ISSN: 2688-9323

Investigation on the Green Supply Chain Decision Making Strategy under Carbon Quota-Constrained Government Conditional Subsidy

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Abstract

The carbon neutrality and carbon peaking targets have attracted much research attention recently. Carbon emission constraints already influence the manufacturing decisions of a company, where the government plays a critical role in the green supply chains. In this paper, the influence of government conditional subsidy policy on green supply chain decisions is investigated, including two government subsidy strategies and two game dominant parties, i.e., the supplier dominance under basic subsidy, the retailer dominance under basic subsidy, the supplier dominance under conditional subsidy, and the retailer dominance under conditional subsidy. First, a Stackelberg game model with carbon quota constraints is constructed, with consideration of consumers' green preferences. Then, the revenue sharing contracts is introduced. Finally, the impact of correlation coefficient analysis on supply chain decisions and profits have been analyzed. The results show that government conditional subsidies are more favorable to green economy development and industrial clusters, and revenue sharing contracts can further increase supply chain profits. This study provides a foundation for company decision makers and government policy makers.

Keywords

Green Supply Chain; Stackelberg Game; Government Subsidies; Carbon Quota Constraint; Revenue Sharing Contract.

1. Introduction

With an increasing demand for green products and the rapid industrial development, the greenhouse effect and environmental pollution have aggravated [1, 2]. Carbon emission is one of the major causes of the greenhouse effect. To achieve goal of "carbon neutrality" and "carbon peaking", governments around the world have established carbon trading markets to control and reduce carbon emissions by using market mechanisms [3-6]. A survey of emerging economies in Asia shows that green supply chain management alleviates environment pollution and improves economic efficiency [7]. Therefore, to promote the green economy, governments have implemented different intervention policies, which aimed at pushing companies to improve the greenness property of their products during production. For example, in China, manufacturers of new energy vehicles can not only accumulate new energy vehicle points for free trade, but also receive government subsidies. In addition, consumers are in favor of purchasing green and low-carbon products due to the increased awareness of social responsibility and environmental protection [8]. Therefore, the impact of carbon emissions, government intervention policies and consumers' preference for green products will prompt firms to consider production and pricing issues in the supply chain.

In this paper, a Stackelberg game model with different power structures is developed, in the context of carbon emission cap-and-trade mechanism and consumers' green preferences, to investigate the production decision problem of suppliers and manufacturers under different government subsidies. The government subsidies can be divided into two types: basic subsidies and conditional subsidies, resulting in four supply chain subsidy structure models: supplier-dominated in basic subsidies (D case), green manufacturer-dominated in basic subsidies (T case), supplier-dominated in conditional subsidies (SD case) and green manufacturer-dominated in conditional subsidies (ST case). By analyzing and comparing the optimal pricing and production decisions under different cases, the revenue sharing contract is introduced to further improve the overall supply chain revenue. The primary contributions of this paper are as follows: 1) the effects of different subsidy policies on green supply chain decisions, carbon emissions and profits under the carbon quota constraint have been compared; 2) the policy effects of conditional subsidies have been evaluated by observing the changes in supply chain revenues and carbon emissions; 3) a coordination contract mechanism is proposed, so that decision makers can achieve the optimal revenues under centralized decisions even when decentralized decisions are made through revenue sharing contracts.

2. Related Work

In this section, two aspects of existing work are reviewed and summarized, including the government policies and carbon emissions.

2.1. Government Policies

Existing studies suggest that appropriate government subsidies can promote the development of a green economy. The impact of government policies on green supply chains have been investigated from different perspectives. From the government intervention mechanisms perspective, a study by Sheu and Chen [9] compared the impact of government green taxes and subsidies acting on green supply chains. Ma et al [10] found that the subsidy mechanism was more effective in influencing green supply chain strategies compared to taxes. From the perspective of the target of government subsidies, Cohen et al. [11] studied the intervention effect of government subsidies acting on different members of the supply chain; Meng et al. [12] found that the government tends to subsidize the core suppliers in the supply chain rather than both manufacturers and upstream suppliers. Hafezalkotob et al. [13] and Meng et al. [14] studied the effect of government subsidy policies on dual-channel green supply chain. They found that appropriate subsidies increase the demand for green products and promote the development of green economy.

2.2. Carbon Emissions

However, most studies are limited to the study of one aspect of carbon emission policies. Li et al. [15] and Wang et al. [16] studied the effects of carbon subsidies and carbon taxes on different types of supply chains from the perspectives of carbon subsidies and carbon taxes, respectively. Li et al. [17] and Xu et al. [18] investigated the intervention effects of different government subsidies on supply chain members' decisions under carbon cap-and-trade mechanisms. Du et al. [19] studied the pricing and decision making of manufacturers considering consumers' environmental awareness under a carbon cap-and-trade system. Xu et al. [20] considered supply chain coordination under carbon cap-and-trade rules. Yang et al. [21] showed that carbon trading policies always outperform carbon emission policies and carbon tax policies when the allocated carbon emissions meet certain conditions.

In summary, the aforementioned studies have only considered the basic subsidy that affect individual decision maker members of green supply chains, or carbon emissions trading and limits. However, the conditional subsidies that can promote industrial clusters and the impact of different power structures on green supply chain decisions have been rarely considered.

3. Problem Description and Assumptions

Figure 1 shows the proposed green supply chain model. Following Su's hypothesis [22], a two-level supply chain Stackelberg game model consisting of a single supplier S and a single green direct-selling manufacturer M (hereafter referred as the green manufacturer) is developed. The green manufacturer under the carbon quota constraint purchases raw materials from suppliers, produces green products and sells them directly to consumers. The government gives the green manufacturer a basic subsidy for producing green products. If the supplier become a compliant supplier by obtaining government qualification certification and moving into the industrial park, the government gives the green manufacturer an additional subsidy for purchasing its raw materials, i.e., a conditional subsidy.

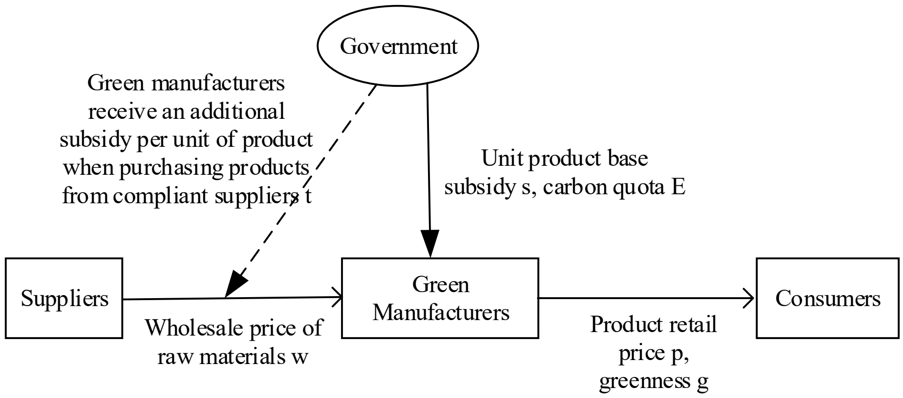

Figure 1. Green Supply Chain Model

3.1. Symbol Definition

Table 1. Symbols and their descriptions

Symbols	Meaning	Symbols	Meaning
w	Wholesale price of raw materials from suppliers	r	Price per unit of carbon credits
p	Retail price of the green manufacturer's product	E	Maximum carbon emissions set by the government
g	Greenness of the product	λ	Carbon reduction rate of the green manufacturer's product when using raw materials from compliant suppliers
q	Market demand for the green product	μ	Potential market coefficient for increased market demand using raw materials from compliant suppliers, μ>1
a	Potential market demand for green products	s	Government basic subsidy for green manufacturers
b	Price sensitivity coefficient for green products	t	Additional subsidies for green manufacturers by choosing compliant suppliers, government conditional subsidies
k	Consumer green preference coefficient	φ	Costs for the suppliers to become compliant suppliers
η	Green manufacturer product development impact factor	Π_i^j	Profit of decision member i under decision model j
e	Carbon emissions per unit of product produced by green supplier		

3.2. Model Assumptions

The following assumptions have been made in this paper.

1) Assume that a green manufacturer consumes exactly one unit of raw material for each unit of green product produced, and the supplier pays a fixed cost of c for producing a unit of raw material.

2) Following the previous studies [20, 23], the market demand for green products is influenced by both retail prices and consumers' green preferences, and consumers prefer to buy products with high greenness and low prices. It is assumed that the market demand of green products is $q = a - bp + kg$. Without loss of generality, $a - bp > 0, p > w > c$, which ensures positive profit of supply chain sales.

