooperate with its well-funded supplier to reduce emissions. The supply chain structure is shown in Figure 1.

Without loss of generality, the carbon emission of unit product produced by the manufacturer before the implementation of EPC is standardized to 1. The carbon reduction target $e\,(0 < e < 1)$ of EPC contract is determined by the manufacturer or the supplier. Therefore, the total emission reduction cost is $k(1-e)^2/2$, in which $k\,(k > 0)$ represents the carbon abatement cost coefficient. In the shared savings EPC, the manufacturer bears the total reduction cost in proportion $\theta\,(0 < \theta < 1)$ and shares the EPC savings in proportion $\lambda\,(0 < \lambda < 1)$ with its supplier.

Based on the previous researches [17–19], the market demand of the final products has a linear relationship with the retail price and reduction target, which can be described as $q = 1 - \mathrm{bp} + \delta(1-e)$, in which $b\,(b > 0)$ denotes the price-sensitive coefficient, p is the retail price of the final products and $\delta\,(\delta > 0)$ denotes the low-carbon preference of consumers.

This paper mainly considers two low-carbon policies: cap-and-trade regulation and carbon tax policy. Under the cap-and-trade regulation, the government allocates a certain carbon quota ϕ to each enterprise. When the carbon emission generated in the process of production is higher than ϕ, the enterprise needs to purchase the excessive quota from the carbon trading market at a certain price p_e. Conversely, the enterprise can sell the remaining quota to the carbon trading market at the same price p_e. Under the carbon tax policy, the government charges manufacturing enterprises' per unit of carbon emissions at a certain tax rate t.

To sum up, this paper totally considers four kinds of decision models which are summarized in Table 1. The decision on the reduction target of the EPC service takes precedence over the pricing decision. Therefore, as is shown in Figure 2, in the Stackelberg game model, the decision-making consequence is that one of the supply chain members firstly decides the reduction target e, and then the supplier decides the wholesale price w, and finally, the manufacturer determines the retail price p.

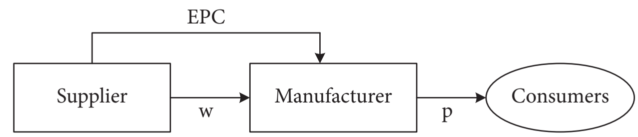

Figure 1: Supply chain structure.

Table 1: Four decision models.

EPC reduction target decision maker	Cap-and-trade regulation	Carbon tax policy
The supplier	Model SE	Model ST
The manufacturer	Model ME	Model MT

Superscript SE, ME, ST, MT are used to represent the equilibrium solutions of corresponding decision models. The following obtains and analyzes the equilibrium solution of each decision model respectively, and finally derives the optimal decision-making strategy through comparative analysis.

4. EPC Carbon Reduction Target Determined by the Supplier

EPC carbon reduction target decided by the supplier is a commonly used decision-making method in existing research. As the ESCO of EPC service, the supplier needs to trade off its investment and share revenue of EPC savings when determining the emission reduction target. The following respectively discuss the game models under cap-and-trade regulation and carbon tax policy.

4.1. Carbon Trading Regulation-Model SE. Under carbon trading regulation, the manufacturer will sell its remaining quota to the carbon trading market when $\phi - e^{SE}q^{SE} > 0$, and will purchase excessive quota when $\phi - e^{SE}q^{SE} < 0$. The EPC savings in Model SE is $p_e q^{SE}(1-e^{SE})$, and the supplier's share revenue of the savings is $\lambda p_e q^{SE}(1-e^{SE})$. The investment of emission abatement borne by the manufacturer is $(k\theta/2)(1-e^{SE})^2$, and that borne by the supplier is $(k(1-\theta)/2)(1-e^{SE})^2$. Therefore, the profit functions of the supplier and the manufacturer can be described as

$$\begin{aligned}\pi_s^{SE} &= w^{SE}q^{SE} - \frac{k(1-\theta)}{2}\left(1-e^{SE}\right)^2 + \lambda p_e q^{SE}\left(1-e^{SE}\right),\\ \pi_m^{SE} &= \left(p^{SE}-w^{SE}\right)q^{SE} - \frac{k\theta}{2}\left(1-e^{SE}\right)^2 - \lambda p_e q^{SE}\left(1-e^{SE}\right) - \left(e^{SE}q^{SE}-\phi\right)p_e.\end{aligned} \tag{1}$$

Using the backward induction method, the equilibrium solution of the Model SE is existing when $B_e > 0, k > (((1+\delta)A_t)/4bF)$ and$kB_e^2[2bkF^2 - \theta A_e^2] + 2\phi p_e(\Delta - A_e^2)^2 > 0$ and is shown in Table 2. All the proofs are shown in Appendix.

