Game Analysis of Green Technology Implementation with Green Consumption Preference Considered under Cap-and-Trade Scheme

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Abstract. Under the scheme of Cap-and-Trade, carbon emissions have become important constraints that generating companies have to take into consideration when making their operational decisions, especially for the product pricing and green technology selection. In this paper, a two-party (one greener and one dirtier manufacturer) game model with green consumption preference considered is proposed. The equilibrium conditions including optimal prices and selection of green technology under different combinations of strategies are obtained. The study finds that whether greener or dirtier manufacturer will implement green technology mainly depends on different scenarios of cost and carbon emission reduction of green technology, and carbon emission for producing per unit of product. How to establish an effective mechanism to make both manufacturers cooperate in green technology implementation and carbon emission reduction is an interesting future research direction.

Introduction

With the rapid development of human society, the contradiction between environmental protection and economic development has become increasingly prominent. All of the world has taken active actions. China, as a major carbon emitter and the 2nd largest economic entity in the world, has always made active efforts to reduce carbon emissions. China established seven emissions trading pilots under Cap-and-Trade scheme in 2011. Cap-and-Trade is a market-based policy that is released to control carbon emissions [1]. The regulator will allocate an initial emission quota to the generating company at the beginning of the compliance period (e.g. one year). If emission quota is insufficient to the target production, the generating company should pay for the excess at the carbon price.

Under Cap-and-Trade scheme, unit carbon emission turns into an important attribute of product [2]. On the one hand, companies have to control emissions to maximize their revenue. On the other hand, due to the green consumption preference which means consumers are willing to pay higher prices for low-carbon products [3], companies are urged to find effective ways to reduce carbon emissions in order to increase their product competitiveness. In addition, emission permit which can be traded in the carbon market can bring profits like any other production resources. Consequently, Cap-and-Trade scheme directly changes the companies’ profit models, and ultimately affects their behaviors.

In this context, the issue of carbon emissions has become a research hotspot. At the macro level, scholars are mainly concerned with the design and evaluation of carbon emissions’ policies [4] and the evaluation of reduction performance [5] etc. At the micro level, many scholars study the impact of Cap-and-Trade scheme on companies’ behaviors, such as inventory management [6], pricing stagey selection [7] and green technology implementation decision [8] etc. However, these research focus on individual company and do not take the influences by other supply chain members into account. Although there are more and more scholars start to conduct multi-enterprises research [9, 10, 11], few of them cast a view on green technology implementation decision and consider green consumption preference at the same time. Meanwhile, a large amount of studies hold that green technology implementation as a continuous decision, and the cost is a quadratic function of emission reduction [12]. However, according to our survey of several generating companies in Shenzhen, the decision of green technology implementation is a “one-zero” discrete decision.
usually implemented as a project with a fix cost and a reduction rate. Hence, traditional methods can’t describe the real decision-making problems accurately.

According, this paper focuses on product pricing and green technology selection for generating companies. A two-party (one greener and one dirtier manufacturer) game model is proposed in this paper, and the model not only captures the characteristics of green technology implementation, but also takes green consumption preference into consideration.

**Problem Description and Modeling**

**Problem Description**

Due to the complexity of the supply chain, this paper only considers two manufacturers. Both of them produce CO2E (Carbon Dioxide Equivalent) during the manufacturing process. According the above problem description, the following assumptions are put forward:

- **Assumption 1.** Two manufacturers produce the same product, but manufacturer 2 is more environmentally friendly than manufacturer 1, so the product of manufacture 2 has lower unit emission \((e_1 > e_2)\) and higher unit production cost \((v_1 < v_2)\).
- **Assumption 2.** Green technology implementation decision should be made at the beginning of the compliance period (one year), and the cost of green technology including technology purchasing cost and annual maintenance cost is a fix cost.
- **Assumption 3.** Carbon emission quota trading between two manufacturers is not allowed.
- **Assumption 4.** The information between two manufacturers is completely symmetrical.

**Notations**

The notations used in this paper are given blow.