3) To satisfy the green demand of consumers, companies increase their R&D investment to improve the technology level. Following the settings in [20], the R&D results are quadratically related to the R&D investment. Assuming that the R&D costs are all borne by the green manufacturer, the R&D cost of green products is $\frac{\eta g^2}{2}$.

4) Under the basic subsidy policy, the unit product subsidy obtained by the green manufacturer is s. Under the conditional subsidy policy, after the supplier pays the cost φ to become a compliant supplier and is purchased by the green manufacturer, the government gives the green manufacturer an additional subsidy t per unit product, at which time the potential market demand for green products becomes higher, and the increase coefficient is $\mu, \mu > 1$, then the demand for green products is $q = \mu a - bp + kg$. The assumption ensures that suppliers have an incentive to pay a certain cost φ, and become a compliant supplier by obtaining the government qualification and moving into the industrial park.

5) Following the settings of carbon emission and trading mechanism in [20, 24], it is assumed that the carbon quota given by the government can be traded twice in the carbon emission rights trading market, the carbon emission per unit of product produced by the manufacturer is e the price per unit of carbon emission right is r, and the maximum carbon emission given by the government to the manufacturer is E. In fact, the government will give extra subsidies to the enterprises purchasing products in the park, which will reduce the carbon emission in the transportation and carbon emissions in the production process. In this paper, we assume that λ is the emission reduction rate when using raw materials from compliant suppliers for production.

3.3. Modeling

We denote the aforementioned four cases, i.e., supplier-dominated scenario in the basic subsidy, the green manufacturer-dominated scenario in the basic subsidy, the supplier-dominated scenario in the conditional subsidy and the green manufacturer-dominated scenario in the conditional subsidy using the index $j = D, T, SD, ST$. The superscript indices denote the equilibrium solutions in the four scenarios, the lower corners S and M denote the suppliers and green manufacturers. Based on the above assumptions, it is known that the supplier profit Π_S^j and the green manufacturer Π_M^j profit under the basic subsidy policy can be expressed as the following:

$$\max_{w} \Pi_S^j = (w - c)(a - bp + kg) \tag{1}$$

$$\max_{p,g} \Pi_M^j = (p - w + s)(a - bp + kg) - r(e(a - bp + kg) - E) - \frac{\eta g^2}{2} \tag{2}$$

The compliance supplier profit Π_S^j and the green manufacturer Π_M^j profit under the conditional subsidy policy are:

$$\max_{w} \Pi_S^j = (w - c)(\mu a - bp + kg) - \varphi \tag{3}$$

$$\max_{p,g} \Pi_M^j = (p - w + s + t)(\mu a - bp + kg) - r(e(1-\lambda)(\mu a - bp + kg) - E) - \frac{\eta g^2}{2} \qquad (4)$$

4. Solutions and Analysis

The optimal decisions and profits of the Stackelberg game between suppliers and green manufacturers are solved and compared under four scenarios, with symmetric information and neutral risk aversion among green supply chain members. The effects of carbon quota constraints, consumer green preferences and different government subsidy policies on green supply chain decisions are analyzed. Then the revenue sharing contract is introduced to adjust the firm's revenue to the level under centralized decision making. The equilibrium solutions of decision variables and profits under each scenario are shown in Table 2.

Table 2. Equilibrium solutions and profits of the model under different scenarios

	D	T	SD	ST
w^*	$\frac{b(M+2c)+a}{2b}$	$\frac{(b(M+4c)+a)\eta - ck^2}{\Upsilon}$	$\frac{(N+2c)b+\mu a}{2b}$	$\frac{(b(N+4c)+\mu a)\eta - ck^2}{\Upsilon}$
p^*	$\frac{bAM+aB}{2bX}$	$\frac{AM+3a\eta}{\Upsilon}$	$\frac{bAN+\mu aB}{2bX}$	$\frac{AN+3a\mu\eta}{\Upsilon}$
g^*	$\frac{k(bM+a)}{2X}$	$\frac{k(a+bM)}{\Upsilon}$	$\frac{k(bN+\mu a)}{2X}$	$\frac{k(bN+\mu a)}{\Upsilon}$
q^*	$\frac{(bM+a)\eta b}{2X}$	$\frac{(bM+a)\eta b}{\Upsilon}$	$\frac{(bN+\mu a)\eta b}{2X}$	$\frac{(bN+\mu a)b\eta}{\Upsilon}$
Π_S^*	$\frac{\eta(bM+a)^2}{4X}$	$\frac{\eta^2 b(bM+a)^2}{\Upsilon^2}$	$\frac{\eta(bN+\mu a)^2}{4X} - \varphi$	$\frac{b\eta^2(bN+\mu a)^2}{\Upsilon^2} - \varphi$
Π_M^*	$\frac{\eta(bM+a)^2}{8X} + Er$	$\frac{\eta(bM+a)^2}{2\Upsilon} + Er$	$\frac{\eta(bN+\mu a)^2}{8X} + Er(1-\lambda)$	$\frac{\eta(bN+\mu a)^2}{2\Upsilon} + Er(1-\lambda)$
Π_{S+M}^*	$\frac{3\eta(bM+a)^2}{8X} + Er$	$\frac{\eta(6b\eta-k^2)(bM+a)^2}{2\Upsilon^2} + Er$	$\frac{3\eta(bN+\mu a)^2}{8X} + Er(1-\lambda) - \varphi$	$\frac{\eta(6b\eta-k^2)(bN+\mu a)^2}{2\Upsilon^2} + Er(1-\lambda) - \varphi$

The meanings of the relevant parameters in the table are as follows.

Table 3. Meaning of the relevant parameters

Parameter	Meaning	Parameter	Meaning
M	$s - er - c$	A	$k^2 - b\eta$
N	$s + t - c - (1-\lambda)er$	B	$3b\eta - k^2$
X	$2b\eta - k^2$	ϒ	$4b\eta - k^2$

4.1. Analysis of Game Results under Different Scenarios

Proposition 1 (1) $w_S^{D*} > w_S^{T*}$; $g_M^{D*} > g_M^{T*}$; $0 < k < \sqrt{b\eta}, p_M^{T*} > p_M^{D*}$; $\sqrt{b\eta} < k < \sqrt{2b\eta}, p_M^{D*} > p_M^{T*}$; $\Pi_S^{D*} > \Pi_S^{T*}$; $0 < k < \sqrt{\frac{4b\eta}{3}}, \Pi_M^{D*} < \Pi_M^{T*}$; $\sqrt{\frac{4b\eta}{3}} < k < \sqrt{2b\eta}, \Pi_M^{D*} > \Pi_M^{T*}$;

(2) $w_S^{SD*} > w_S^{ST*}$; $g_M^{SD*} > g_M^{ST*}$; $0 < k < \sqrt{b\eta}, p_M^{ST*} > p_M^{SD*}$; $\sqrt{b\eta} < k < \sqrt{2b\eta}, p_M^{SD*} > p_M^{ST*}$; $\Pi_S^{SD*} > \Pi_S^{ST*}$; $0 < k < \sqrt{\frac{4b\eta}{3}}, \Pi_M^{SD*} < \Pi_M^{ST*}$; $\sqrt{\frac{4b\eta}{3}} < k < \sqrt{2b\eta}, \Pi_M^{SD*} > \Pi_M^{ST*}$.

ISSN: 2688-9323

Proposition 1 reveals that the optimal wholesale price, product greenness and supplier profit are greater in the supplier-dominated model than in the green manufacturer-dominated model, regardless of the subsidy method. This is because that the suppliers have more power of speech in the "seller's market", while the green manufacturer-dominated model is equivalent to corporate “tendering”. This is due to the fact that suppliers in the "seller's market" have more speech power, while the green manufacturer-led model is equivalent to corporate "bidding" behavior, and suppliers must reduce the wholesale price to obtain orders, thus compressing profit margins. When consumer green preferences are low, the retail prices and profits of products are higher when green manufacturers dominate than when suppliers dominate. In contrast, when consumer green preferences are high, the opposite is true. This indicates that green manufacturers are more sensitive to the perception of consumers' green preferences due to their direct contact with consumers, and consumers' green preferences have a stronger influence on their decision-making behavior.