4.2. Carbon Tax Policy-Model ST. Under carbon tax policy, the government taxes per unit carbon emission of the manufacturer at a certain tax rate t. The EPC savings in Model ST is $tq^{ST}(1-e^{ST})$, and the manufacturer shares a

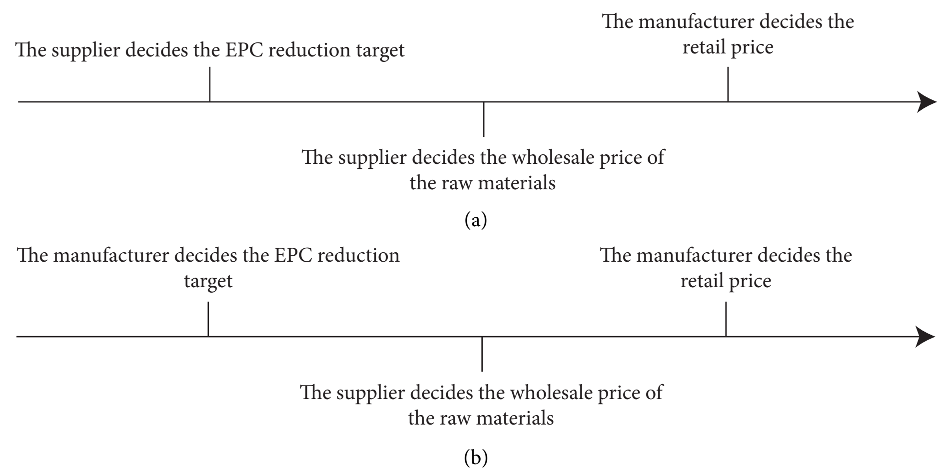

Figure 2: Game sequence of all decision models.

Table 2: Equilibrium solutions of Model SE and Model ST.

	Model SE	Model ST
p	$(kF(bp_e+3)-p_e(1+\delta)A_e)/(\Delta-A_e^2)$	$((kF(bt+3)-t(1+\delta)A_t)/\Delta-A_t^2)$
E	$((\Delta-(1+\delta)A_e)/\Delta-A_e^2)$	$((\Delta-(1+\delta)A_t)/\Delta-(1+\delta)A_t)$
W	$((B_e(2kF-\lambda p_e A_e))/\Delta-A_e^2)$	$((B_t(2kF-\lambda t A_t))/\Delta-A_t^2)$
π_s	$(kFB_e^2/2(\Delta-A_e^2))$	$(kFB_t^2/2(\Delta-A_t^2))$
π_m	$((kB_e^2[2bkF^2-\theta A_e^2])/2(\Delta-A_e^2)^2+\phi p_e)$	$((kB_t^2[2bkF^2-\theta A_t^2])/2(\Delta-A_t^2)^2)$

Where $\Delta=4bk(1-\theta)$, $F=1-\theta$, $A_e=bp_e+\delta$, $A_t=bt+\delta$, $B_e=1-bp_e$ and $B_t=1-bt$.

portion of the savings $\lambda tq^{ST}(1-e^{ST})$ to the supplier. The manufacturer also bears a portion of the total investment of EPC $(k\theta/2)(1-e^{ST})^2$. Therefore, the profit functions of the supplier and the manufacturer in Model ST can be obtained as

$$\pi_s^{ST}=w^{ST}q^{ST}-\frac{k(1-\theta)}{2}\left(1-e^{ST}\right)^2+\lambda tq^{ST}\left(1-e^{ST}\right), \tag{2}$$

$$\pi_m^{ST}=\left(p^{ST}-w^{ST}\right)q^{ST}-\frac{k\theta}{2}\left(1-e^{ST}\right)^2-\lambda tq^{ST}\left(1-e^{ST}\right)-te^{ST}q^{ST}. \tag{3}$$

Using the backward induction method, the equilibrium solution of the Model ST is existing when $B_t>0$ and $k>\max\{(((1+\delta)A_t)/4bF), (\theta A_t^2/2bF^2)\}$ and is shown in Table 2.

5. EPC Carbon Reduction Target Determined by the Manufacturer

This section considers the optimal pricing and reduction decision when the emission reduction targets are decided by the manufacturer. It is also a decision-making method rarely considered in current research. The reduction and pricing strategies of supply chain members are also discussed under two low-carbon policies.

5.1. Carbon Trading Regulation-Model ME. The profit functions of the supplier and the manufacturer in Model ME can be obtained as follows.

$$\begin{aligned}\pi_S^{ME}&=w^{ME}q^{ME}-\frac{k(1-\theta)}{2}\left(1-e^{ME}\right)^2+\lambda p_e q^{ME}\left(1-e^{ME}\right),\\ \pi_S^{ME}&=\left(p^{ME}-w^{ME}\right)q^{ME}-\frac{k\theta}{2}\left(1-e^{ME}\right)^2-\lambda p_e q^{ME}\left(1-e^{ME}\right)-\left(e^{ME}q^{ME}-\phi\right)p_e.\end{aligned} \tag{4}$$

It can be found that the profit functions of the supplier and the manufacturer in Model ME are the same as that of Model SE. Because Model ME and Model SE are both developed under carbon trading regulation, and the only difference between them is the calculations in backward induction method because of the different decider of the reduction targets. Using the backward method, the equilibrium solution of the Model ME is existing when $B_e > 0$ and $k > \max\{(FA_e^2/16b\theta^2), ((1+\delta)A_e/8b\theta)\}$ and is shown in Table 3.