- Parameters (for which values are assumed to be known):
  - \(i = 1, 2\). Manufacture 1 and manufacture 2.
  - \(a_i\). The market capacity of products.
  - \(b\). The price elasticity of product demand.
  - \(\lambda\). The green consumption preference.
  - \(r\). The reduction rate of carbon emissions after implement green technology. \(0 < r < 1\).
  - \(e_i, e_{3-i}\). Unit carbon emission.
  - \(c\). The cost of green technology
  - \(v_i\). Unit production cost.
  - \(p_c\). Carbon price.
  - \(q_i\). Carbon emission quota.
- Decision variables (for which values are obtained from the model solution):
  - \(p_i, p_{3-i}\). The price of product.
  - \(z_i, z_{3-i}\). Decision of whether to implement green technology or not, 1 for implementation, 0 for not.

**Mathematical Model**

Manufacturers are constrained by Cap-and-Trade scheme, so their profit functions are composed of four parts: sales revenue, production cost, green technology cost and excessive emission cost. The objective of each manufacturer is to maximize its profit.

Objective function:

\[
\max \pi_i = p_i D_i - v_i D_i - z_i c - p_c [D_i e_i (1 - rz_i) - q_i].
\]  
\(D_i\) is the market demands of product.  
\(D_i = a_i - bp_i + bp_{3-i} - \lambda e_i (1 - rz_i) + \lambda e_{3-i} (1 - rz_{3-i}).\)  
Constraints:

\[
D_i > 0.
\]
\( p_i, p_{3-i} > 0. \)

Solving the equations can yield the second derivation for manufacturers 1 and 2 as follows.

\[
\frac{d^2 \pi_1}{dp_1^2} = -2b < 0. 
\]  \hspace{1cm} (4)

\[
\frac{d^2 \pi_2}{dp_2^2} = -2b < 0. 
\]  \hspace{1cm} (5)

The profit functions are concave, so the optimal price and profit functions can be acquired.

\[
\pi_1^* = \frac{a_1 + b p_2 - \lambda e_1 (1-r z_1) + \lambda e_2 (1-r z_2) + b (v_1 + p_c e_1 (1-r z_1))}{2b}. 
\]  \hspace{1cm} (7)

\[
\pi_2^* = \frac{a_2 + b p_1 - \lambda e_2 (1-r z_2) + \lambda e_1 (1-r z_1) + b (v_2 + p_c e_2 (1-r z_2))}{2b}. 
\]  \hspace{1cm} (8)

\[
\pi_1^* = p_c q_1 - z_1 c + \frac{\{a_1 + b p_2 - \lambda e_1 (1-r z_1) + \lambda e_2 (1-r z_2) - b (v_1 + p_c e_1 (1-r z_1))\}^2}{4b}. 
\]  \hspace{1cm} (9)

\[
\pi_2^* = p_c q_2 - z_2 c + \frac{\{a_2 + b p_1 - \lambda e_2 (1-r z_2) + \lambda e_1 (1-r z_1) - b (v_2 + p_c e_2 (1-r z_2))\}^2}{4b}. 
\]  \hspace{1cm} (10)

**Payoff Matrix**

Four combinations of green technology implementation strategies are discussed.

**Strategies combination 1.** None of the manufacturers implements green technology.

\[
\pi_1^* |_{z_1=0, z_2=0} = p_c q_1 + \frac{(2a_1 + a_2 + b [p_c (e_2 - e_1) - v_1 + v_2]+ \lambda (e_2 - e_1))^2}{9b}. 
\]  \hspace{1cm} (11)

\[
\pi_2^* |_{z_1=0, z_2=0} = p_c q_2 + \frac{(2a_1 + a_2 + b [p_c (e_1 - e_2) - v_1 + v_2]+ \lambda (e_1 - e_2))^2}{9b}. 
\]  \hspace{1cm} (12)

**Strategies combination 2.** Manufacturer 1 implements green technology, while manufacturer 2 does not.

\[
\pi_1^* |_{z_1=1, z_2=0} = p_c q_1 - c + \frac{(2a_1 + a_2 + b [p_c (e_2 - e_1 (1-r)) - v_1 + v_2] + \lambda (e_2 - e_1 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (13)

\[
\pi_2^* |_{z_1=1, z_2=0} = p_c q_2 + \frac{(2a_1 + a_2 - b [p_c (e_1 - e_2 (1-r)) - v_1 + v_2] - \lambda (e_2 - e_1 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (14)

**Strategies combination 3.** Manufacturer 2 implements green technology, while manufacturer 1 does not.

\[
\pi_1^* |_{z_1=0, z_2=1} = p_c q_1 + \frac{(2a_1 + a_2 - b [p_c (e_1 - e_2 (1-r)) + v_1 - v_2] - \lambda (e_1 - e_2 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (15)

\[
\pi_2^* |_{z_1=0, z_2=1} = p_c q_2 - c + \frac{(2a_1 + a_2 + b [p_c (e_1 - e_2 (1-r)) + v_1 - v_2] + \lambda (e_1 - e_2 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (16)

