Carbon emission reduction cooperation in supply chain with government subsidies

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Abstract. Environmental sustainability has become the key index to evaluate the success of supply chain management. This paper aims at the problem of joint emission reduction in supply chain with government subsidies under the Cap-and-Trade mechanism (C&T). Three mathematical models considering green technology investment and two subsidy methods are constructed. It is found that government subsidies cannot ensure that enterprises reduce total carbon emissions. Compared with subsidies based on green investment costs, subsidies based on emission reduction have greater emission reductions, but the total carbon emissions are also greater.

1. Introduction

C&T mechanism is an effective strategy to achieve energy conservation and emission reduction by comprehensively using supervision and market methods. In order to gain profit or avoid penalty under C&T, and reduce their emission, many enterprises adopt green technology to produce green products. However, government subsidy is also indispensable for green technology adoption because of its high investment cost. Government subsidies are regarded as financial incentives for enterprises to reduce carbon emissions under C&T conditions [1].

In addition, to promote retailers to carry out green marketing for green products, manufacturers need to share a proportion of marketing cost with retailers [2]. Therefore, green-marketing cost-sharing contract is crucial for cooperation among enterprises in a supply chain. Many articles focused on supply chain cooperation with government financial subsidies which could benefit both manufacturers and retailers [3-4]. However, they do not consider the combination of subsidies with other current carbon emission reduction policies, such as C&T policy. Some other studies pay attention to the influence of C&T policy on supply chain but ignore government subsidies [5-6]. However, government subsidies and C&T policy can be combined to support carbon emission reduction of a supply chain. Retailers' green marketing effort is another important but ignored issue in supply chain carbon emission reduction cooperation literatures.

In addition, based on our survey, it is found that investing in green technology is a process in which enterprises choose one or more green technologies and pay a fixed amount [7-8]. Therefore, green technology investment is a discrete decision variable in practice, not a continuous decision variable [9].

This study considers the joint carbon emission reduction of supply chain with retailers' green marketing efforts by combining government subsidies (subsidy based on green investment cost and subsidy based on emission reduction) and C&T policy, with consideration of discrete decision on green technology.
2. Assumptions and models
This paper considers a two-level supply chain with manufacturer as the leader and retailer as the follower under the C&T mechanism. Manufacturer spends a fixed investment cost on green technology. Retailer buys products provided by manufacturer and sells them to consumers with preference on green products. In the cooperation, manufacturers produce green products, retailers promote green products, and manufacturers will share green marketing costs with retailers.

2.1. Assumptions and parameters
The decision variables and parameters related to this paper are shown in Table 1. In addition, it is assumed that retailer’s green marketing efforts is expressed as \( y(0 \leq y \leq 1) \), green marketing cost is \( y^2 \), and its cost coefficient is assumed to be 1. Also, product demand is related to product price, green technology emission reduction rate, consumer green awareness and retailer's green marketing effort level. Without losing generality, consumer utility \( U \) is regarded as a linear utility function. \( U \) which is a uniformly distributed random variable with a cumulative distribution function \( F(x) \) on \( x \in [0, \bar{U}] \), where \( \bar{U} = 1 \) is the maximal utility. The consumer demand function can be expressed as \( u = U - p + bxr + y \), and the demand function is \( q(p, x, y) = P[U > p - bxr - y] = 1 - p + bxr + y \) [2,10].

| Decision variables | Description |
|--------------------|-------------|
| \( x \)            | The manufacturer’s decision on green technology investment, \( x \in \{0, 1\} \), \( x = 1 \) indicates it will invest in the technology, otherwise \( x = 0 \) |
| \( w \)            | The unit wholesale price of the product, \( w > 0 \) |
| \( t \)            | The sharing ratio of green marketing cost from manufacturer, \( 0 \leq t < 1 \), \( t = 0 \) indicates no cooperation |
| \( p \)            | The unit retail price of the product, \( p > 0 \) |
| \( y \)            | The retailer's green marketing efforts, \( y > 0 \), \( y = 0 \) indicates no cooperation |