Proposition 2 $\frac{\partial \Pi_M^j}{\partial E} > 0$; $\frac{\partial \Pi_S^j}{\partial er} < 0, \frac{\partial \Pi_M^j}{\partial er} < 0, \frac{\partial w_S^j}{\partial er} < 0, \frac{\partial g_M^j}{\partial er} < 0$; $0 < k < \sqrt{b\eta}, \frac{\partial p_M^j}{\partial er} > 0, \sqrt{b\eta} < k < \sqrt{2b\eta}, \frac{\partial p_M^j}{\partial er} < 0$, where $j = D, T, SD, ST$.

Proposition 2 shows that regardless of the subsidy method, the green manufacturer profit is an incremental function of the government-given carbon allowance. This is because that with the establishment of the carbon trading market, carbon emission rights become an asset of the firm itself due to its tradable nature. The optimal wholesale price, product greenness, and supplier and green manufacturer profits decrease as the cost of carbon increases, and the retail price increases and then decreases with the cost of carbon as consumer green preferences increase. Green suppliers can offset part of the negative effect of carbon emission cost with the carbon allowance given by the government.

Proposition 3 (1) $\varphi < \varphi_1, \Pi_S^{SD*} > \Pi_S^{D*}$; $\lambda > \lambda_1, \Pi_M^{SD*} > \Pi_M^{D*}$;

(2) $\varphi < \varphi_2, \Pi_S^{ST*} > \Pi_S^{T*}$; $\lambda > \lambda_2, \Pi_M^{ST*} > \Pi_M^{T*}$.

Where $\varphi_1 = \frac{\eta\left(b(2s+t-(2-\lambda)er-2c)+a(\mu+1)\right)\left(b(\lambda er+t)+a(\mu-1)\right)}{4(2b\eta-k^2)}$,

$$\lambda_1 = \frac{1}{\eta b^2 e^2 r}\left(b^2\eta e(er+c-s-t) + 8b\eta\left(E - \frac{\mu a e}{8}\right) - 4Ek^2 - \sqrt{b^4e^4\eta^2r^2 - 2\eta^2b^3e^3r(a-b(c-s)) + 16\eta b^2e^2\left(Er\left(b\eta - \frac{k^2}{2}\right) + \frac{\eta(a-b(c-s))^2}{16}\right) - 16b\eta Ee\left(b\eta - \frac{k^2}{2}\right)(\mu a - b(c-s-t)) + 64E^2\left(b\eta - \frac{k^2}{2}\right)^2}\right)$$

$$\varphi_2 = \frac{b\eta^2\left(b(2s+t-(2-\lambda)er-2c)+a(\mu+1)\right)\left(b(\lambda er+t)+a(\mu-1)\right)}{(4b\eta-k^2)^2},$$

$$\lambda_2 = \frac{1}{\eta b^2 e^2 r}\left(b^2\eta e(er+c-s-t) + 4b\eta\left(E - \frac{\mu a e}{4}\right) - Ek^2 - \sqrt{b^4e^4\eta^2r^2 - 2\eta^2b^3e^3r(a-b(c-s)) + 8\eta b^2e^2\left(Er\left(b\eta - \frac{k^2}{4}\right) + \frac{\eta(a-b(c-s))^2}{8}\right) - 8b\eta Ee\left(b\eta - \frac{k^2}{4}\right)(\mu a - b(c-s-t)) + 16E^2\left(b\eta - \frac{k^2}{4}\right)^2}\right)$$

Proposition 3 compares the optimal profits of both suppliers and green manufacturers under different subsidy policies. It is found that only by setting appropriate compliance costs, the profits of suppliers after compliance can be greater than those before compliance, and the compliance cost thresholds under supplier and green manufacturer domination are φ_1 and φ_2, respectively, which are positively related to the market expansion coefficient and carbon reduction rate. $\varphi_1 > \varphi_2$ indicates that the compliance cost threshold is lower under green manufacturer domination. Meanwhile, the carbon reduction rate needs to be greater than a certain threshold for the profit of green manufacturers under the conditional subsidy to be greater than the basic subsidy, and thresholds of the carbon reduction rate under supplier and green manufacturer domination are λ_1 and λ_2, respectively. Therefore, the compliance cost is reasonably set to meet a certain carbon reduction rate for procurement in the park for the conditional subsidy policy to effectively promote industrial agglomeration and green development.

Proposition 4 $w_S^{SD*} > w_S^{D*}, w_S^{ST*} > w_S^{T*}$; $g_M^{SD*} > g_M^{D*}, g_M^{ST*} > g_M^{T*}$; $q^{SD*} > q^{D*}, q^{ST*} > q^{T*}$; $0 < k < k_1, p_M^{SD*} < p_M^{D*}, k_1 < k < \sqrt{2b\eta}, p_M^{SD*} > p_M^{D*}$; $0 < k < k_2, p_M^{ST*} < p_M^{T*}, k_2 < k < \sqrt{2b\eta}, p_M^{ST*} > p_M^{T*}$;

where $k_1 = \sqrt{b\eta\big(b(er\lambda + t) + a(3\mu - 1)\big)}$, $k_2 = \sqrt{\eta\big(b(er\lambda + t) + a(3\mu - 1)\big)}$.

Proposition 4 shows that the optimal wholesale price, greenness, market demand and supplier profit are higher under the conditional subsidy policy than under the basic subsidy. When consumer green preferences are low, the conditional subsidy policy will make green manufacturers reduce retail prices voluntarily, and green manufacturers who receive more subsidies choose to give profits to consumers; while when green preferences are high, the retail prices of green manufacturers under conditional subsidies are higher than under a single subsidy, indicating that consumers care more about the greenness of products at this time, and their acceptance of prices increases accordingly.

Proposition 5 $\frac{\partial w_S^j}{\partial(s+t)} > 0$; $\frac{\partial w_S^j}{\partial\mu} > 0$; $\frac{\partial w_S^j}{\partial\lambda} > 0$; $\frac{\partial g_M^j}{\partial(s+t)} > 0$; $\frac{\partial g_M^j}{\partial\mu} > 0$; $\frac{\partial g_M^j}{\partial\lambda} > 0$; $\frac{\partial \Pi_S^j}{\partial(s+t)} > 0$; $\frac{\partial \Pi_S^j}{\partial\mu} > 0$; $\frac{\partial \Pi_S^j}{\partial\lambda} > 0$; $\frac{\partial \Pi_M^j}{\partial(s+t)} > 0$; $\frac{\partial \Pi_M^j}{\partial\mu} > 0$; $\frac{\partial \Pi_M^j}{\partial\lambda} > 0$; $\frac{\partial p_M^j}{\partial\mu} > 0$; $0 < k < \sqrt{b\eta}, \frac{\partial p_M^j}{\partial\lambda} < 0, \frac{\partial p_M^j}{\partial(s+t)} < 0, \sqrt{b\eta} < k < \sqrt{2b\eta}, \frac{\partial p_M^j}{\partial\lambda} > 0, \frac{\partial p_M^j}{\partial(s+t)} > 0$, where $j = SD, ST$.

From Proposition 5, we know that under the conditional subsidy policy, wholesale price, greenness and profit of each firm are incremental functions of government conditional subsidy, market increase coefficient and carbon reduction coefficient, and retail price is an incremental function of market increase coefficient. When consumer green preference is low, the retail price of green manufacturers is a decreasing function of the emission reduction rate and the government conditional subsidy; when consumer green preference is high, the retail price of green manufacturers is an increasing function of the emission reduction rate and the government subsidy. Combined with Proposition 2, the green manufacturer will transfer part of the carbon emission cost to the supplier, and the supplier increases the wholesale price to maintain its own profit; the strength of the government conditional subsidy, the expansion of market demand can offset part of the negative effect of the increase of carbon emission cost, and the supplier tends to obtain the government compliance qualification; and the direct-selling green manufacturer is in the downstream of the supply chain, the consumer green preference has a more sensitive impact on the green manufacturer's pricing The impact of consumer green preferences is more sensitive to the pricing decisions of green manufacturers, and green manufacturers can use carbon allowances more rationally to obtain higher returns.

