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A Decision-Making Model of Low-Carbon Supply Chain Based on Government Subsidy

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Abstract

In order to study the role of government subsidy in a low-carbon supply chain, a two-stage game model for the subsidy of low-carbon technology and the subsidy of recycling is built. And the optimized subsidy strategy under the two kinds of subsidy policies is obtained. This paper also studies the impacts of carbon emission abatement, subsidy and the factors of subsidy on the supply chain and the government, so as to compare the two kinds of subsidy strategy. This study shows that the coefficient of environmental benefits has a positive impact on the two kinds of subsidy. The subsidy can stimulate the carbon emission abatement, and the fixed cost has a negative impact on the will of the carbon emission abatement for the enterprises. Besides, the low-carbon preference of the consumers has a positive impact on the carbon emission abatement under the subsidy of low-carbon technology. Furthermore, the government under takes the main costs of the low-carbon technology under the subsidy of low-carbon technology. The environmental benefit also has a positive impact on the subsidy and profits of the government and the profits of the supply chain under the recycling subsidy. Both kinds of subsidy strategies can achieve supply chain coordination.

Keywords: supply chain, government subsidy, low-carbon technology, recycling, game theory

1. Introduction

The problems of climate and energy have greatly attracted the attention of the international community. The increasingly stringent international environmental laws, such as the United Nations Framework Convention on Climate Change and the Kyoto Protocol, have made the government, enterprises, and consumers pay more attention to low carbon. However, because of the externality of low carbon, the low-carbon strategies of enterprises driven by the market might not be the best one, and varied strategies of the government are needed to promote the investment of enterprises. Subsidies are more positive compared to restrictive policies, such as carbon tax, carbon emissions trading.

Technical innovation is the core of achieving low-carbon society, so the investment of technology must be sustained and large-scale. Meanwhile, invest in technology can be very risky, so the investment is costly currently. Wang (2011) pointed out that fund shortage has severely restricted the development of low-carbon technology, so the improvement of subsidy system is vital and impending. Zhou (2011) pointed out government policies had significant impacts on the technological innovation of low-carbon technology. And investments from the government subsidy plans on the creation of low-carbon technology innovation platforms and the commercial applications of the achievement can push the developments of the low-carbon technology. Fang (2012) studied a three-stage game model of the government and a duopoly supply chain, and respectively analyzed the impact of government's subsiding enterprises' R&D and product innovation on research investment and social welfare. Meng (2010) also analyzed the impact of subsidy on the carbon emission reduction and social welfare under different emission taxes.

Recycling has made forward supply chains convert to closed-loop supply chains. Sameek et al. (2006) showed that closed-loop supply chains could have the impact of energy saving and emission reduction on environmental protection and resource utilization. Karine et al. (2006) pointed out that closed-loop supply chains could be regarded as an effective carrier to promote the development of low-carbon economy, with the development of low carbon concept and sustainability awareness, and many countries and research institutions had greatly supported closed-loop supply chains. Zhu et al. (2010) studied the efficient of recycling under government subsidy, and found the enterprise's maximum return rate when the government was to maximize, meanwhile the subsidy had positive impact on the profits of enterprises in the supply chains. Zhou et al. (2011) built a two-echelon supply chain model and found the conclusion that recycling subsidy had positive effect on the profits of enterprises in the supply chain, return rates and carbon emissions.

Most of existing literatures had separately studied the impact of low-carbon-technology subsidy on enterprise profits, emission reduction and the impact of recycling subsidy on return rate and enterprise profits. However, there are few literatures which have compared the two kinds of subsidies, and study their factors and influences. Herein, in this paper, we will concentrate on analyzing the decision of the government and the companies in the supply chain, under the two kinds of subsidy strategies. This paper includes three main parts: (1) the factors which would affect low-carbon-technology subsidy, recycling subsidy and carbon abatement; (2) the impact of the low-carbon-technology subsidy and recycling subsidy on low-carbon efficiency and profits of the government and enterprises in the supply chain; (3) the differences of the impacts which low-carbon-technology subsidy and recycling subsidy have on the supply chain and government administration. Based on the study above, this paper may provide some helpful suggestions for supply chain's decision of investment in low-carbon technology, the decision of recycling and government subsidy strategies.

2. Supply Chain Decision-Making Model under Government Subsidy Strategy

2.1 Problem Description and Parameters

This paper considers a two-echelon supply chain which consists of one manufacturer and one retailer. And the manufacturer and retailer have an equal partnership. The manufacturer generates carbon emissions during the production, and the retailer generates carbon emissions during the circulation of products. The enterprises can abate carbon emissions by investing in low-carbon technology and recycling. Both low-carbon technology and recycling will have a strong effect on enterprises' costs and profits. The government would give proper subsidies to encourage the enterprises in carbon abatement.

By building the model of low-carbon technology investment and the model of recycling, under government subsidy, this paper studied the optimized subsidy strategy and carbon-abating strategy. So, a two-echelon game model under two ways of carbon abatement is built, and the model includes: (1) the government makes the subsidy policy at the first stage; (2) the enterprises in the supply chain make the decision of carbon abatement. The major notations in our following model are summarized in Table 1.