**Strategies combination 4.** Both manufacturers implement green technology.

\[
\pi_1^* |_{z_1=1, z_2=1} = p_c q_1 - c + \frac{(2a_1 + a_2 - b [p_c (e_1 - e_2 (1-r)) + v_1 - v_2] - \lambda (e_1 - e_2 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (17)

\[
\pi_2^* |_{z_1=1, z_2=1} = p_c q_2 - c + \frac{(2a_1 + a_2 + b [p_c (e_1 - e_2 (1-r)) + v_1 - v_2] + \lambda (e_1 - e_2 (1-r)))^2}{9b}. 
\]  \hspace{1cm} (18)

Based on the above discussion and analysis, the payoff matrix is presented as follows.
Table 1. The payoff matrix of green technology implementation strategies for manufacturer 1 and 2.

<table>
<thead>
<tr>
<th>manufacturer 1</th>
<th>manufacturer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not implement</td>
</tr>
<tr>
<td></td>
<td>First quadrant</td>
</tr>
<tr>
<td>Not implement</td>
<td>[\pi^*_1</td>
</tr>
<tr>
<td></td>
<td>[\pi^*_1</td>
</tr>
<tr>
<td>implement</td>
<td>Third quadrant</td>
</tr>
<tr>
<td></td>
<td>[\pi^*_1</td>
</tr>
<tr>
<td></td>
<td>[\pi^*_2</td>
</tr>
</tbody>
</table>

**Model Analysis**

Because manufacturer 1 and 2 have the characteristics of limited rationality and mutual influence, and the strategies chosen at the beginning are not necessarily the optimal strategies, two players will eventually come into equilibrium after constantly learning and strategies selecting. In this paper two strategies combinations’ equilibrium conditions (Fourth and First quadrant) are analyzed.

**Fourth Quadrant**

Two manufacturers achieve the equilibrium requirement under the strategies combination \((z_1 = 1, z_2 = 1)\) while satisfying the following two conditions simultaneously.

\[
\pi^*_1|z_1=1,z_2=1 - \pi^*_1|z_1=0,z_2=1 > 0. \tag{19}
\]

\[
\pi^*_2|z_1=1,z_2=1 - \pi^*_2|z_1=1,z_2=0 > 0. \tag{20}
\]

By solving and analyzing the functions, equilibrium conditions can be obtained.

1) If \(v_2 - v_1 \geq \frac{a_2-a_1+(e_1-e_2)(bp_c+\lambda)}{2b}\), when \(0 \leq c \leq \frac{r[-a_1-2a_2-e_1(1-r)(bp_c+\lambda)+b(v_2-v_1)]^2}{9b(2-r)}\), \([e^{(4)}_1 \min', e^{(4)}_1 \max']\) for manufacture 1 and \([e^{(4)}_2 \min', e^{(4)}_2 \max']\) for manufacture 2;

2) If \(0 < v_2 - v_1 < \frac{a_2-a_1+(e_1-e_2)(bp_c+\lambda)}{2b}\), when \(0 \leq c \leq \frac{r[-2a_1-a_2-e_2(1-r)(bp_c+\lambda)+b(v_1-v_2)]^2}{9b(2-r)}\), \([e^{(4)}_1 \min', e^{(4)}_1 \max']\) for manufacture 1 and \([e^{(4)}_2 \min', e^{(4)}_2 \max']\) for manufacture 2.

\(e^{(4)}_1 \min', e^{(4)}_1 \max'\) are the roots of function \((\pi^*_1|z_1=1,z_2=1 - \pi^*_1|z_1=0,z_2=1)\), and \(e^{(4)}_2 \min', e^{(4)}_2 \max'\) are the roots of function \((\pi^*_2|z_1=1,z_2=1 - \pi^*_2|z_1=0,z_2=0)\).