4.2. Supply Chain Coordination Strategy based on Revenue Sharing Contract

According to the above proposition, it is known that the profit of each firm in the supply chain under situation SD is higher than other models, but the double marginal effect due to decentralized decision making often makes the overall supply chain revenue not yet achieved a Pareto optimum. Cooperation among supply chain members can improve the overall revenue and environmental benefits [25]. Therefore, based on the case SD, we developed a revenue sharing contract following the settings in studies [26, 27]. Our goal is to guide decentralized

ISSN: 2688-9323

decision making to reach the level of centralized decision making and achieve supply chain coordination. The revenue sharing contract (θ, τ) coordination mechanism is as follows: the green manufacturer bears θ proportion of the carbon emission cost and green R&D cost, and the rest $(1-\theta)$ is borne by the compliant supplier; meanwhile, the green manufacturer transfers $(1-\tau)p$ of the sales revenue to the compliant supplier after selling the product, where $0<\theta,\tau<1$. In this paper, the superscripts SC and SH are used to denote the centralized decision making scenario under conditional subsidies and supplier-led contractual coordination case, and the profit functions of the compliant supplier and the green manufacturer in the SH case can be denoted as:

$$\underset{w}{\text{Max}}\, \Pi_S^{SH} = \left((1-\tau)p + w - c\right)(\mu a - bp + kg) - \varphi - (1-\theta)\left((r(1-\lambda)(e(\mu a - bp + kg) - E) + \frac{\eta g^2}{2}\right) \tag{5}$$

$$\underset{p,g}{\max}\, \Pi_M^{SH} = (\tau p - w + s + t)(\mu a - bp + kg) - \theta\left(r(1-\lambda)(e(\mu a - bp + kg) - E) + \frac{\eta g^2}{2}\right) \tag{6}$$

Proposition 6 $\frac{4Er(\lambda-1)\mathrm{X}^2+\eta(b\mathrm{N}+\mu a)^2\left(4b\eta\left(\tau-\frac{1}{2}\right)+k^2\right)}{4Er(\lambda-1)\mathrm{X}^2+2k^2\eta(b\mathrm{N}+\mu a)^2} < \theta < \frac{8Er(\lambda-1)\mathrm{X}^2+\eta(b\mathrm{N}+\mu a)^2\left(8b\eta\left(\tau-\frac{1}{4}\right)+k^2\right)}{8Er(\lambda-1)\mathrm{X}^2+4k^2\eta(b\mathrm{N}+\mu a)^2}$; $\frac{8Er(1-\lambda)\mathrm{X}^2(1-\theta)+k^2\eta(b\mathrm{N}+\mu a)^2(4\theta-1)+2b\eta^2(b\mathrm{N}+\mu a)^2}{8b\eta^2(b\mathrm{N}+\mu a)^2} < \tau < \frac{4Er(1-\lambda)\mathrm{X}^2(1-\theta)+k^2\eta(b\mathrm{N}+\mu a)^2(2\theta-1)+2b\eta^2(b\mathrm{N}+\mu a)^2}{4b\eta^2(b\mathrm{N}+\mu a)^2}$, $p_M^{SH*} = p_M^{SC*}, g_M^{SH*} = g_M^{SC*}, \Pi_S^{SH*} = \Pi_S^{SC*} > \Pi_S^{SD*}, \Pi_M^{SH*} = \Pi_M^{SC*} > \Pi_M^{SD*}$.

Proposition 6 shows that when the parameters θ,τ of the revenue sharing contract satisfy certain conditions, the retail price and greenness of the product under the coordinated contract are equal to the optimal results under the centralized decision. The profits of both the compliant supplier and the green manufacturer are improved more after the introduction of the contract, and the overall profit of the supply chain is equal to the level at the centralized decision, indicating that the contract can effectively coordinate the green supply chain under the decentralized decision and eliminate the double marginal effect.

Proposition 7 $\frac{\partial \Pi_S^{SH*}}{\partial \theta} < 0, \frac{\partial \Pi_S^{SH*}}{\partial \tau} < 0, \frac{\partial \Pi_M^{SH*}}{\partial \theta} > 0, \frac{\partial \Pi_M^{SH*}}{\partial \tau} > 0.$

Proposition 7 shows that in the process of introducing a revenue sharing contract to coordinate the supply chain, the compliant supplier and the green manufacturer can decide the distribution of supply chain profits by adjusting the values of the contract parameters, and as the contract parameters θ,τ increase, the profits of the compliant supplier decrease while the profits of the green manufacturer increase.

5. Numerical Simulation Results

Considering that the expressions in the above model are complex and have many parameters, this section will use Matlab and Maple software to conduct numerical simulations to further analyze the above theoretical results. Combining with the assumptions proposed before in this paper, let $a=100, b=1, c=20, k=2, \eta=10, e=0.01, \lambda=0.36, E=1000, r=35, s=10, t=20, \mu=5, \varphi=2000$.

5.1. Analysis of the Effect of Government-given Carbon Quota Amount on Supply Chain Profit in Different Scenarios

Figure 2 shows that under the basic subsidy, the power structure has little effect on the overall profit of green supply chain; under the conditional subsidy policy, the overall profit of supply chain under supplier-led is higher than that of manufacturer-led. The overall profit of the supply chain under the conditional subsidy policy is significantly higher than that of the basic subsidy, achieving economies of scale. As the amount of carbon quota increases, the overall

ISSN: 2688-9323

profit gap between the two subsidy policies becomes smaller, which is caused by the tradable nature of carbon quota.

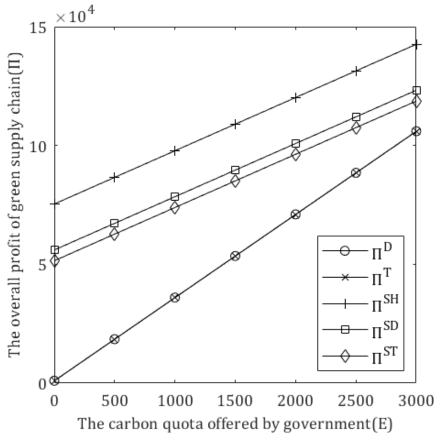

Figure 2. Effect of government-given carbon quotas on the overall profit of green supply chain

5.2. Analysis of the Impact of Government Subsidy Policy on the Greenness of Products, Market Demand and Profit under Different Scenarios

The conditional subsidy policy mainly involves several variables such as potential market demand increase factor, compliance cost, emission reduction rate, and conditional subsidy. In this section, the impact of each of these variables on profits is analyzed.

Figure 3-8 shows that after the implementation of the conditional subsidy policy, the greenness of the product, the market demand for green products and the market potential demand increase coefficient. The emission reduction rate and the conditional subsidy are positively proportional, and the implementation of the conditional subsidy policy can provide consumers with products with higher greenness, expand the scale of market demand, and promote the development of the local green economy.

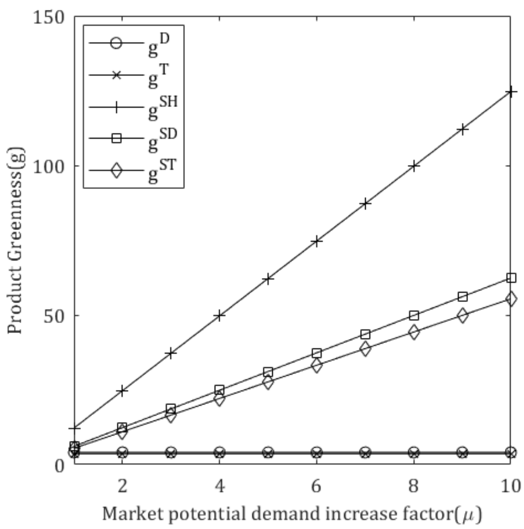

Figure 3. Effect of potential market demand increase factor on greenness of products

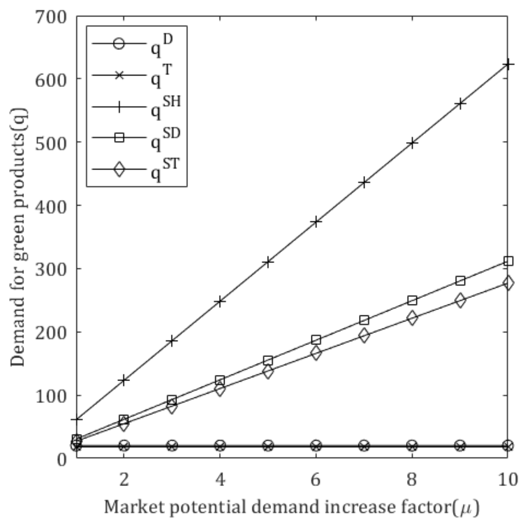

Figure 4. Effect of market potential demand increase factor on the market demand of green products