Table 1. Model parameters and the definitions

Parameters	definitions
w	The unit wholesale price of products charged by the manufacturer
p	Retail price per unit of product
C	Unit production cost of the manufacturer of product
D	Demand of market d
Π_m,Π_r,Π_g	Expected profits of the retailer, manufacturer and the supply chain
CO_m,CO_r	Carbon emissions of the retailer and manufacturer per product
C_m,C_r	Costs of carbon abatement for the retailer and manufacturer cost coefficient of low-carbon technology
ΔD	Change in demands when consumers have low-carbon preference
δ	Raise coefficient of demands when products are low-carbon
θ_m,θ_r	Emission reduction rates of retailer and manufacturer per product
α,β	Impact factors of retailer and manufacturer's investment in low-carbon product
λ_m,λ_r	Subsidy rates which the government invest in retailer and manufacturer's low-carbon technology
RF	Environmental profits coefficient of enterprise's investment in carbon abatement
A	Fixed costs of recycling
τ	Rate of recycling
e	Cost coefficient of recycling
s	Subsidy coefficient of recycling
ΔE	Changes in carbon emissions of one product
p_1	Unit price at which the retailer buys recycling products from the consumers
w_1	Unit wholesale price at which the manufacturer buys recycling products from the retailer
c_{mr}	Unit cost of remanufacturerd products
ξ	Carbon emission of one remanufacturerd product during the remanufacturing process

2.2 Supply Chain Decision-Making Model under Low-Carbon-Technology Subsidy

2.2.1 Model Assumptions

Assumption 1. Low-carbon products and traditional products are substitutable.

Assumption 2. Low-carbon technology needs the investment of technology and equipment. According to previous literatures about R&D, in this paper, we assume that Costs of low-carbon technology have a quadratic functional relationship between the emission reduction rates of retailer and manufacturer, and the functions are as follows:

$$C_m = \frac{1}{2}\gamma\theta_m^{\ 2} \ C_r = \frac{1}{2}\gamma\theta_r^{\ 2}$$

The γ in the functions above is cost coefficient of low-carbon technology, and represents the difficulty level of low-carbon technology. θ_m, θ_r are respectively the emission reduction rates of manufacturer and retailer, and $0 \leq \theta_m < 1$, $0 \leq \theta_r < 1$. So the total change in carbon emission is:

$$\Delta E = (\theta_m CO_m + \theta_r CO_r)D$$

Assumption 3. Consumers have the preference of low carbon, and low-carbon products have bigger market demand. So the sales amount of the products consists of two main parts, i.e., the original demand D and the change in demand ΔD.

$$\Delta D = \delta C_m^{\ \alpha} C_r^{\ \beta}$$

In the functions above, δ represents the raise of demands when products are low-carbon, and it reflects consumers' preference of low carbon. The α, β are factors which measure how retailer and manufacturer's investment in low-carbon technology affect products' low carbonization, and $0<\alpha<0.5$, $0<\beta<0.5$.

Assumption 4. The manufacturer and retailer have an equal partnership. There is exists information symmetry in the three parties of the manufacturer, retailer and government, i.e., the government knows the supply chain's investment in low carbonization. The government gives proper subsidies to the manufacturer and retailer for the expenditure of low carbon, and the subsidy coefficients are λ_m, λ_r respectively.

Assumption 5. The manufacturer supply products according to the maximum demand D+ΔD.

2.2.2 Modeling and Analysis

Base on the above description and assumptions, the supply chain optimization model under low-carbon-technology subsidy is built. In the model, the government gives proper subsidies to the manufacturer and retailer for the expenditure of low carbon, and the subsidy coefficients are λ_m, λ_r respectively. θ_m, θ_r are decision variable, and objective functions are the enterprises in the supply chain and the government's profits.

1) Profit function of the manufacturer

The profit of the manufacturer includes the income from selling products to the retailer, $w(D + \Delta D)$, and government's subsidy $\lambda_m C_m$. The cost of the manufacturer includes production cost, $c(D + \Delta D)$, and the investment in low-carbon technology, C_m. So the profit function can be described as the formula (1).

$$\begin{aligned}\Pi_m &= (w-c)(D+\Delta D) - C_m + \lambda_m C_m \\ &= (w-c)(D + \delta C_m^{\ \alpha} C_r^{\ \beta}) - C_m + \lambda_m C_m \\ &= (w-c)[D + \delta(\frac{1}{2}\gamma\theta_m^{\ 2})^{\alpha}(\frac{1}{2}\gamma\theta_r^{\ 2})^{\beta})] - \frac{1}{2}\gamma\theta_m^{\ 2} + \frac{1}{2}\gamma\theta_m^{\ 2}\lambda_m\end{aligned} \tag{1}$$

2) Profit function of the retailer

The profit of the retailer includes the income from selling products to the consumers, $p(D + \Delta D)$, and government subsidy $\lambda_r C_r$. The costs of the retailer includes cost of purchasing products from the manufacturer, $w(D + \Delta D)$, and the investment in low-carbon technology, C_r. So the profit function of the retailer is as the formula (2).

$$\begin{aligned}\Pi_r &= (p-w)(D+\Delta D) - C_r + \lambda_r C_r \\ &= (p-w)(D+\delta C_m^{\alpha} C_r^{\beta}) - C_r + \lambda_r C_r \\ &= (p-w)[D+\delta(\frac{1}{2}\gamma\theta_m^2)^{\alpha}(\frac{1}{2}\gamma\theta_r^2)^{\beta}] - \frac{1}{2}\gamma\theta_r^2 + \frac{1}{2}\gamma\theta_r^2\lambda_r\end{aligned} \tag{2}$$