5.2. Carbon Tax Policy-Model MT. Facing carbon tax policy, the profit functions in Model MT can be described as.

$$\pi_s^{MT} = w^{MT}q^{MT} - \frac{k(1-\theta)}{2}\left(1-e^{MT}\right)^2 + \lambda t q^{MT}\left(1-e^{MT}\right),$$
$$\pi_s^{MT} = \left(p^{MT} - w^{MT}\right)q^{MT} - \frac{k\theta}{2}\left(1-e^{MT}\right)^2 - \lambda t q^{MT}\left(1-e^{MT}\right) - te^{MT}q^{MT}. \quad (5)$$

The profit functions of the supplier and the manufacturer are the same as equation (2) and (3) for the same reasons as above. And the optimal solution of Model MT is existing when $B_t > 0$ and $k > \max\{(FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$ and is shown in Table 3.

Proposition 1

(i) In addition to the manufacturer's profit, when $p_e = t$, the equilibrium solutions obtained under two different low-carbon policies are the same when the EPC carbon reduction targets are both decided by the same player.

(ii) $\pi_m^{SE} - \pi_m^{ST} = \pi_m^{ME} - \pi_m^{MT} = \phi p_e$.

Comparing the equilibrium solutions of the above four decision-making models in Table 2 and Table 3, when the carbon trading price is equal to the carbon tax rate, the equilibrium solutions are similar under two low-carbon policies if the reduction targets are decided by the same supply chain members. That is, these two low-carbon policies have the same impact on the decision making of supply chain members when the EPC reduction targets are determined by the same supply chain member. The only difference is the manufacturer's profit, which is higher under carbon trading regulation. This conclusion is similar to that of Anand and Giraud-Carrier [9]. To facilitate comparison and discussion, the following analysis takes the carbon tax policy as an example, and the conclusion is also valid under carbon trading regulation.

6. Analysis and Comparison

This section firstly analyses the impact of the cost-sharing rate θ on decision making, and then compares the optimal equilibrium solutions and profits in different decision models. Finally, we figure out the optimal reduction and pricing strategies of supply chain members under different circumstances.

6.1. The Impact of the Cost-Sharing Rate θ on Emission Reduction Targets and Optimal Retail Prices

Proposition 2. *When $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$,*

(i) $(\partial e^{ST^*}/\partial\theta) < (0\partial e^{MT^*}/\partial\theta) > 0;$

(ii) If $0 < \delta < (bt/3)$, $(\partial p^{ST^*}/\partial\theta) < 0$, $(\partial p^{MT^*}/\partial\theta) > 0$, *if* $\delta > (bt/3)$, $(\partial p^{ST^*}/\partial\theta) > 0$, $(\partial p^{MT^*}/\partial\theta) < 0$.

Proposition 2 indicates that (i) the impact of the cost-sharing rate on emission reduction targets is opposite in different decision models. That is, the increase in the cost-sharing rate decreases the reduction target in Model ST, while increases the target in Model MT. This is because a higher θ means a higher proportion of reduction cost borne by the manufacturer and a lower the proportion borne by the supplier. Therefore, with the increase of θ, the supplier prefers to take more emission abatement effort to obtain a higher profit from sharing revenue of EPC savings. While in Model MT, the capital-constricted manufacturer has to increase its target to reduce total emission reduction cost.

Proposition 2 (ii) demonstrates that the impact of the cost-sharing rate on the optimal retail prices will be influenced by the low-carbon preference of consumers and is also opposite in different decision models. When δ is within a low range (i.e. $0 < \delta < (bt/3)$), the optimal retail price decreases with θ in Model ST, while increases with θ in Model MT. When δ is relatively high (i.e. $\delta > (bt/3)$), the results are opposite.

This is because when δ is within a low range ($0 < \delta < (bt/3)$), the product demand will be lightly influenced by the reduction of unit carbon emission and significantly affected by the retail price according to the demand function. Therefore, the manufacturer prefers to set a lower retail price in Model ST to earn more profits from sales revenue and EPC savings with the increase of θ. When δ is relatively high, the reduction of unit carbon emission has a significant impact on demand, therefore the manufacturer can also obtain high demand even if the retail price is higher.

While in Model MT, when δ is within a low range, with the increase of θ, the demand will lightly decrease because of the increase of the target which enable the manufacturer to lightly increase the retail price to earn more profits from sales revenue. When δ is relatively high, the demand will significantly decrease with the increase of θ. As a result, the manufacturer has to decrease the retail price to ensure the demand.

Table 3: Equilibrium solutions of Model ME and Model MT.