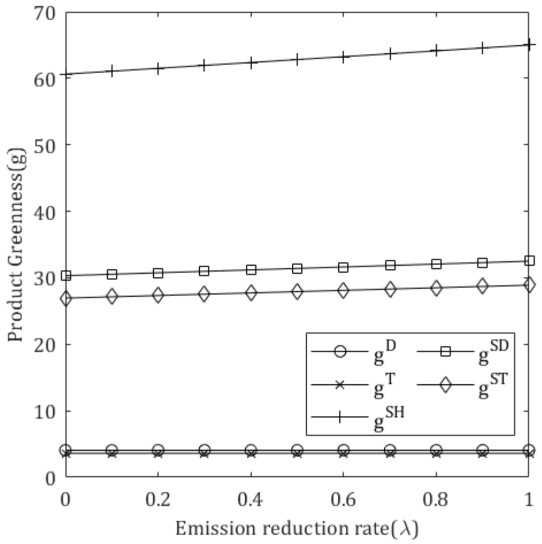

Figure 5. Effect of emission reduction rate on greenness of products

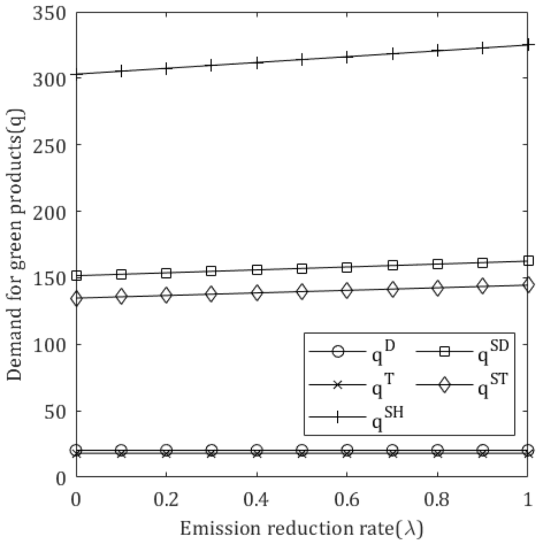

Figure 6. Effect of emission reduction rate on market demand for green products

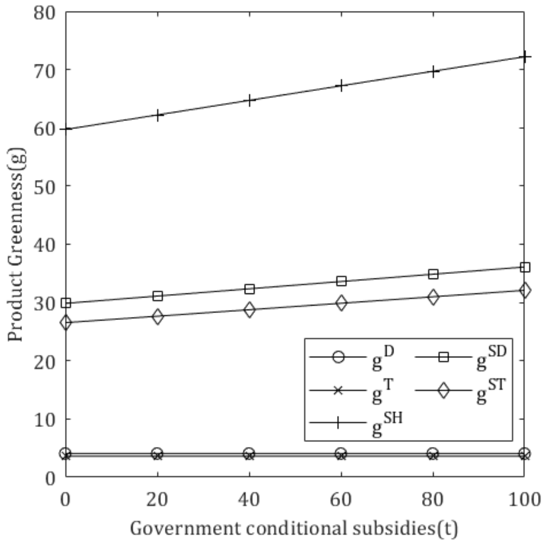

Figure 7. Effect of government conditional subsidies on the greenness of the product

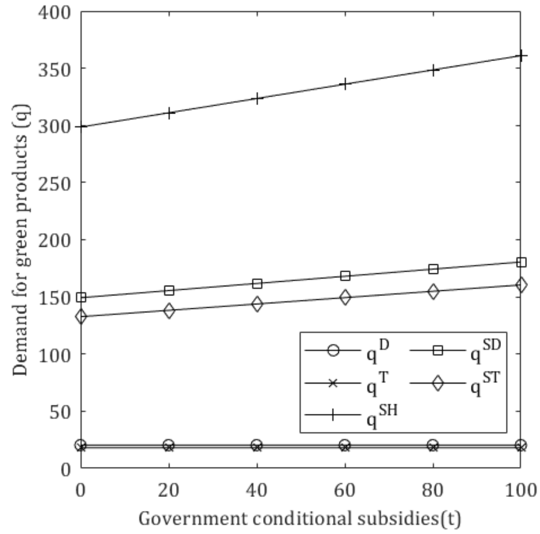

Figure 8. Effect of government conditional subsidies on the market demand for green products

Figures 9-11 show that the coefficient of increase in potential market demand for green products μ and supplier compliance cost φ need to meet certain conditions before suppliers are willing to enter the park to become compliant suppliers, which is consistent with Proposition 3. The profit of suppliers increases with the increase of conditional subsidies, which achieves the government's purpose of implementing conditional subsidy policies to promote local economic development.

Figure 12 shows that the overall profit of green supply chain under conditional subsidy is significantly higher than the basic subsidy regardless of who is the dominant player, suppliers and green manufacturers are motivated to accept the conditional subsidy policy, and the overall profit increases with the increase of conditional subsidy intensity.

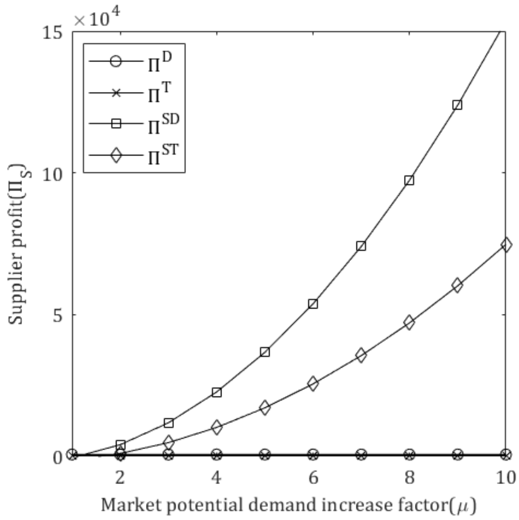

Figure 9. Effect of potential market demand increase factor on supplier profit

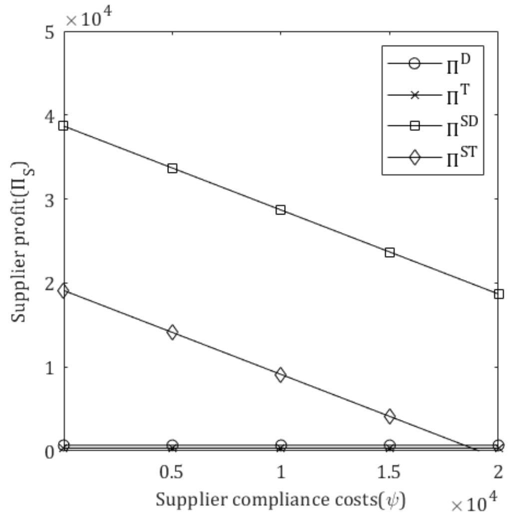

Figure 10. Impact of supplier compliance cost on supplier profit

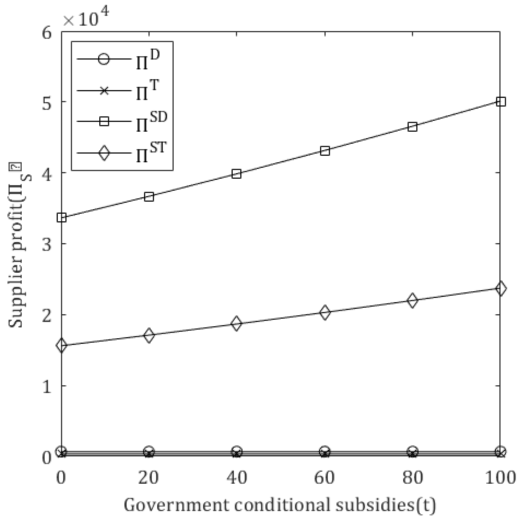

Figure 11. Impact of government conditional subsidies on supplier profits

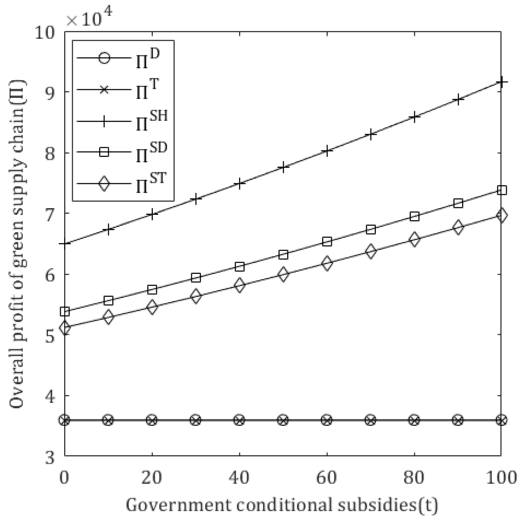

Figure 12. Impact of government conditional subsidies on overall profit of green supply chain

5.3. Analysis of the Impact of Introducing Revenue Sharing Contracts on Supply Chain Profits

Figure 3-8 and Figure 12 show that after the introduction of revenue sharing contract, the greenness of the product, the market demand for green products and the overall profit of green supply have increased significantly compared with the previous, indicating that the revenue sharing contract can eliminate the double marginal effect caused by decentralized decision making, which is consistent with the content of Proposition 6.