3) Profit function of the government

The profit of the government includes environmental benefits from the enterprises' investment in low carbon, (C_m+ C_r) RF, and total profit of the supply chain, $\Pi_m+\Pi_r$. The cost of government is the subsidy for low-carbon technology, $\lambda_m C_m+\lambda_r C_r$. So the profit function of government is as the formula (3).

$$\begin{aligned}\Pi_g &= (C_m + C_r)RF + \Pi_m + \Pi_r - \lambda_m C_m - \lambda_r C_r \\ &= (\frac{1}{2}\gamma\theta_m^2 + \frac{1}{2}\gamma\theta_r^2)(RF-1) + (p-c)[D+\delta(\frac{1}{2}\gamma\theta_m^2)^{\alpha}(\frac{1}{2}\gamma\theta_r^2)^{\beta}]\end{aligned} \tag{3}$$

In the above formula, RF represents the environmental profits coefficient of enterprise's investment in carbon abatement, and 0<RF<1.

Proposition 1. On the condition of 0<RF<1，0<α,β<0.5, there exists the unique equilibrium solution of subsidy rates which the government invest in enterprises and emission reduction rates of enterprises, λ_m^*, λ_r^*, θ_m^*, θ_r^*, as follows.

$$\lambda_m^* = 1 - \alpha(w-c)\left[\frac{(1-RF)(1-\alpha-\beta)}{(1-2\alpha)(p-c)}\right]^{\frac{1}{1-\alpha-\beta}}$$

$$\lambda_r^* = 1 - \beta(p-w)\left[\frac{(1-RF)(1-\alpha-\beta)}{(1-2\beta)(p-c)}\right]^{\frac{1}{1-\alpha-\beta}}$$

$$\theta_m^* = \sqrt{\frac{2}{\gamma}\delta^{\frac{1}{2(1-\alpha-\beta)}}\left[\frac{\alpha(w-c)}{1-\lambda_m}\right]^{\frac{1-\beta}{2(1-\alpha-\beta)}}\left[\frac{\beta(p-w)}{1-\lambda_r}\right]^{\frac{\beta}{2(1-\alpha-\beta)}}}$$

$$\theta_r^* = \sqrt{\frac{2}{\gamma}\delta^{\frac{1}{2(1-\alpha-\beta)}}\left[\frac{\alpha(w-c)}{1-\lambda_m}\right]^{\frac{\alpha}{2(1-\alpha-\beta)}}\left[\frac{\beta(p-w)}{1-\lambda_r}\right]^{\frac{1-\alpha}{2(1-\alpha-\beta)}}}$$

Proof of Proposition 1. Using the method of inverse solution, in the second stage of the game, the government has set the subsidy rate, and both the manufacturer and retailer try to maximize their own benefits. Then the problem could be changed as follows:

$$\max_{0\le\theta_m<1}\Pi_m = (w-c)[D+\delta(\frac{1}{2}\gamma\theta_m^2)^{\alpha}(\frac{1}{2}\gamma\theta_r^2)^{\beta}] - \frac{1}{2}\gamma\theta_m^2 + \frac{1}{2}\gamma\theta_m^2\lambda_m \tag{4}$$

$$\max_{0\le\theta_r<1}\Pi_r = (p-w)[D+\delta(\frac{1}{2}\gamma\theta_m^2)^{\alpha}(\frac{1}{2}\gamma\theta_r^2)^{\beta}] - \frac{1}{2}\gamma\theta_r^2 + \frac{1}{2}\gamma\theta_r^2\lambda_r \tag{5}$$

For formula (4), (5), the first-order conditions (FOC) are as follows:

$$\frac{\partial\Pi_m}{\partial\theta_m} = 2\alpha(w-c)\delta(\frac{1}{2}\gamma)^{\alpha}\theta_m^{2\alpha-1}(\frac{1}{2}\gamma\theta_r^2)^{\beta} - \gamma\theta_m + \gamma\theta_m\lambda_m = 0 \tag{6}$$

$$\frac{\partial\Pi_r}{\partial\theta_r} = 2\beta(p-w)\delta(\frac{1}{2}\gamma)^{\beta}\theta_r^{2\beta-1}(\frac{1}{2}\gamma\theta_m^2)^{\alpha} - \gamma\theta_r + \gamma\theta_r\lambda_r = 0 \tag{7}$$

By solving the system of the two first-order conditions, formula (6), (7), the following solution is gained.

$$\theta_m^* = \sqrt{\frac{2}{\gamma}\delta^{\frac{1}{2(1-\alpha-\beta)}}\left[\frac{\alpha(w-c)}{1-\lambda_m}\right]^{\frac{1-\beta}{2(1-\alpha-\beta)}}\left[\frac{\beta(p-w)}{1-\lambda_r}\right]^{\frac{\beta}{2(1-\alpha-\beta)}}} \tag{8}$$

$$\theta_r^* = \sqrt{\frac{2}{\gamma}\delta^{\frac{1}{2(1-\alpha-\beta)}}\left[\frac{\alpha(w-c)}{1-\lambda_m}\right]^{\frac{\alpha}{2(1-\alpha-\beta)}}\left[\frac{\beta(p-w)}{1-\lambda_r}\right]^{\frac{1-\alpha}{2(1-\alpha-\beta)}}} \tag{9}$$