	Model ME	Model MT
p	$((2k\theta(bp_e+3)-p_e(1+\delta)A_e)/8bk\theta-A_e^2)$	$((2k\theta(bt+3)-t(1+\delta)A_t)/8bk\theta-A_t^2)$
E	$((8bk\theta-(1+\delta)A_e)/8bk\theta-A_e^2)$	$((8bk\theta-(1+\delta)A_t)/8bk\theta-A_t^2)$
w	$((B_e(4k\theta-\lambda p_eA_e))/8bk\theta-A_e^2)$	$((B_t(4k\theta-\lambda tA_t))/8bk\theta-A_t^2)$
π_s	$((kB_e^2(16bk\theta^2-FA_e^2))/2(8bk\theta-A_e^2)^2)$	$((kB_t^2(16bk\theta^2-FA_t^2))/2(8bk\theta-A_t^2)^2)$
π_m	$((k\theta B_e^2)/2(8bk\theta-A_e^2))+\phi p_e$	$((k\theta B_t^2)/2(8bk\theta-A_t^2))$

Where $F=1-\theta, A_e=bp_e+\delta, A_t=bt+\delta, B_e=1-bp_e$ and $B_t=1-bt$.

6.2. Comparative Analysis of Different Decision-Making Methods. This section compares and analyzes the equilibrium solutions obtained in Model ST and Model MT and discusses the strategy choice of the decider of the EPC reduction target in different circumstances.

6.2.1. The Comparison of the Reduction Targets of the EPC Service

Proposition 3. *When $B_t>0$ and $k>\max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$, if $0<\theta<(1/3), e^{ST^*}>e^{MT^*}$, if $(1/3)<\theta<1, e^{ST^*}<e^{MT^*}$.*

Proposition 3 shows that the reduction targets will be influenced by the cost-sharing rate. When θ is within a low range $(0<\theta<(1/3))$, the reduction target is lower in Model MT, that is, the manufacturer prefers to take more emission abatement effort than the supplier. Otherwise $((1/3)<\theta<1)$, the target is lower in Model ST.

The reason is that the supplier will bear most of reduction cost when θ is relatively low $(0<\theta<(1/3))$, which induces the supplier to place a higher reduction target to reduce the cost and encourages the manufacturer to set a lower target to earn more profits from sales revenue and carbon tax savings.

When θ is within a high range, both supply chain members will take opposite reduction decisions. The capital-constricted manufacturer has to set a higher target because of the high sharing rate, and the supplier prefers to lower the target to earn more profits from sharing revenue of EPC savings and wholesale revenues.

6.2.2. The Comparison of the Optimal Wholesale Prices

Proposition 4. *The supplier's optimal wholesale prices in different decision models will be jointly affected by the EPC savings sharing rate λ, the cost-sharing rate θ and the consumers' low-carbon preference δ, and the comparison results are shown in Table 4.*

Proposition 4 indicates that when the sharing rate λ is within a low range (i.e. $0<\lambda<(1/2)$), the optimal wholesale prices will be affected by the cost-sharing rate θ. When θ is low (i.e. $0<\theta<(1/3)$), the wholesale price is higher in Model MT. Otherwise (i.e. $(1/3)<\theta<1$), it is higher in Model ST. The reason is that the supplier cannot obtain higher revenue from offering EPC service if the sharing rate is low. According to Proposition 3, the lower reduction target increases the final product demand and therefore enable the supplier to set a higher wholesale price to maximizing its profit from selling raw products.

When λ is relatively high (i.e. $(1/2)<\lambda<1$), the wholesale prices will be jointly affected by the cost-sharing rate and consumers' low-carbon preference. If both θ and δ are within a low or high range (i.e. $(1-3\theta)[\delta-bt(2\lambda-1)]>0$), the wholesale price in Model MT is higher. Conversely, the wholesale price in Model ST is higher. This is because the product demand will be jointly affected by the reduction target and retail price referring to the demand function. If θ and δ are both within a low or high range, product demand is higher in Model MT. As a result, the supplier can set a higher wholesale price to earn more profits from selling raw materials as well as sharing revenue of EPC. The reason is similar in Model ST if one parameter is high while the other is low.

6.2.3. The Comparison of the Optimal Retail Prices

Proposition 5. *When $B_t>0$ and $k>\max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$,*

(i) When $0<\delta<(bt/3)$, if $0<\theta<(1/3), p^{ST^*}>p^{MT^*}$, if $(1/3)<\theta<1, p^{ST^*}<p^{MT^*}$;

(ii) When $\delta>(bt/3)$, if $0<\theta<(1/3), p^{ST^*}<p^{MT^*}$, if $(1/3)<\theta<1, p^{ST^*}>p^{MT^*}$.

Proposition 5 shows that the optimal retail prices under two models will be jointly affected by the cost-sharing rate and consumers' low-carbon preference. When θ and δ are both within a high or low range (i.e. $(1-3\theta)(bt-3\delta)>0$), the retail price is higher in Model ST. Otherwise, it is higher in Model MT.

The reason is that when δ is within a low range $(0<\delta<(bt/3))$, the retail price will significantly influence the demand. As a result, the manufacturer will set a higher retail price for the decision model with higher reduction target to reduce demand and thus reduce the cost of carbon tax. When δ is relatively high (i.e. $\delta>(bt/3)$), the manufacturer prefers to set a higher retail price for the decision model with lower reduction target to earn more profits from sales revenue and savings revenue of EPC service.