| Parameters | Description |
|------------|-------------|
| \( s \)    | Government subsidy to manufacturer investing in green technology, \( 0 < s < 1 \) |
| \( c \)    | The unit production cost, \( c > 0 \) |
| \( b \)    | The low-carbon awareness of consumers, \( 0 < b < 1 \) |
| \( r \)    | The carbon emission reduction rate of the product, \( 0 < r < 1 \) |
| \( e \)    | Initial carbon emissions per unit product from the manufacturer, \( e > 0 \) |
| \( z \)    | Carbon price, \( e > 0 \) |
| \( A \)    | Carbon allowance allocated by the government, \( A > 0 \) |
| \( F \)    | Fixed cost of implementing green technology, \( F > 0 \) |
| \( q \)    | The production quantity |
| \( \pi^x \) | Enterprises' profit, \( x = M, R, SC \) denotes the manufacturer, retailer and the supply chain, respectively |
| \( E \)    | Total carbon emission of manufacturer |

2.2. Models

2.2.1. Model 0(M0): no green technology investment and no subsidy model
When the manufacturer chooses not to invest in green technology, that is \( x = 0 \), the government will not subsidize the manufacturer, and the retailer will not cooperate with the manufacturer in green marketing. Under the C&T mechanism, the manufacturer obtains the fixed carbon emission quota allocated by the government. Therefore, based on the consumer demand function \( (q = 1 - p + bxr + y) \), the trading value of the manufacturer's carbon emission rights in the carbon trading market can be expressed as \( z(e(1 - p) - A) \). The profit of the manufacturer is equal to the income minus the production cost and the carbon emission trading cost (or plus the carbon trading income). The profit of the retailer is equal to the income minus the cost of purchasing product.

\[
\pi^w_M(w) = (w - c)(1 - p) - z(e(1 - p) - A) \tag{1}
\]
\[ \pi_b(p) = (p - w)(1 - p) \]  
Subject to \( 1 - p \geq 0, \ p \geq 0 \)  

2.2.2. Model 1 (M1): Subsidy rule based on fixed investment cost considering green technology investment (FC subsidy) 

When the manufacturer chooses to invest in green technology (\( x = 1 \)), the government provides a certain proportion of subsidies to the manufacturer according to the fixed investment cost of green technology (FC subsidies). At this time, the total amount of subsidies can be expressed as \( sF \). If the retailer decides to cooperate with the manufacturer in green marketing, the retailer's green marketing cost is equal to \((1 - t)y^2\) and the manufacturer's green marketing cost is equal to \( ty^2 \). 

\[ \pi^*_b(w, t) = (w - c)(1 - p + br + y) - (1 - s)F - z[(1 - r)e(1 - p + br + y) - A] - ty^2 \]  
\[ \pi^*_b(p, y) = (p - w)(1 - p + br + y) - (1 - t)y^2 \]  
Subject to \( 1 - p + br + y \geq 0, \ p \geq 0 \)  

2.2.3. Model 2 (M2): subsidy rules based on carbon emission reduction considering green technology investment (ER subsidy) 

When the manufacturer chooses to invest in green technology (\( x = 1 \)), the government provides a certain proportion of subsidies (ER subsidies) to the manufacturer according to the manufacturer's carbon emission reduction. At this time, the total amount of subsidies can be expressed as \( srez(1 - p + br + y) \). Similarly, the retailer's green marketing cost equals to \((1 - t)y^2\) and the manufacturer's green marketing cost is equal to \( ty^2 \). 

\[ \pi^*_b(w, t) = (w - c - r)[1 - (s + r)(1 - y^2)]e(1 - p + br + y) - F - z[e(1 - p + br + y) - A] - ty^2 \]  
\[ \pi^*_b(p, y) = (p - w)(1 - p + br + y) - (1 - t)y^2 \]  
Subject to \( 1 - p + br + y \geq 0, \ p \geq 0 \)  

3. Result and discussion 

Through the analysis of the above model, we can get the optimal product price and the optimal values of other decision variables under the C&T mechanism. Through these optimal values, we can analyse the best conditions for investing in green technology, the total carbon emissions and the effect of cooperation strategies under the two subsidy methods, and compare the differences between the two subsidy rules. 