In the first stage of the game, the government set the optimal subsidy rate to maximize its profit, so the objective function is as follow.

$$\max_{0\le\lambda_m\le1, 0\le\lambda_r\le1}\Pi_g = (\frac{1}{2}\gamma\theta_m^2 + \frac{1}{2}\gamma\theta_r^2)RF + (p-c)[D+\delta(\frac{1}{2}\gamma\theta_m^2)^{\alpha}(\frac{1}{2}\gamma\theta_r^2)^{\beta}] \tag{10}$$

Take formula (8), (9) into formula (10), and take the first derivative of formula (6) with respect to λ_m, λ_r respectively. The subsidy rates, λ_m, λ_r, can be obtained. Then take formula (11), (12) into formula(8), (9), so θ_m^*, θ_r^* can be obtained. Thus, proposition 1 is true.

$$\lambda_m = 1 - \alpha(w - c)\left[\frac{(1 - RF)(1 - \alpha - \beta)}{(1 - 2\alpha)(p - c)}\right]^{\frac{1}{1-\alpha-\beta}} \tag{11}$$

$$\lambda_r = 1 - \beta(p - w)\left[\frac{(1 - RF)(1 - \alpha - \beta)}{(1 - 2\beta)(p - c)}\right]^{\frac{1}{1-\alpha-\beta}} \tag{12}$$

Property 1. From formula (8) and (9), we can find that $\frac{\partial\theta_m}{\partial\lambda_m} > 0, \frac{\partial\theta_r}{\partial\lambda_r} > 0, \frac{\partial\theta_m}{\partial\delta} > 0, \frac{\partial\theta_r}{\partial\delta} > 0, \frac{\partial\theta_m}{\partial\gamma} < 0, \frac{\partial\theta_r}{\partial\gamma} < 0$, i.e. the government subsidies and consumers' preference for low carbon have positive impact on the enterprises' carbon abatement, however, the cost coefficient of low-carbon technology has negative cost coefficient of low-carbon technology.

Property 2. From formula (11), (12), we can find that $\frac{\partial\lambda_m}{\partial RF} > 0, \frac{\partial\lambda_r}{\partial RF} > 0$, under the condition of 0 < RF < 1. RF has a positive impact on λr, i.e. the environment benefits more from the low-carbon technology, the government would be more willing to encourage enterprises in carbon abatement.

Property 3. From formula (11), (12), we can know $\frac{\partial\lambda_m}{\partial w} < 0, \frac{\partial\lambda_r}{\partial w} > 0$, so w is the determining factor in profit distribution of the manufacturer and retailer, when p and c are settled. When w is bigger, the manufacturer would get more benefit, then the government would give less subsidy to the manufacturer and give the retailer more subsidy, and vice versa. So the government's subsidy for low-carbon technology can balance the manufacturer and retailer's investment in carbon abatement, and the two enterprises can obtain the best benefit.

2.3 Supply Chain Decision-Making Model under Recycling Subsidy

2.3.1 Model Assumptions

Assumption 1. The manufacturer can not only use new materials to make new products, but also can use recycling products to make remanufacturerd products. And the market doesn't differentiate the two kinds of products.

Assumption 2. The retailer sells the products and recycles used products from consumers through its selling channels, and unit recycling price is p_1. The manufacturer recycles used products from the retailer to make remanufacturerd products, and the unit recycling price is w_1, the unit cost of remanufacturing is c_{mr}. the remanufacturerd products are also sold to retailer at the price of w, and $p_1 < w_1 < c - c_{mr}$. The government makes subsidy coefficient of recycling subsidies, s, according to the rate of recycling τ.

Assumption 3. The fixed cost of recycling is A(τ), and it is related to τ, and A(τ)would increase when τ increases. The functional relationship between A(τ)and τ is as follows.

$$A(\tau) = e\tau^2$$

The e in the function above is cost coefficient of recycling, and e > 0.

Assumption 4. The carbon emission during the manufacturer's remanufacturing process is ξ times of carbon emission during production with new materials, and 0<ξ<1, so the change in carbon emissions is ΔE.

$$\Delta E = \tau D(1-\xi)CO_m$$

2.3.2 Modeling and Analysis

Base on the description and assumptions above, the low-carbon supply chain decision model under recycling subsidy is built. In the model, the government gives proper subsidies to the manufacturer and retailer according to rate of recycling, and rate of recycling τ and subsidy coefficient of recycling s are decision variables and objective functions are the enterprises in the supply chain and the government's profits. This subsidy strategy is aimed to encourage the enterprises in recycling.