Figure 13 gives the range of values of contract parameters θ and τ (the shaded SH part) when the profits of the compliant supplier and green manufacturer are improved respectively in the SH case. Figures 15 and 16 show the profit changes of the compliant supplier and the green manufacturer in the SH case, respectively, the dark gray is the profit of the supplier and the green manufacturer before the introduction of the contract, and the light gray is the profit after the introduction of the contract. From Figures 14 and 15, it can be seen that with the increase of the contract parameters θ and τ, the profit of the green manufacturer tends to increase while the profit of the compliant supplier tends to decrease, which is consistent with Proposition 7.

ISSN: 2688-9323

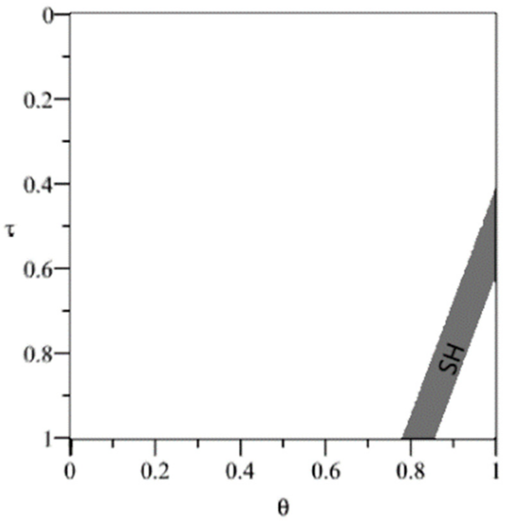

Figure 13. Range of contract parameters when revenue sharing contract is effective

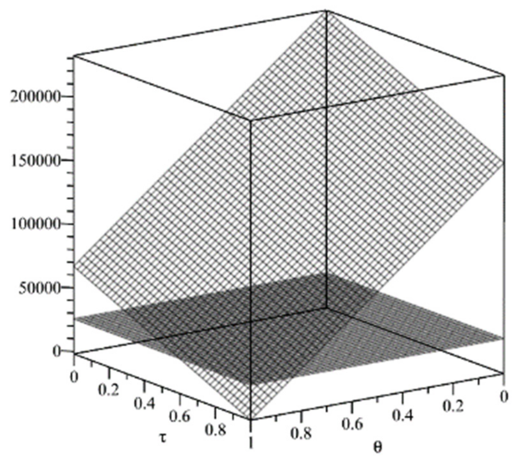

Figure 14. Profit of suppliers before and after the introduction of the covenant

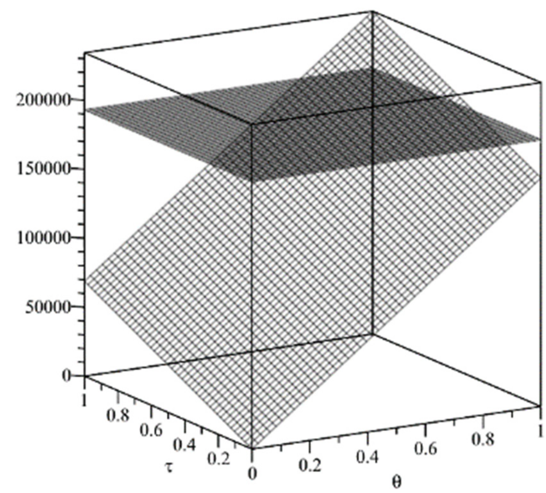

Figure 15. Profit of the green manufacturer before and after the introduction of the covenant

6. Conclusion

In this paper, we analyze the effects of the power structure of enterprises and different subsidy policies on the decision making of green supply chain members, profits, and industrial clusters under the assumptions of carbon quota constraint and different government subsidy policies by constructing a two-stage game model. We found that the greenness of products is higher in the supplier-dominated Stackelberg game than in the manufacturer-dominated game, and the emergence of a "buyer's market" will increase the greenness of products. Furthermore, the government's conditional subsidy policy promotes industrial clusters, provides products with high greenness, expands domestic demand for green products, and promotes the development of a clean and low-energy economy. Finally, green supply chains achieve win-win situation by introducing revenue-sharing contracts for deeper cooperation and maximizing industrial clustering effect.

In the future, the incomplete information as well as the behavior of risk avoidance and reciprocal preference of enterprises can be incorporated into the model. Furthermore, the situation that green products will generate secondary sales of carbon credits has not yet been considered, however, some new energy vehicle manufacturers have already gained considerable revenue by selling carbon in reality. This will be the next step of research.

References

[1] J.X. Chen, J .Chen: Supply chain carbon footprinting and responsibility allocation under emission regulations (Journal of Environmental Management), Vol.188 (2017), p.255-267.

[2] A. Rajeev, R.K. Pati, S.S. Padhi, et al: Evolution of sustainability in supply chain management: A literature review (Journal of Cleaner Production), Vol.162 (2017), p.299-314.

[3] C . Wang, J. Lin, W. J. Cai, et al: China's carbon mitigation strategies: Enough? (Energy Policy), Vol.73 (2014), p.47-56.

[4] F. Dong, Y.F. Hua, B.L. Yu: Peak Carbon Emissions in China: Status, Key Factors and Countermeasures-A Literature Review (Sustainability), Vol.10 (2018) No.8,p.34.

[5] W.J. Yang, R.Q. Zhao, X.W. Chuai, et al: China's pathway to a low carbon economy (Carbon Balance and Management), Vol.14 (2019) No.1, p.12.

[6] C.N. Zou, B. Xiong, H.Q. Xue, et al: The role of new energy in carbon neutral (Petroleum Exploration and Development), Vol.48 (2021) No.2, p.480-491.

[7] R.Q. Geng, A. Mansouri, E. Aktas: The relationship between green supply chain management and performance: A meta-analysis of empirical evidences in Asian emerging economies (International Journal of Production Economics), Vol.183 (2017), p.245-258.

[8] Y. Parag, S. Darby: Consumer–supplier–government triangular relations: Rethinking the UK policy path for carbon emissions reduction from the UK residential sector (Energy Policy),Vol.37 (2009) No.10, p.3984-3992.

[9] J.B. Sheu, Y.M.J. Chen: Impact of government financial intervention on competition among green supply chains (International Journal of Production Economics), Vol.138 (2012) No.1, p.201-213.

[10] Y.T. Ma, X.L. Shi, Y. Qiu: Pricing, quality level and greening decisions for green and non-green products with government interventions (Environmental Engineering and Management Journal), Vol.19 (2020) No.8, p.1379-1387.

[11] Cohen M C, Lobel R, Perakis G. The Impact of Demand Uncertainty on Consumer Subsidies for Green Technology Adoption [J]. Management Science, 2016, 62(5): 1235-1258.

[12] Q.C. Meng, Y.T. Wang, Z. Zhang, et al: Supply chain green innovation subsidy strategy considering consumer heterogeneity (Journal of Cleaner Production), Vol.281 (2021) p.16.

[13] A. Hafezalkotob: Direct and indirect intervention schemas of government in the competition between green and non-green supply chains (Journal of Cleaner Production), Vol.170 (2018), p.753-772.

[14] Meng Q F, Li M W, Liu W Y, et al. Pricing policies of dual-channel green supply chain: Considering government subsidies and consumers' dual preferences (Sustainable Production and Consumption), Vol.26 (2021), p.1021-1030.

[15] J. Li, W.H. Du, F.M. Yang, et al: The Carbon Subsidy Analysis in Remanufacturing Closed-Loop Supply Chain (Sustainability), Vol.6 (2014) No.6, p.3861-3877.

[16] C. X. Wang, W. Wang, R.B. Huang: Supply chain enterprise operations and government carbon tax decisions considering carbon emissions (Journal of Cleaner Production), Vol.152 (2017), p.271-280.

[17] Z.M. Li, Y.C. Pan, W. Yang, et al: Effects of government subsidies on green technology investment and green marketing coordination of supply chain under the cap-and-trade mechanism (Energy Economics), Vol.101 (2021), p14.

[18] L. Xu, C.X. Wang, Z. Miao, et al: Governmental subsidy policies and supply chain decisions with carbon emission limit and consumer's environmental awareness (Rairo-Operations Research), Vol.53 (2019) No.5, p.1675-1689.

[19] S.F. Du, W.Z. Tang, M. Song. Low-carbon production with low-carbon premium in cap-and-trade regulation (Journal of Cleaner Production), Vol.134 (2016), p.652-662.