3.1. Comparison of optimal values 

We can get the optimal wholesale price (\( w^* \)), retail price (\( p^* \)), manufacturer's green marketing cost sharing ratio (\( t^* \)), retailer's green marketing effort level (\( y^* \)), and the corresponding optimal output (\( q^* \)), manufacturer's and retailer's profit (\( \pi^*_R, \pi^*_E \)) and total carbon emission (\( E^* \)) (Table 2). 

**Theorem 1.** \( w^1 > w^2, \ t^1 = t^2 = \frac{1}{3}, \ p^*_1 > p^*_2, \ q^*_1 < q^*_2, \ y^*_1 > y^*_2 > 0, \ \pi^*_R > \pi^*_R, \ E^*_2 > E^*_1 \). 

Theorem 1 shows that compared with FC subsidy, the wholesale price and retail price under ER subsidy become lower due to subsidy effect. Under FC subsidy, the supply chain uses higher price to reduce production to achieve the purpose of reducing total carbon emissions. This means that FC subsidy has a better effect on total carbon emissions control. Under both methods, manufacturers are willing to share 1/3 of green marketing costs for retailers, and retailers are also willing to cooperate with manufacturers to improve corporate profits. In addition, retailers' green marketing effort under ER subsidies is higher. Therefore, compared with FC subsidies, retailers have higher output and better profits under ER subsidies, which means that retailers prefer manufacturers to invest in green technologies and governments to implement ER subsidies. 

**Corollary 1.** Except for the proportion of cost sharing \( t^*_2 \), the optimal values of variables and parameters under ER subsidy are all affected by government subsidies. However, among the optimal values of variables and parameters under FC subsidy, only the profit of manufacturers is affected by
subsidies. The relationship between optimal values and subsidies is as follows: \( \frac{\partial w^*}{\partial s} < 0, \frac{\partial p^*}{\partial s} < 0, \frac{\partial q^*}{\partial s} > 0, \frac{\partial \pi^*}{\partial s} > 0, \frac{\partial E^*}{\partial s} > 0 \).

Corollary 1 shows that in FC subsidies, government subsidies only have a positive impact on the profits of manufacturers, they have no direct effect on other parameters. However, in ER subsidies, government subsidies will affect the decision-making of the whole supply chain: the more subsidies, the lower the wholesale price and retail price, the greater the green marketing efforts, and the more orders quantity, the more profits the supply chain members will get. At the same time, due to the higher output, the carbon emission under ER subsidies is larger than that under FC subsidies.

### Table 2. Optimal values of each parameter in three scenarios.

| Parameter | M0 | M1 | M2 |
|-----------|----|----|----|
| \( w^* \) | \( c + ez + 1 \) | \( 10ez(1 - r) + 13br + 10c + 13 \) | \( 10ez(1 - (s + 1)r) + 13br + 10c + 13 \) |
| \( p^* \) | \( c + ez + 3 \) | \( 2ez(1 - r) + 21br + 2c + 21 \) | \( 2ez(1 - (s + 1)r) + 21br + 2c + 21 \) |
| \( q^* \) | \( 1 - c - ez \) | \( (ez(r - 1) + br - c + 1)8 \) | \( (ez(r(s + 1) - 1) + br - c + 1)8 \) |
| \( t^* \) | \( 4 \) | \( \frac{1}{23} \) | \( \frac{1}{23} \) |
| \( y^* \) | \( 4 \) | \( \frac{1}{3} \) | \( \frac{1}{3} \) |
| \( \pi^\text{M*} \) | \( \frac{(ez + c - 1)^2}{8} \) | \( \frac{4(br + ez(r - 1) - c + 1)^2}{23} + \frac{Az}{4} \) | \( \frac{4(br + ez(r(s + 1) - 1) - c + 1)^2}{23} + \frac{Az}{4} \) |
| \( \pi^\text{R*} \) | \( \frac{(ez + c - 1)^2}{16} \) | \( \frac{240(ze(r - 1) + br - c + 1)^2}{23} + \frac{Az}{4} + \frac{(s - 1)F}{23} \) | \( \frac{240(ze(r(s + 1) - 1) + br - c + 1)^2}{23} + \frac{Az}{4} + \frac{(s - 1)F}{23} \) |
| \( E^* \) | \( e(1 - c - ez) \) | \( e(1 - r)(ez(r - 1) + br - c + 1)8 \) | \( e(1 - r)(ez(r(s + 1) - 1) + br - c + 1)8 \) |