1) Profit function of the manufacturer

The profit of the manufacturer includes the income from selling products to the retailer, wD. The cost of the manufacturer includes production cost, but because of recycling the unit cost turns into $(1-\tau)c+\tau(c_{mr}+w_1)$, after simplification it is $c-\tau c+\tau c_{mr}+\tau w_1$. So the total production cost is$(c-\tau c+\tau c_{mr}+\tau w_1)D$. So the profit function is as the formula (13).

$$\Pi_m = (w-c+\tau c-\tau c_{mr}-\tau w_1)D \quad (13)$$

2) Profit function of the retailer

The profit of the retailer includes the income from selling products to the consumers,pD, the income from selling recovered products to the manufacturer, $w_1\tau D$, and government's subsidy $s\tau$. The cost of the manufacturer includes production cost, cD, the fixed cost of recycling A, and the cost of recycling used products from the consumer $p_1\tau D$. So the profit function of the retailer is as the formula (14).

$$\begin{aligned}\Pi_r &= (p-w+\tau w_1-\tau p_1)D - A + s\tau \\ &= (p-w+\tau w_1-\tau p_1)D - e\tau^2 + s\tau\end{aligned} \quad (14)$$

3) Profit function of the government

The profit of the government includes environmental benefits from the enterprises' investment in low carbon ARF, and total profit of the supply chain, $\Pi_m+\Pi_r$. The cost of government is the subsidy for recycling. So the profit function of government is as the formula (15).

$$\begin{aligned}\Pi_g &= e\tau^2 RF + \Pi_m + \Pi_r - s\tau \\ &= e\tau^2 RF + (p-c+\tau c-\tau c_{mr}-\tau p_1)D - e\tau^2\end{aligned} \quad (15)$$

Proposition 2. On the condition of 0<RF<1，there exists the unique equilibrium solution of governmental subsidy rates and rate of recycling.

$$(s^*,\tau^*) = \left(\frac{c-c_{mr}-p_1}{1-RF} - (w_1-p_1)D, \frac{c-c_{mr}-p_1}{2e(1-RF)}\right)$$

Proof of Proposition 2. From formula (13) we can know τ has positive effect on profit of the manufacturer, as $c > w_1+c_{mr}$. Using the method of inverse solution, in the second stage of the game, the government has set the subsidy rate s, and the retailer make decisions to maximize its own benefit. Then the problem could be changed as follow:

$$\max_{0\le\tau\le1} \Pi_r = (p-w+\tau w_1-\tau p_1)D - e\tau^2 + s\tau \quad (16)$$

Take the first derivative of formula (16) with respect to τ, make the derivative equals to zero, and solve the equation. Then we can get formula (17).

$$\frac{\partial \Pi_r}{\partial \tau} = (w_1-p_1)D - 2e\tau + s = 0$$

$$\tau = \frac{(w_1-p_1)D+s}{2e} \quad (17)$$

In the first stage of the game, consider τ is known, the objective function is as follow.

$$\max_{s\ge0} \Pi_g = e\tau^2 RF + (p-c+\tau c-\tau c_{mr}-\tau p_1)D - e\tau^2 \quad (18)$$

Take formula (17) into formula (18), and take the first derivative of formula (18) with respect to s.

$$\frac{\partial \Pi_g}{\partial s} = 2e(RF-1)\frac{(w_1-p_1)D+s}{2e}\tau_{(s)}' + (c-c_{mr}-p_1)D\tau_{(s)}' = 0$$

Solve the equation above. So we can get s^*, as formula (19).

$$s^* = \frac{c-c_{mr}-p_1}{1-RF} - (w_1-p_1)D \quad (19)$$

Take formula (19) into formula (17), then τ^* can be obtained as formula (20). Thus, proposition 2 is true.

$$\tau^* = \frac{c-c_{mr}-p_1}{2e(1-RF)} \quad (20)$$

Property 4. From formula (17), we can know $\tau>0$ when s=0, i.e. the enterprises will spontaneously recycle used products even when the government doesn't give subsidy. And $\frac{\partial \tau}{\partial s}=\frac{1}{2e}>0$, $\frac{\partial \tau}{\partial e}<0$, so subsidy coefficient of recycling s has positive impact on the rate of recycling τ, and cost coefficient of recycling e has negative impact on τ.

Property 5. From formula (19), on the condition of 0 < RF < 1, RF has positive impact on s. This means when the environment benefits more from recycling, the government would be more willing to subsidize the retailer.

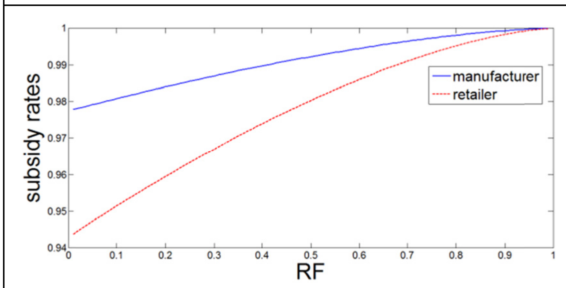
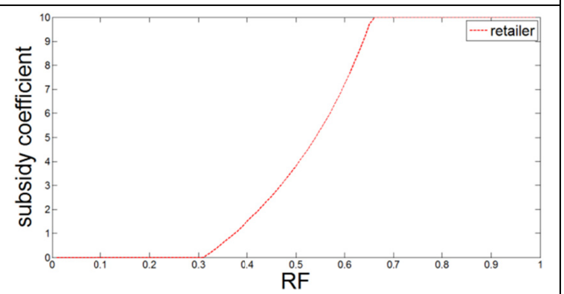
Property 6. From formula (17), $\tau=\frac{(w_1-p_1)D}{2e}$ when s=0, and w_1-p_1 is marginal profit of the retailer from recycling. So, without the government's subsidy, τ depends on the profit from recycling. From formula (20), c-cmr-p1 is marginal profit of the supply chain from recycling, so even with the government's subsidy, the retailer makes decisions according to the supply chain's profit. So recycling makes the retailer make decisions considering the whole supply chain instead of its own profits.