[20] X.P. Xu, P. He, H. Xu, et al: Supply chain coordination with green technology under cap-and-trade regulation (International Journal of Production Economics), Vol.183 (2017), p.433-442.
[21] L. Yang, C.S. Zheng, M.H. Xu: Comparisons of low carbon policies in supply chain coordination (Journal of Systems Science and Systems Engineering), Vol.23 (2014) No.3, p.342-361.
[22] C. Su, X.J. Liu, W.Y. Du: Green Supply Chain Decisions Considering Consumers' Low-Carbon Awareness under Different Government Subsidies (Sustainability), Vol.12 (2020) No.6, p.12.
[23] Z.G. Liu, T.D. Anderson, J.M. Cruz: Consumer environmental awareness and competition in two-stage supply chains (European Journal of Operational Research), Vol.218 (2012) No,3, p.602-613.
[24] J.N. Ji, Z.Y. Zhang, L. Yang: Carbon emission reduction decisions in the retail-/dual-channel supply chain with consumers' preference (Journal of Cleaner Production), Vol.141 (2017), p.852-867.
[25] H.P. Ding, Q.L. Zhao, Z.R. An, et al: Collaborative mechanism of a sustainable supply chain with environmental constraints and carbon caps (International Journal of Production Economics), Vol.181 (2016), p.191-207.
[26] S.F. Du, J. Zhu, H.F. Jiao, et al: Game-theoretical analysis for supply chain with consumer preference to low carbon (International Journal of Production Research), Vol.53 (2015) No.12, p.3753-3768.
[27] H.X. Yang, W.B. Chen: Retailer-driven carbon emission abatement with consumer environmental awareness and carbon tax: Revenue-sharing versus Cost-sharing (Omega-International Journal of Management Science), Vol.78 (2018), p.179-191.

Appendix

Proof of Proposition 1:

$w_S^{D*} - w_S^{T*} = \frac{b(s-er+c)+a}{2b} - \frac{\eta((s+3c-er)b+a)-ck^2}{4b\eta-k^2} = \frac{(2b\eta-k^2)(b(s-er+c)+a)}{2b(4b\eta-k^2)} > 0$;

$g_M^{D*} - g_M^{T*} = \frac{k(b(s-er-c)+a)}{2(2b\eta-k^2)} - \frac{k(a+b(s-er-c))}{4b\eta-k^2} = \frac{k^3(b(s-er-c)+a)}{2(2b\eta-k^2)(4b\eta-k^2)} > 0$; $p_M^{D*} - p_M^{T*} = \frac{b(k^2-b\eta)(s-er-c)+a(3b\eta-k^2)}{2b(2b\eta-k^2)} - \frac{(k^2-b\eta)(s-er-c)+3a\eta}{4b\eta-k^2} = \frac{k^2(k^2-b\eta)(b(s-er-c)+a)}{2(2b\eta-k^2)(4b\eta-k^2)}$.

It is easy to know when $0 < k < \sqrt{b\eta}, p_M^{D*} - p_M^{T*} < 0, \sqrt{b\eta} < k < \sqrt{2b\eta}, p_M^{D*} - p_M^{T*} > 0$; $\Pi_S^{D*} > \Pi_S^{T*} = \frac{\eta(b(s-er-c)+a)^2}{4(2b\eta-k^2)} - \frac{b\eta^2((s-c-er)b+a)^2}{(4b\eta-k^2)^2} = \frac{\eta(b(s-er-c)+a)^2}{4b\eta-k^2} > 0$; $\Pi_M^{D*} - \Pi_M^{T*} = \frac{\eta(b(s-er-c)+a)^2}{8(2b\eta-k^2)} + Er - \frac{\eta(b(s-er-c)+a)^2}{8(4b\eta-k^2)} - Er = \frac{\eta(b(s-er-c)+a)^2(3k^2-4b\eta)}{8(2b\eta-k^2)(4b\eta-k^2)}$. Combined with Eq. (2), when Hesse matrix is negative definite, $2b\eta - k^2 > 0$, it can be derived that when $0 < k < \sqrt{\frac{4b\eta}{3}}, \Pi_M^{D*} < \Pi_M^{T*}, \sqrt{\frac{4b\eta}{3}} < k < \sqrt{2b\eta}, \Pi_M^{D*} > \Pi_M^{T*}$.

Proof of Proposition 2:

$\frac{\partial \Pi_M^{D*}}{\partial E} = r > 0$; $\frac{\partial \Pi_S^{D*}}{\partial er} = \frac{b\eta(b(e+c-s)-a)}{2(2b\eta-k^2)} < 0, \frac{\partial \Pi_M^{D*}}{\partial er} = \frac{b\eta(b(e+c-s)-a)}{2(2b\eta-k^2)} < 0, \frac{\partial w_S^{D*}}{\partial er} = -\frac{r}{2} < 0, \frac{\partial g_M^{D*}}{\partial er} = \frac{-bk}{2(2b\eta-k^2)} < 0$; $\frac{\partial p_M^{D*}}{\partial er} = \frac{b\eta-k^2}{2(2b\eta-k^2)}$. Combined with Eq. (2), when Hesse matrix is negative definite, $2b\eta - k^2 > 0$, it can be derived that when $0 < k < \sqrt{b\eta}$, $\frac{\partial p_M^j}{\partial er} > 0, \sqrt{b\eta} < k < \sqrt{2b\eta}, \frac{\partial p_M^j}{\partial er} < 0$.Proof omission in the T* case.

Proof of Proposition 3:

(1) From$\Pi_S^{SD*} > \Pi_S^{D*}$we get,

$$\varphi < \varphi_1 = \frac{\eta(b(2s+t-(2-\lambda)er-2c)+a(\mu+1))(b(\lambda er+t)+a(\mu-1))}{4(2b\eta-k^2)};$$

From $\Pi_M^{SD*} > \Pi_M^{D*}$we get,

$$\lambda > \lambda_1 = \frac{1}{\eta b^2 e^2 r}(b^2\eta e(er+c-s-t) + 8b\eta\left(E - \frac{\mu a e}{8}\right) - 4Ek^2 - \sqrt{b^4e^4\eta^2r^2 - 2\eta^2b^3e^3r\big(a-b(c-s)\big) + 16\eta b^2e^2\left(Er\left(b\eta - \frac{k^2}{2}\right) + \frac{\eta\big(a-b(c-s)\big)^2}{16}\right) - 16b\eta Ee\left(b\eta - \frac{k^2}{2}\right)\big(\mu a - b(c-s-t)\big) + 64E^2\left(b\eta - \frac{k^2}{2}\right)^2});$$

(2) From $\Pi_S^{ST*} > \Pi_S^{T*}$ we get,

$$\varphi < \varphi_2 = \frac{b\eta^2\big(b(2s+t-(2-\lambda)er-2c)+a(\mu+1)\big)\big(b(\lambda er+t)+a(\mu-1)\big)}{(4b\eta-k^2)^2};$$

From $\Pi_M^{ST*} > \Pi_M^{T*}$ we get:

$$\lambda > \lambda_2 = \frac{1}{\eta b^2 e^2 r}\left(b^2\eta e(er+c-s-t) + 4b\eta\left(E - \frac{\mu a e}{4}\right) - Ek^2 - \sqrt{b^4e^4\eta^2r^2 - 2\eta^2b^3e^3r\big(a-b(c-s)\big) + 8\eta b^2e^2\left(Er\left(b\eta - \frac{k^2}{4}\right) + \frac{\eta\big(a-b(c-s)\big)^2}{8}\right) - 8b\eta Ee\left(b\eta - \frac{k^2}{4}\right)\big(\mu a - b(c-s-t)\big) + 16E^2\left(b\eta - \frac{k^2}{4}\right)^2}\right);$$

Proof of Proposition 4:

Since $\mu > 1, 0 < \lambda < 1, t > 0$, it is easy to know that $w_S^{SD*} > w_S^{D*}, w_S^{ST*} > w_S^{T*}$; $g_M^{SD*} > g_M^{D*}, g_M^{ST*} > g_M^{T*}$; $q^{SD*} > q^{D*}, q^{ST*} > q^{T*}$;

$\Pi_S^{SD*} - \Pi_S^{ST*} = \frac{\eta(b(s+t-(1-\lambda)er-c)+\mu a)^2}{4(2b\eta-k^2)} - \varphi - \frac{b\eta^2\big((s+t-c-(1-\lambda)er)b+\mu a\big)^2}{(4b\eta-k^2)^2} + \varphi = \frac{\eta(b(s+t-(1-\lambda)er-c)+\mu a)^2}{4b\eta-k^2} > 0$;