6.2.4. The comparison of the profits of the supplier, the manufacturer and the supply chain

Proposition 6. *When $B_t>0$ and $k>\max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$,*

Table 4: The comparison results of the supplier's optimal wholesale prices in different decision models.

Sharing rate of EPC service	Cost-sharing rate	Consumers' low-carbon preference	Comparison results
$0 < \lambda < (1/2)$	$0 < \theta < (1/3)$		$w^{ST^*} < w^{MT^*}$
	$(1/3) < \theta < 1$		$w^{ST^*} > w^{MT^*}$
$(1/2) < \lambda < 1$	$0 < \theta < (1/3)$	$0 < \delta < bt(2\lambda - 1)$	$w^{ST^*} < w^{MT^*}$
		$\delta > bt(2\lambda - 1)$	$w^{ST^*} > w^{MT^*}$
	$(1/3) < \theta < 1$	$0 < \delta < bt(2\lambda - 1)$	$w^{ST^*} > w^{MT^*}$
		$\delta > bt(2\lambda - 1)$	$w^{ST^*} < w^{MT^*}$

Table 5: Profits of supply chain members after coordination.

	$0 < \theta < ((8bk - A_t^2)/16bk)$	$((8bk - A_t^2)/16bk) < \theta < 1$
π_s	$((kFB_t^2)/2(\Delta - A_t^2)) - f_1$	$((kFB_t^2)/2(\Delta - A_t^2))$
π_m	$((k\theta B_t^2)/2(8bk\theta - A_t^2))$	$((k\theta B_t^2)/2(8bk\theta - A_t^2)) - f_2$

Where $\Delta = 4bk(1-\theta), F = 1-\theta, A_t = bt + \delta, B_t = 1 - bt, f_1 = ((bk^2 A_t^2 B_t^2 (1-3\theta)^2)/(8bk\theta - A_t^2)(\Delta - A_t^2)^2), f_2 = ((2bk^2 A_t^2 B_t^2 \ (1-3\theta)^2)/(\Delta - A_t^2)(8bk\theta - A_t^2)^2)$.

(i) $\pi_s^{ST^*} > \pi_s^{MT^*}, \pi_m^{ST^*} < \pi_m^{MT^*}$;

(ii) When $0 < \theta < ((8bk - A_t^2)/16bk), \pi_{sc}^{ST^*} > \pi_{sc}^{MT^*}$, *when* $((8bk - A_t^2)/16bk) < \theta < 1, \pi_{sc}^{ST^*} < \pi_{sc}^{MT^*}$.

Proposition 6 (i) shows that in decentralized decision model, rational decision makers aim at maximizing their own profits and can always obtain a higher profit when the reduction target is made by themselves. That is, both supply chain members both prefer to determine the reduction target by themselves. This is because the decision of reduction targets determines the total reduction cost and further influences the demand and all price decisions, and ultimately affects the profits of supply chain members.

Proposition 6 (ii) demonstrates that if the cost-sharing rate is within a low range $(0 < \theta < ((8bk - A_t^2)/16bk))$, the total profit is higher in Model ST. Otherwise (i.e. $((8bk - A_t^2)/16bk) < \theta < 1$), the total profit in Model MT is higher. That is, the total profit of supply chain is higher in the decision model which decision maker of reduction target bears a higher proportion of emission reduction costs.

This is because a lower range of θ results in a lower reduction target and a higher sales revenue in Model MT. However, higher sales revenue cannot compensate for the higher cost of emission reduction and carbon tax. Therefore, the total profit is higher in Model ST when θ is within a low range. The reason is similarly when θ is relatively high. Proposition 6 (ii) also means that for the total profit of supply chain, the lower the emission reduction targets are not the better.

Considering the total profit of supply chain, the supply chain coordination under different decision models can be realized through the revenue sharing contracts. Therefore, when $\pi_{sc}^{ST^*} > \pi_{sc}^{MT^*}$, Pareto improvement can be realized in the supply chain when the reduction target is determined by the supplier. And the revenue sharing contract needs to satisfy $\pi_m^{ST^*} + f_1 \geq \pi_m^{MT^*}$ and $\pi_s^{ST^*} - f_1 \geq \pi_s^{MT^*}$. When $\pi_{sc}^{ST^*} < \pi_{sc}^{MT^*}$, supply chain achieves a Pareto improvement when the target is decided by the manufacturer. And the revenue sharing contract needs to satisfy $\pi_s^{MT^*} + f_2 \geq \pi_s^{ST^*}$ and $\pi_m^{MT^*} - f_2 \geq \pi_m^{ST^*}$. The profits of supply chain members after coordination are shown in Table 5.

7. Conclusion and Discussions

Under the background of the capital-constrained manufacturer's demand for emission reduction, considering two different low-carbon policies, this paper studies the selection of the decision maker of emission reduction target in a two-tier supply chain to realize cooperative carbon reduction through EPC services. Respectively obtains the equilibrium solutions of four decision models with backward induction approach, analyzes the impact of the emission reduction cost-sharing rate on the optimal reduction targets and retail prices, and compares the equilibrium solutions and profits in different decision models.