3. Comparative Analysis of Low-Carbon-Technology Subsidy and Recycling Subsidy

Herein, we use matlab (R2012b) to carry out the numerical simulation and find the solution of the above models. Through comparing low-carbon-technology subsidy and recycling subsidy, and analyzing the factors which affect government subsidies and carbon abatement, we can know how RF affects the profits of all the members in the subsidy strategy. This paper tries to provide some theoretical suggestions for enterprises in the supply chain and related departments of the government.

The parameters are set as follows: p=15, w=12, c=10, D=50, CO_m=5, CO_r=3,α=0.15, β=0.2, δ=0.01, γ=1000, c_{mr} =3, p1=0.1, w_1=0.3, e=10, ξ=0.3.

3.1 Analysis of Factors Influencing Subsidy Rates under the Two Subsidy Strategies

<table>
<tr><td>Low-carbon-technology subsidy</td><td>Recycling subsidy</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Figure 1(a). RF's impact on low-carbon subsidy</td><td>Figure 1(b). RF's impact on recycling subsidy</td></tr>
</table>

From the two pictures above, we can know that RF has positive impacts on both subsidy rates in low-carbon-technology subsidy and recycling subsidy, so this validates property 2 and property 5. Compare the two pictures, we can know the subsidy rate of low-carbon-technology subsidy is higher than the subsidy rate of recycling subsidy when RF = 0 (λ_m, λ_r > 0.9), and the subsidy rate increases as RF increases until it get 1, i.e., the government subsidizes completely. In the recycling subsidy strategy, there is no subsidy when RF < 0.3, and the subsidy rate increases as RF increases when 0.3 ≤ RF < 0.65, when RF ≥ 0.65 the subsidy rate equals to 10 and won't change any more.

Set RF = 0.5, w∈ (c, p), and the other parameters will not change, we can get Figure 1(c).

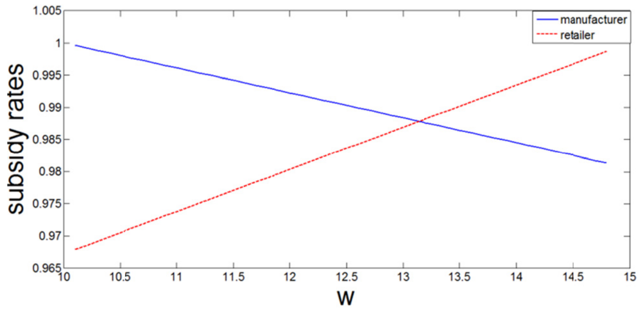


Figure 1(c). W's effect on supply chain members' subsidy rates under low-carbon technology

From Figure 1(c), we can know when w increases, the manufacturer's profit increases, but its subsidy decreases, at the same time retailer's profit decreases, but its subsidy increases. So the government's subsidy can balance the manufacturer and retailer's investment in carbon abatement and this validates property 3.

RF has positive impacts on the subsidy rates of low-carbon-technology subsidy and recycling subsidy strategy, but their growth patterns are different. The government should decide the subsidy rates according to profit distribution of the manufacturer and retailer in order to balance the two enterprises' investment in carbon abatement under low-carbon-technology subsidy. When coming to recycling subsidy, the government should give subsidy according to environment's benefit from recycling.

3.2 Analysis of Factors Influencing Carbon Abatement under the Two Subsidy Strategies

Low-carbon-technology subsidy	Recycling subsidy

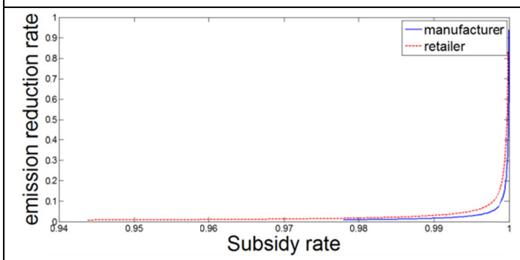
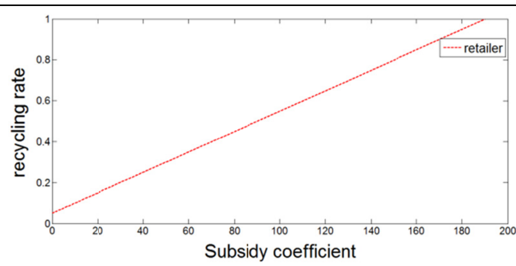

	

Figure 2(a). Subsidy rate's effect on emission reduction rate	Figure 2(b). Subsidy coefficient's effect on recycling rate