$p_M^{SD*} - p_M^{D*} = \frac{b(k^2-b\eta)(s+t-(1-\lambda)er-c)+\mu a(3b\eta-k^2)}{2b(2b\eta-k^2)} - \frac{b(k^2-b\eta)(s-er-c)+a(3b\eta-k^2)}{2b(2b\eta-k^2)} = \frac{b(k^2-b\eta)(\lambda er+t)+a(\mu-1)(3b\eta-k^2)}{2b(2b\eta-k^2)}$, it can be easily derived that when $0 < k < k_1 = \sqrt{b\eta\big(b(er\lambda+t)+a(3\mu-1)\big)}$, $p_M^{SD*} < p_M^{D*}$, and when $k_1 < k < \sqrt{2b\eta}$, $p_M^{SD*} > p_M^{D*}$; $p_M^{ST*} - p_M^{T*} = \frac{(k^2-b\eta)(s+t-(1-\lambda)er-c)+3\mu a\eta}{4b\eta-k^2} - \frac{(k^2-b\eta)(s-er-c)+3a\eta}{4b\eta-k^2} = \frac{(k^2-b\eta)(\lambda er+t)+3a\eta(\mu-1)}{4b\eta-k^2}$, it can be easily derived that $0 < k < k_2 = \sqrt{\eta\big(b(er\lambda+t)+a(3\mu-1)\big)}, p_M^{ST*} < p_M^{T*}, k_2 < k < \sqrt{2b\eta}, p_M^{ST*} > p_M^{T*}$.

Proof of Proposition 5:

(1) $\frac{\partial w_S^{SD*}}{\partial(s+t)} = \frac{1}{2} > 0$; $\frac{\partial w_S^{SD*}}{\partial\mu} = \frac{a}{2b} > 0$; $\frac{\partial w_S^{SD*}}{\partial\lambda} = \frac{er}{2} > 0$; $\frac{\partial g_M^{SD*}}{\partial(s+t)} = \frac{kb}{2(2b\eta-k^2)} > 0$; $\frac{\partial g_M^{SD*}}{\partial\mu} = \frac{a}{2(2b\eta-k^2)} > 0$; $\frac{\partial g_M^{SD*}}{\partial\lambda} = \frac{ker}{2(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_S^{SD*}}{\partial(s+t)} = \frac{\eta b(s+t-(1-\lambda)er-c)+\mu a)}{2(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_S^{SD*}}{\partial\mu} = \frac{\eta ab(s+t-(1-\lambda)er-c)+\mu a)}{4(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_S^{SD*}}{\partial\lambda} = \frac{\eta ber(s+t-(1-\lambda)er-c)+\mu a)}{4(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_M^{SD*}}{\partial(s+t)} = \frac{\eta b(s+t-(1-\lambda)er-c)+\mu a)}{4(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_M^{SD*}}{\partial\mu} = \frac{\eta ab(s+t-(1-\lambda)er-c)+\mu a)}{8(2b\eta-k^2)} > 0$; $\frac{\partial \Pi_M^{SD*}}{\partial\lambda} = \frac{\eta ber(s+t-(1-\lambda)er-c)+\mu a)}{4(2b\eta-k^2)} > 0$; $\frac{\partial p_M^{SD*}}{\partial\mu} = \frac{a(3b\eta-k^2)}{2b(2b\eta-k^2)} > 0$;

(2) $\frac{\partial p_M^{SD*}}{\partial\lambda} = \frac{er(k^2-b\eta)}{2(2b\eta-k^2)}, \frac{\partial p_M^j}{\partial(s+t)} = \frac{k^2-b\eta}{2(2b\eta-k^2)}$, it can be easily derived that when $0 < k < \sqrt{b\eta}, \frac{\partial p_M^{SD*}}{\partial\lambda} < 0, \frac{\partial p_M^{SD*}}{\partial(s+t)} < 0, \sqrt{b\eta} < k < \sqrt{2b\eta}, \frac{\partial p_M^{SD*}}{\partial\lambda} > 0, \frac{\partial p_M^{SD*}}{\partial(s+t)} > 0$;

Proof omission in the $j = ST*$ case.

Proof of Proposition 6:

For (6), we find the partial derivatives and let the first order partial derivatives $\frac{\partial \Pi_S^{SH}}{\partial p} = 0, \frac{\partial \Pi_S^{SH}}{\partial g} = 0$, and find the optimal selling price and product greenness as following:

$$p^{SH*} = \frac{(-er(\lambda-1)\theta-s-t+w)b+\tau(a\mu+kg)}{2b\tau}, g^{SH*} = \frac{(er(\lambda-1)\theta+p\tau+s+t-w)k}{\eta\theta}$$

When the selling price and greenness of the product in the decentralized mode are equal to those in the centralized mode, i.e., $p^{SH*} = p^{SC*}, g^{SH*} = g^{SC*}$, the solution to the above equation yields: $w^{SH*} = s + t - \theta(1-\lambda)er - \tau(s + t - c - (1-\lambda)er)$.
Substituting the optimal wholesale price w^{SH*}, the optimal selling pricep^{SH*} and the greenness g^{SH*}into equations (5) and (6) shows that the optimal profits of the supplier and the green manufacturer after introducing the contract to coordinate the supply chain are:

$$\Pi_S^{SH*} = \frac{2Er(1-\lambda)(1-\theta)X^2 + \eta(2(1-\tau)b\eta - (1-\theta)k^2)(bN+\mu a)^2}{2X^2} - \varphi$$

$$\Pi_S^{SH*} = \frac{2Er(1-\lambda)\theta X^2 + \eta(2\tau b\eta - \theta k^2)(bN+\mu a)^2}{2X^2}$$

From the above equation, the total supply chain profit of the green supply chain after the introduction of the contract is $\Pi_{S+M}^{SH*} = \frac{\eta(b\mathrm{N}+\mu a)^2}{2\mathrm{X}^2} + Er(1-\lambda) - \varphi$.
Under the coordination contract, the overall profit of the supply chain is equal to that under centralized decision making. Both parties are willing to accept the contract only if the profits of both suppliers and green manufacturers are improved, i.e., $\Pi_S^{SH*} > \Pi_S^{SD*}, \Pi_M^{SH*} > \Pi_M^{SD*}$, and thus the respective comparisons yield:

$$\frac{4Er(\lambda-1)\mathrm{X}^2+\eta(b\mathrm{N}+\mu a)^2\left(4b\eta\left(\tau-\frac{1}{2}\right)+k^2\right)}{4Er(\lambda-1)\mathrm{X}^2+2k^2\eta(b\mathrm{N}+\mu a)^2} < \theta < \frac{8Er(\lambda-1)\mathrm{X}^2+\eta(b\mathrm{N}+\mu a)^2\left(8b\eta\left(\tau-\frac{1}{4}\right)+k^2\right)}{8Er(\lambda-1)\mathrm{X}^2+4k^2\eta(b\mathrm{N}+\mu a)^2}, \frac{8Er(1-\lambda)\mathrm{X}^2(1-\theta)+k^2\eta(b\mathrm{N}+\mu a)^2(4\theta-1)+2b\eta^2(b\mathrm{N}+\mu a)^2}{8b\eta^2(b\mathrm{N}+\mu a)^2} < \tau < \frac{4Er(1-\lambda)\mathrm{X}^2(1-\theta)+k^2\eta(b\mathrm{N}+\mu a)^2(2\theta-1)+2b\eta^2(b\mathrm{N}+\mu a)^2}{4b\eta^2(b\mathrm{N}+\mu a)^2}$$

When θ, τ satisfies the above conditions, the profits of both the compliant supplier and the green manufacturer are improved after the introduction of the contract compared to the absence of the contract.

Proof of Proposition 7:

$$\frac{\partial \Pi_S^{SH*}}{\partial \tau} = -\frac{k^2\eta(b\mathrm{N}+\mu a)^2}{2\mathrm{X}^2} - Er(1-\lambda) < 0; \frac{\partial \Pi_S^{SH*}}{\partial \tau} = -2b\eta^2(b\mathrm{N}+\mu a)^2 < 0; \frac{\partial \Pi_M^{SH*}}{\partial \tau} = \frac{k^2\eta(b\mathrm{N}+\mu a)^2}{2\mathrm{X}^2} + Er(1-\lambda) > 0; \frac{\partial \Pi_M^{SH*}}{\partial \tau} = 2b\eta^2(b\mathrm{N}+\mu a)^2 > 0.$$