This research finds that, the cap-and-trade regulation and carbon tax policy have the same impact on the optimal pricing and emission reduction decision in the monopoly supply chain, but the manufacturer's profit is higher under cap-and-trade regulation. Furthermore, when the cost-sharing coefficient is within a low range, the emission reduction targets decided by the manufacturer are lower. Otherwise, the targets decided by the supplier are lower. Meanwhile, supply chain members can obtain higher profit when the reduction targets are determined by themselves, and supply chain coordination under different decision models could be realized through revenue sharing contracts. Based on the overall profit of the supply chain, when the cost-sharing rate is within a low range, the supply chain can achieve a Pareto improvement if the supplier determines the emission reduction targets. When the cost-sharing coefficient is relatively high, the reduction targets decided by the manufacturer can realize a Pareto improvement.

This study also has a lot to expend. For example, this paper only considers a simple supply chain structure composed by a single supplier and a single manufacturer. In practical, a large scale supplier has multiple small and medium-sized downstream manufacturers. What will the pricing and emission reduction of supply chain members be when the supply chain structure is more complex? It can also consider two competing supply chains to compare the optimal pricing and reduction decision with and without EPC.

Appendix

A. Proof of the equilibrium solution of Model SE

Using the backward induction approach, the manufacturer decides the retail price firstly,

$$\frac{\partial \pi_m^{SE}}{\partial p} = 1 + \delta(1-e) - 2bp + b[w + (e + \lambda - e\lambda)p_e]. \quad (A.1)$$

Make it equal to 0, and we get $p^{SE} = (1+\delta(1-e) + b[w + (e+\lambda-e\lambda)p_e]/2b)$. And $(\partial^2\pi_m^{SE}/\partial p^2) = -2b < 0$, which means π_m^{SE} is a concave function with respect to p^{SE}. Substituting p^{SE} into π_m^{SE} and π_s^{SE}, the supplier decides the wholesale price,

$$\frac{\partial \pi_s^{SE}}{\partial w} = 1 + \delta(1-e) - 2bw - bp_e[2\lambda(1-e) + e]. \tag{A.2}$$

Also make it equal to 0, and we get $w^{SE} = (1+\delta(1-e) - bp_e[2\lambda(1-e)+e]/2b)$. Also substituting w^{SE} into π_m^{SE} and π_s^{SE}.

Finally, the supplier decides the reduction target,

$$\frac{\partial \pi_s^{SE}}{\partial e} = \Delta - (1+\delta)A_e - \left(\Delta - A_e^2\right)e. \tag{A.3}$$

The corresponding Hessian Matrix is

$$H_1(w,e) = \begin{bmatrix} -b & -\dfrac{[\delta + bp_e(1-2\lambda)]}{2} \\ -\dfrac{[\delta + bp_e(1-2\lambda)]}{2} & \lambda p_e[\delta + bp_e(1-\lambda)] - kF \end{bmatrix}. \tag{A.4}$$

It is easily to check that $H_1(w,e)$ is a negative definite matrix when $k > (A_e^2/4bF)$. Let $(\partial\pi_s^{SE}/\partial e) = 0$, we can get $e^{SE^*} = (\Delta - (1+\delta)A_e/\Delta - A_e^2)$. Substituting e^{SE^*} back into $p^{SE}, w^{SE}, \pi_s^{SE}$ and π_m^{SE}, we can get the equilibrium solutions and the optimal profits of supply chain members. In order to satisfy the conditions of $0 < e^{SE^*} < 1$ and $\pi_m^{SE} > 0$, we have $B_e > 0, \Delta > (1+\delta)A_e$ and$kB_e^2[2bkF^2 - \theta A_e^2] + 2\phi p_e(\Delta - A_e^2)^2 > 0$.

B. Proof of the equilibrium solution of Model ST

The game sequence of Model ST is similar to Model SE. Firstly, the manufacturer decides the retail price,

$$\frac{\partial \pi_m^{ST}}{\partial p} = 1 + \delta(1-e) - 2bp + b[w + (e+\lambda-e\lambda)t]. \tag{B.1}$$

Make it equal to 0, and we get $p^{ST} = (1+\delta(1-e) + b[w + (e+\lambda-e\lambda)t]/2b)$. And $(\partial^2\pi_m^{ST}/\partial p^2) = -2b < 0$, which means π_m^{ST} is a concave function with respect to p^{ST}. Substituting p^{ST} into π_m^{ST} and π_s^{ST}.

Then, the supplier decides the wholesale price,

$$\frac{\partial \pi_s^{ST}}{\partial w} = 1 + \delta(1-e) - 2bw - bt[2\lambda(1-e) + e]. \tag{B.2}$$

Also make it equal to 0, and we can get $w^{ST} = (1+\delta(1-e) - bt[2\lambda(1-e)+e]/2b)$. Also substituting w^{ST} into π_m^{ST} and π_s^{ST}.