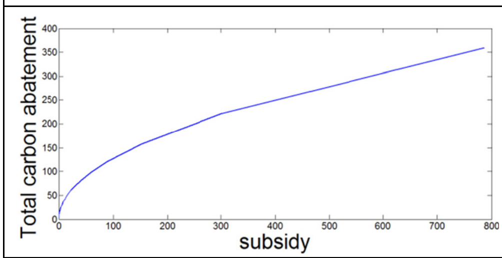
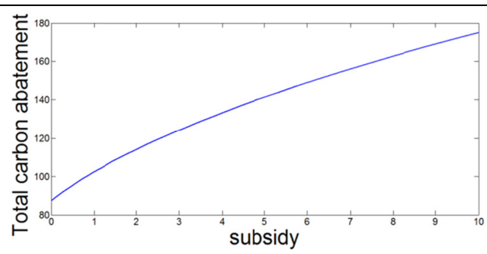

	

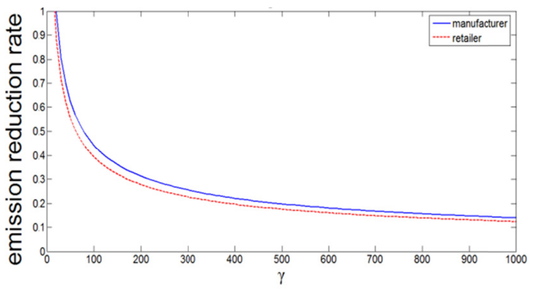
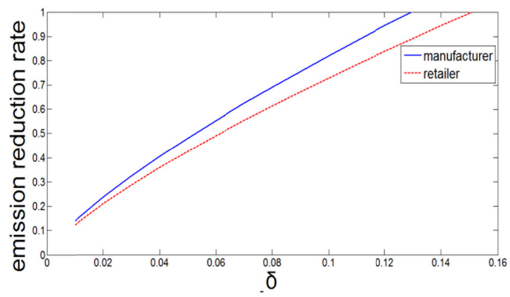
Figure 2(c). Low-carbon-technology subsidy's effect on carbon abatement	Figure 2(d). Recycling subsidy's effect on carbon abatement

We can know subsidy rates have positive impact on emission reduction rates from Figure 2(a), so this validates the relevant content in property 1. Under low-carbon-technology subsidy, the emission reduction rate increases very slowly at first, but when subsidy rate is close to 100%, then emission reduction rate increases quickly to 100%. From Figure 2(b), we can see subsidy rate has positive impact on recycling rate, and the recycling rate is 50% when subsidy rate equals to zero, so the enterprises will spontaneously recycle used products even when the government doesn't give subsidy, and this validates the relevant content in property 4.

Compare Figure 2(c) and Figure 2(d), we can find the highest amount of carbon abatement of low-carbon-technology subsidy is higher than recycling subsidy, and the reason is that both the manufacturer and retailer invest in carbon abatement in low-carbon-technology subsidy, but only the manufacturer reduces its carbon emission in recycling subsidy.

Except the subsidy, there are other factors affecting the supply chains carbon abatement. The cost coefficient of low-carbon technology γ and consumer's preference to low-carbon products δ also affect carbon abatement, as Figure 2(e) and Figure 2(f).

Set RF = 0.9, γ∈(0, 1000), and the other parameters will not change, we can get Figure 2(e). When γ<17, the emission reduction rates equal to 100%, and decrease when γ increases. Set RF = 0.9, δ∈ (0, 1), and the other parameters will not change, we can get Figure 2(f). We can see consumer's preference to low-carbon products δ has positive impaction emission reduction rates. The property 1 has been validated completely so far.

<table>
<tr><td colspan="2">Low-carbon-technology subsidy</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Figure 2(e). The γ's effect on emission reduction rates</td><td>Figure 2(f). The δ's effect on emission reduction rates</td></tr>
</table>

Under recycling subsidy, cost coefficient of recycling e also affects recycling rate. Set RF = 0.5, e∈(0, 100) and the other parameters will not change, we can get Figure 2(g).When e is very low the recycling rate is 100%. And recycling rate decreases when e increases. The property 4 has been validated completely so far.

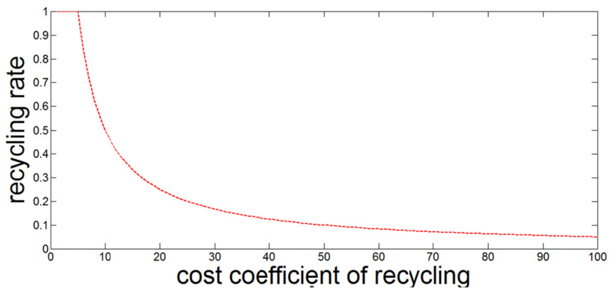


Figure 2(g). The e's effect on recycling rate

To sum up, under low-carbon-technology subsidy strategy, the factors affect emission reduction rates are subsidy rates, the cost coefficient of low-carbon technology, and consumer's preference to low-carbon products. Under recycling subsidy strategy, the factors affect recycling rates include subsidy rate sand cost coefficient of recycling. The subsidy rates have positive impact on both emission reduction rate and recycling rate, but the growth patterns are different. And cost coefficients have negative impact on both emission reduction rate and recycling rate. Besides consumer's preference to low-carbon products also has positive impact on emission reduction rate.