### 3.2. Comparison of Carbon Emissions

According to the sum of theorem 1, the optimal order quantity of ER subsidy is larger than FC subsidy, so at the same emission reduction rate, the carbon emission reduction of ER subsidy is larger, but the total carbon emission is also larger. Thus, if we need to find the lowest total carbon emission model among the three models, we just need to compare the total carbon emissions of FC subsidy model (M1) and no green technology investment no subsidy model (M0).

**Theorem 2.** Under different values of carbon emission reduction rate \( r \), there are five relationships between carbon emission intensity \( e \) and carbon emission difference of M0 and M1 models \( \Delta E_{10} = E^*_1 - E^*_0 \), as shown in Table 3 (see the proof in the appendix).

Theorem 2 indicates that government subsidies may not guarantee the manufacturer’s reduction of total carbon emissions. Because manufacturer will increase its production after receiving subsidies, thus increasing their total carbon emissions. When the emission reduction rate of green technology is lower than a small threshold, the difference of carbon emissions between M0 and M1 models is a concave function of carbon emission intensity. Government subsidies for manufacturer whose carbon emissions exceeds the carbon emission threshold can help enterprises reduce their total carbon emissions significantly, while subsidies for manufacturer whose carbon emission is lower than the carbon emission threshold will increase its emission after receiving subsidies.

On the contrary, when the emission reduction rate is higher than a larger threshold, the difference of carbon emission between M0 and M1 models is a convex function of carbon emission intensity. Subsidizing manufacturer whose carbon emission is lower than the carbon emission threshold can achieve the goal of carbon emission reduction. Otherwise, the total carbon emission will be higher than that without green technology and subsidy. If the emission reduction rate is between the two thresholds, no subsidy and green technology get lower total emission.
Table 3. Minimum carbon emission model corresponding to different situations.

| \( r \)       | \( e \)       | \( \Delta E_{10} = E_1^* - E_0^* \) | Minimum emission model |
|--------------|--------------|---------------------------------|-----------------------|
| \( 0 < r < 1 - \frac{23}{32}^{1/2} \) | \( 0 < e < e_1 \) | \( \Delta E_{10} > 0 \) | M0                     |
|              | \( e > e_1 \) | \( \Delta E_{10} < 0 \) | M1                     |
| \( r = 1 - \frac{23}{32}^{1/2} \) | \( \forall e \) | \( \Delta E_{10} > 0 \) | M0                     |
| \( 1 - \frac{23}{32}^{1/2} < r < r_1 \) | \( r = r_1 \) | \( \forall e \) | M0                     |
| \( r_1 < r < 1 \) | \( 0 < e < e_1 \) | \( \Delta E_{10} < 0 \) | M1                     |
|              | \( e > e_1 \) | \( \Delta E_{10} > 0 \) | M0                     |

Where \( r_1 = \frac{-32(b+c-1) - ((32(b+c-1))^2 - 4(-32b) + 9(1-c))^{1/2}}{2(-32b)} \), \( e_1 = \frac{-2(1-r)(br-c+1) - 23(1-c)}{92} + \frac{32(1-r)(br-c+1) - 23(1-c)}{92}z^{-1} \).

4. Conclusion
This paper focuses on the joint emission reduction of supply chain with government subsidies under C&T mechanism. According to the theoretical deduction and analysis, the following conclusions can be drawn:

Government subsidies cannot ensure that enterprises reduce total carbon emissions. Because there may be a situation that enterprises will increase their output after receiving subsidies, the total carbon emissions will increase consequently.

Under ER subsidies, government subsidies will affect the decision-making of the whole supply chain: the more subsidies, the lower the wholesale price and retail price, the greater the green marketing efforts, and the more orders quantity, the more profits the supply chain members will get. At the same time, due to the higher output, the carbon emission under ER subsidies is larger than that under FC subsidies.