Finally, the supplier decides the reduction target,

$$\frac{\partial \pi_s^{ST}}{\partial e} = \Delta - (1+\delta)A_t - \left(\Delta - A_t^2\right)e. \tag{B.3}$$

The corresponding Hessian Matrix is

$$H_2(w,e) = \begin{bmatrix} -b & -\dfrac{[\delta + bt(1-2\lambda)]}{2} \\ -\dfrac{[\delta + bt(1-2\lambda)]}{2} & \lambda t[\delta + bt(1-\lambda)] - k(1-\theta) \end{bmatrix}. \tag{B.4}$$

It is easily to check that $H_2(w,e)$ is a negative definite matrix when $k > (A_t^2/4bF)$. Let $(\partial\pi_s^{ST}/\partial e) = 0$, we can get $e^{ST^*} = (\Delta - (1+\delta)A_t/(\Delta - A_t^2))$. Substituting e^{ST^*} back into $p^{ST}, w^{ST}, \pi_s^{ST}$ and π_m^{ST}, we can get the equilibrium solutions and the optimal profits of supply chain members. In order to satisfy the condition of $0 < e^{ST^*} < 1$ and $\pi_m^{ST} > 0$, we have $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2)\}$.

C. Proof of the equilibrium solution of Model ME

The only difference between Model SE and Model ME is the decider of the reduction target. Therefore, the solving process of the first two stages is similar to Model SE. After solving p^{ME} and w^{ME} which are similar to p^{SE} and w^{SE} respectively, the manufacturer finally decides the reduction target,

$$\frac{\partial \pi_m^{ME}}{\partial e} = 8bk\theta - (1+\delta)A_e - \left(8bk\theta - A_e^2\right)e. \tag{C.1}$$

The corresponding Hessian Matrix is $H_3(p,e) = \begin{bmatrix} -2b & ((bp_e - 3\delta)/2) \\ ((bp_e - 3\delta)/2) & \delta p_e - k\theta - (\delta^2/b) \end{bmatrix}$.It is easily to check that $H_3(p,e)$ is a negative definite matrix when $k > (A_e^2/8b\theta)$. Let $(\partial\pi_m^{ME}/\partial e) = 0$, we can get $e^{ME^*} = ((8bk\theta - (1+\delta)A_e)/8bk\theta - A_e^2)$. Substituting e^{ME^*} back into $p^{ME}, w^{ME}, \pi_s^{ME}$ and π_m^{ME}, we can get the equilibrium solutions and the optimal profits of supply chain members. In order to satisfy the conditions of $0 < e^{ME^*} < 1$ and $\pi_s^{ME} > 0$, we have $B_e > 0$ and $k > \max\left\{(FA_e^2/16b\theta^2), (1+\delta)A_e/8b\theta\right\}$.

D. Proof of the equilibrium solution of Model MT

The solving process of the first two stages is similar to Model ST. After solving p^{MT} and w^{MT} which are similar to p^{ST} and w^{ST} respectively, the manufacturer finally decides the reduction target,

$$\frac{\partial \pi_m^{MT}}{\partial e} = 8bk\theta - (1+\delta)A_t - \left(8bk\theta - A_t^2\right)e. \tag{D.1}$$

The corresponding Hessian Matrix is $H_4(p,e) = \begin{bmatrix} -2b & ((bt - 3\delta)/2) \\ ((bt - 3\delta)/2) & \delta t - k\theta - (\delta^2/b) \end{bmatrix}$.It is easily to check that $H_4(p,e)$ is a negative definite matrix when $k > (A_t^2/8b\theta)$. Let $(\partial\pi_m^{MT}/\partial e) = 0$, we can get $e^{MT^*} = ((8bk\theta - (1+\delta)A_t)/8bk\theta - A_t^2)$. Substituting e^{MT^*} back into $p^{MT}, w^{MT}, \pi_s^{MT}$ and π_m^{MT}, we can get the equilibrium solutions and the optimal profits of supply chain members. In order to satisfy the conditions of $0 < e^{MT^*} < 1$ and $\pi_s^{MT} > 0$, we have $B_t > 0$ and $k > \max\{(FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$.

E. Proof of Proposition 1

When $p_e = t$, besides the profit of the manufacturer, it is easily to figure out that the equilibrium solutions of Model SE is similar to those in Model ST, and the equilibrium solutions of Model ME is also similar to those in Model MT.

As for the manufacturer's profit, it is higher under cap-and-trade regulation than under carbon tax policy, and the difference equals to the product of the manufacturer's initial carbon quota ϕ and the carbon trading price p_e.

F. Proof of Proposition 2

When $B_t > 0$ and. $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$

(i) $(\partial e^{ST^*}/\partial\theta) = -(4bkA_tB_t/(\Delta - A_t^2)^2) < 0, (\partial e^{MT^*}/\partial\theta) = (8bkA_tB_t/(8bk\theta - A_t^2)^2) > 0$

(ii) We have $(\partial p^{ST^*}/\partial\theta) = (-kA_tB_t(bt - 3\delta)/(\Delta - A_t^2)^2)$. When $bt - 3\delta > 0$, i.e. $0 < \delta < (bt/3)$, $(\partial p^{ST^*}/\partial\theta) < 0$, when $bt - 3\delta < 0$, i.e. $\delta > (bt/3)$, $(\partial p^{ST^*}/\partial\theta) > 0$.