3.3 The Impact Analysis of RF on Supply Chain Members' Profits under the Two Subsidy Strategies

Low-carbon-technology subsidy	Recycling subsidy

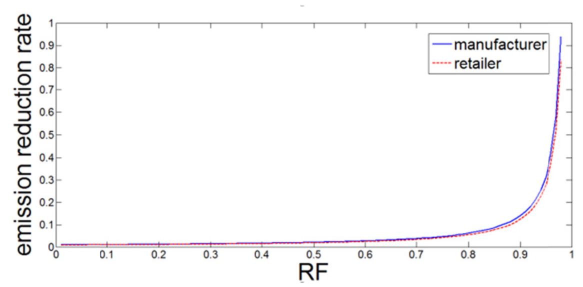
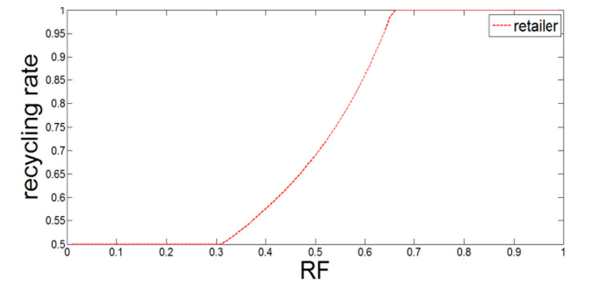

	

Figure 3(a). RF's effect on emission reduction rate	Figure 3(b). RF's effect on recycling rate

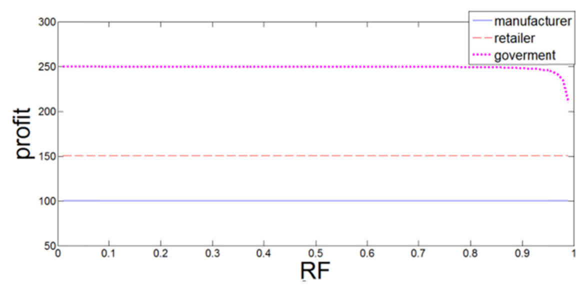
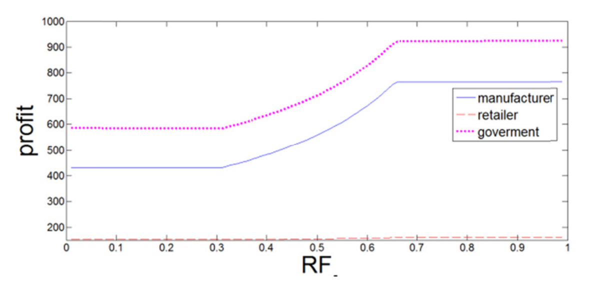

	

Figure 3(c). RF's effect on members' profits under low-carbon-technology subsidy	Figure 3(d). RF's effect on members' profits under recycling rate

From Figure 3(a) and Figure 3(c), we can know that under low-carbon-technology subsidy strategy, as RF increases, the emission reduction rates increases, but the profits of supply chain members just increase a little. When RF > 0.9, profit of the government decreases quickly as government under takes the most investment in low-carbon technology through giving subsidies.

From Figure 3(b) and Figure 3(d), we can know that under recycling subsidy strategy, when RF < 0.3, government doesn't give subsidy and recycling rates, profits keep unchanged. When 0.3 ≤ RF < 0.65, government subsidy rates, recycling rates and profits increase as RF increases. When RF ≥ 0.65, recycling rates reach 100%, profits reach the maximum value, and government will not give subsidy any more. So when government gives subsidy for recycling, all the members in the recycling subsidy strategy could gain more profit.

To sum up, low-carbon-technology subsidy strategy and recycling subsidy strategy have different impact on the members' profits. The profits of the members just change a little under low-carbon-technology subsidy strategy, and the government undertakes the most investment in low-carbon technology. Under recycling subsidy strategy, when RF increases to a point where the government is willing to give subsidies, all the members' profits increase as RF increase until the retailer's recycling rate reaches 100%.

4. Conclusion

This paper analyzes the factors which affect carbon abatement and subsidies under two kinds of subsidy strategies as well as how the subsidies affect the supply chain and the government. Moreover, we also compare the similarities and differences of the two subsidy strategies by building a two-stage game model under the subsidy of low-carbon technology and the subsidy of recycling. Based on the above analysis and discussions, we can have the following conclusions.

(1) RF has positive impact on the subsidy rates of low-carbon-technology subsidy and recycling subsidy strategy, but their growth patterns are different. The government should decide subsidy rates according to profit distribution of the manufacturer and retailer, under low-carbon-technology subsidy. Under recycling subsidy, the government should give subsidy according to environment's benefit from recycling.

(2) The subsidy rate shows positive impact on both emission reduction rate and recycling rate, while the cost

coefficients have negative impacts on both emission reduction rate and recycling rate. Consumer's preference to low-carbon products also has positive impact on emission reduction rate. So the government should help consumers to enhance their awareness of low-carbon life concepts to improve the emission reduction rate.

(3) As RF increases, the profits of the members just change a little under low-carbon-technology subsidy strategy, and the government undertakes most of the investments in low-carbon technology. However, when $0.3 \le RF < 0.65$, the government is willing to give subsidies, and all the members' profits increase as RF increase.

(4) The government subsidies are given according to the profit distribution of the enterprises, which can balance the manufacturer and retailer's investment in carbon abatement under low-carbon technology subsidy strategy. The recycling subsidy makes the retailer make decisions considering the whole supply chain instead of its own profits.

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