Under both subsidy methods, manufacturers are willing to share 1/3 of green marketing costs for retailers, and retailers are also willing to cooperate with manufacturers to improve profits. In addition, retailers’ green marketing efforts under ER subsidies are also affected by subsidies and become higher. Therefore, compared with FC subsidies, retailers have higher output and better profits under ER subsidies, which means that retailers prefer manufacturers to invest in green technologies and governments to implement ER subsidies.

5. Appendices
The proof of theorem 2:

\[
\Delta E_{10} = E_1^* - E_0^* = \frac{e(1-r)(e_1z+br-c+1)b}{23} - \frac{e(1-c-e_2)}{23-32(1-r)^2} \cdot \frac{ Ze^2 + \frac{32(1-r)(br-c+1) - 23(1-c)}{92} e}{2(-32b)}.
\]

The intersection of \( \Delta E_{10} \) and horizontal axis is: \( \frac{-32(b+c+1) - ((32(b+c+1))^2 - 4(-32b) + 9(1-c))^{1/2}}{2(-32b)} \), \( e_1 = \frac{-2(1-r)(br-c+1) - 23(1-c)}{92} + \frac{32(1-r)(br-c+1) - 23(1-c)}{92}z^{-1} \). Let \( e_1 \) be the abscissa of orthogonal points. Let \( f(r) = 32(1-r)(br-c+1) - 23(1-c) = -32br^2 + 32(b+c-1)r + 9(1-c). \) The intersection of function \( f(r) \) and horizontal axis is: \( \frac{-32(b+c+1) - ((32(b+c+1))^2 - 4(-32b) + 9(1-c))^{1/2}}{2(-32b)} \), \( 0 \). Let \( r_1 \) be the abscissa of orthogonal points, i.e. \( r_1 = \frac{-32(b+c+1) - ((32(b+c+1))^2 - 4(-32b) + 9(1-c))^{1/2}}{2(-32b)} \). It can be proved that \( 1 - \frac{23}{32}^{1/2} < r_1 < 1 \).

(1) If \( 23 - 32(1-r)^2 > 0 \), that is, \( r > 1 - \frac{23}{32}^{1/2} \).

1) When \( 32(1-r)(br-c+1) - 23(1-c) = 0 \), \( r = r_1 = \frac{-32(b+c+1) - 32(b+c+1)^2 - 4(-32b) + 9(1-c))^{1/2}}{2(-32b)} \). At this time, \( \Delta E_{10} \) has an intersection with horizontal axis, and the intersection is at the origin.

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Therefore, for \( \forall e \), there exists \( \Delta E_{10} = E^*_1 - E^*_0 > 0 \), i.e. \( E^*_1 > E^*_0 \), and the M0 model has the lowest carbon emission.

2) When \( 32(1-r)(br-c+1)-23(1-c) > 0 \), that is, \( 1 - \left(\frac{23}{32}\right)^{1/2} < r < r_1 \). At this time, there are two intersections between \( \Delta E_{10} \) and horizontal axis, one is at the origin and the other is negative.

Therefore, for \( \forall e \), there exists \( \Delta E_{10} = E^*_1 - E^*_0 > 0 \), i.e. \( E^*_1 > E^*_0 \), and the M0 model has the lowest carbon emission.

3) When \( 32(1-r)(br-c+1)-23(1-c) < 0 \), that is, \( r_1 < r < 1 \). There are two intersections between \( \Delta E_{10} \) and horizontal axis, one is at the origin and the other is positive.

Therefore, when \( 0 < e < e_1 \), there exists \( \Delta E_{10} = E^*_1 - E^*_0 < 0 \), i.e. \( E^*_1 < E^*_0 \), and the M1 model has the lowest carbon emission. When \( e > e_1 \), there exists \( \Delta E_{10} = E^*_1 - E^*_0 > 0 \), i.e. \( E^*_1 > E^*_0 \), and the M0 model has the lowest carbon emission.

The proof of this theorem under the other situations is similar and omitted.

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