We also have $(\partial p^{MT^*}/\partial\theta) = (2kA_tB_t(bt - 3\delta)/(8bk\theta - A_t^2)^2)$. When $bt - 3\delta > 0$, i.e. $0 < \delta < (bt/3)$, $(\partial p^{MT^*}/\partial\theta) > 0$, when $bt - 3\delta < 0$, i.e. $\delta > (bt/3)$, $(\partial p^{MT^*}/\partial\theta) < 0$.

G. Proof of Proposition 3

When $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}, e^{ST^*} - e^{MT^*} = (4bkA_tB_t(1-3\theta)/(\Delta - A_t^2)(8bk\theta - A_t^2))$. It is easily to figure out that when $0 < \theta < (1/3), e^{ST^*} > e^{MT^*}$, when $(1/3) < \theta < 1, e^{ST^*} < e^{MT^*}$.

H. Proof of Proposition 4

When $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}, w^{ST^*} - w^{MT^*} = -(2kA_tB_t(1-3\theta)[\delta + bt(1-2\lambda)]/(\Delta - A_t^2)(8bk\theta - A_t^2))$. It is easily to figure out that when $0 < \lambda < (1/2), \delta + bt(1-2\lambda) > 0$. Therefore, if $0 < \theta < (1/3), w^{ST^*} < w^{MT^*}$, if $(1/3) < \theta < 1$, $w^{ST^*} > w^{MT^*}$.

When $(1/2) < \lambda < 1$, if $0 < \theta < (1/3)$ and $0 < \delta < bt(2\lambda - 1)$, we have $w^{ST^*} < w^{MT^*}$, if $0 < \theta < (1/3)$ and $\delta > bt(2\lambda - 1)$, we have $w^{ST^*} > w^{MT^*}$. If $(1/3) < \theta < 1$ and $0 < \delta < bt(2\lambda - 1), w^{ST^*} > w^{MT^*}$, if $(1/3) < \theta < 1$ and $\delta > bt(2\lambda - 1), w^{ST^*} < w^{MT^*}$.

I. Proof of Proposition 5

When $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}, p^{ST^*} - p^{MT^*} = kA_tB_t(1-3\theta)(bt - 3\delta)/(\Delta - A_t^2)(8bk\theta - A_t^2)$. When $(1-3\theta)(bt - 3\delta) > 0, p^{ST^*} > p^{MT^*}$, when $(1-3\theta)(bt-3\delta) < 0$, $p^{ST^*} < p^{MT^*}$. Therefore, when $0 < \delta < (bt/3)$, if $0 < \theta < (1/3), p^{ST^*} > p^{MT^*}$, else $p^{ST^*} < p^{MT^*}$. When $\delta < (bt/3)$, if $0 < \theta < (1/3), p^{ST^*} < p^{MT^*}$, else $p^{ST^*} > p^{MT^*}$.

J. Proof of Proposition 6

When $B_t > 0$ and $k > \max\{((1+\delta)A_t/4bF), (\theta A_t^2/2bF^2), (FA_t^2/16b\theta^2), ((1+\delta)A_t/8b\theta)\}$.

(i) $\pi_s^{ST^*} - \pi_s^{MT^*} = 2bk^2A_t^2B_t^2(1-3\theta)^2/(\Delta - A_t^2)(8bk\theta - A_t^2)^2 > 0, \pi_m^{MT^*} - \pi_m^{ST^*} = bk^2A_t^2B_t^2(1-3\theta)^2/(8bk\theta - A_t^2)(\Delta - A_t^2)^2 > 0$;

(ii) $\pi_{sc}^{MT^*} - \pi_{sc}^{ST^*} = bk^2A_t^2B_t^2(1-3\theta)^2[A_t^2 - 8bk(1-2\theta)]/(8bk\theta - A_t^2)^2(\Delta - A_t^2)^2$. If $A_t^2 - 8bk(1-2\theta) > 0$, $\pi_{sc}^{MT^*} > \pi_{sc}^{ST^*}$, else $\pi_{sc}^{ST^*} > \pi_{sc}^{MT^*}$. Let $A_t^2 - 8bk(1-2\theta) = 0$, we can get $\theta_1 = (8bk - A_t^2/16bk)$. And according to $H_2(w,e)$, we have $k > (A_t^2/4bF)$, i.e. $(A_t^2/4bk) < F = 1 - \theta < 1$. Therefore, it is easily to check that $8bk > A_t^2$, i.e. $\theta_1 > 0$. As a result, if $0 < \theta < ((8bk - A_t^2)/16bk), \pi_{sc}^{MT^*} - \pi_{sc}^{ST^*} < 0$, and if $((8bk - A_t^2)/16bk) < \theta < 1, \pi_{sc}^{MT^*} - \pi_{sc}^{ST^*} > 0$.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

All authors declare no possible conflicts of interest.

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