The optimal prices are,

\[
p^*_1|z_1=1,z_2=1 = \frac{2a_1+a_2+b[p_c(2e_1+e_2)(1-r)+2v_1+v_2]-\lambda(e_1-e_2)(1-r)}{3b}. \tag{21}
\]

\[
p^*_2|z_1=1,z_2=1 = \frac{a_1+2a_2+b[p_c(e_1+2e_2)(1-r)+v_1+2v_2]+\lambda(e_1-e_2)(1-r)}{3b}. \tag{22}
\]

**First Quadrant**

Two manufacturers achieve the equilibrium requirement under the strategies combination \((z_1 = 0, z_2 = 0)\) while satisfying the following two conditions simultaneously.

\[
\pi^*_1|z_1=1,z_2=0 - \pi^*_1|z_1=0,z_2=0 < 0. \tag{23}
\]

\[
\pi^*_2|z_1=0,z_2=1 - \pi^*_2|z_1=0,z_2=0 < 0. \tag{24}
\]

By solving and analyzing the functions, equilibrium conditions can be obtained.

1) If \(v_2 - v_1 \geq \frac{a_2-a_1+(e_1-e_2)(bp_c+\lambda)}{2b}\),
1.1) when \(0 \leq c < \frac{r[-a_1-2a_2-e_1(b_p+c)+b(v_2-v_1)]^2}{9b(2-r)}\), \((0, e_1^{(1)}_{\text{min}}) \cup (e_1^{(1)}_{\text{max}}', +\infty)\) for manufature 1 and \((0, e_2^{(1)}_{\text{min}}) \cup (e_2^{(1)}_{\text{max}}', +\infty)\) for manufature 2;
1.2) when \(c > \frac{r[-a_1-2a_2-e_2(b_p+c)+b(v_1-v_2)]^2}{9b(2-r)}\), \((0, +\infty)\) for both manufature 1 and 2;
2) If \(0 < v_2 - v_1 < \frac{a_2-a_1+(e_1-e_2)(b_p+c)}{2b}\),
2.1) when \(0 \leq c < \frac{r[-a_1-2a_2-e_2(b_p+c)+b(v_1-v_2)]^2}{9b(2-r)}\), \((0, e_1^{(1)}_{\text{min}}) \cup (e_1^{(1)}_{\text{max}}', +\infty)\) for manufature 1 and \((0, e_2^{(1)}_{\text{min}}) \cup (e_2^{(1)}_{\text{max}}', +\infty)\) for manufature 2;
2.2) when \(c > \frac{r[-a_1-2a_2-e_2(b_p+c)+b(v_1-v_2)]^2}{9b(2-r)}\), \((0, +\infty)\) for both manufature 1 and 2.

\(^*_{\text{e}}(1)_{\text{min}}^{(1)}_{\text{max}}, e_1^{(1)}_{\text{max}}\) are the roots of function \((\pi_1^{(1)}|_{z_1=1,z_2=0} - \pi_1^{(1)}|_{z_1=0,z_2=0})\), and \(e_2^{(1)}_{\text{min}}, e_2^{(1)}_{\text{max}}\) are the roots of function \((\pi_2^{(1)}|_{z_1=0,z_2=1} - \pi_2^{(1)}|_{z_1=0,z_2=0})\).

The optimal prices are
\[
\begin{align*}
p_1^{(1)}|_{z_1=0,z_2=0} &= \frac{2a_1+a_2+b[p_c(2e_1+e_2)+2v_1+v_2]+\lambda(e_2-e_1)}{3b}, \quad (25) \\
p_2^{(1)}|_{z_1=0,z_2=0} &= \frac{a_1+2a_2+b[p_c(2e_2+e_1)+v_1+2v_2]+\lambda(e_1-e_2)}{3b}. \quad (26)
\end{align*}
\]

Conclusion and Discussion

This study proposed a two-party game model to help generating companies make decisions on pricing and green technology implementation under the Cap-and-Trade scheme. The theoretical analysis reveals some interesting and valuable results. (1) Under different scenarios, either the cleaner manufacturer or the dirtier manufacturer may implement green technology, or both of them will (not) implement green technology. (2) The cost of green technology is a main factor that influence companies’ selection of green technology. Because if the cost is too high, the profits they make when implement green technology will even lower than they are not implement. Therefore, with the development of green technology, the cost of it may decline, and the probability of companies implement green technology would increase. (3) Unit carbon emission is also a very crucial factor. For example, in the fourth quadrant, only manufacturer with some specific ranges of unit carbon emission will implement green technology. If the unit carbon emission is too high or too low, the manufacturer will not implement green technology because of the tradeoff between implementation cost and revenue. Namely, high unit carbon emission leads to low production quantity, which is not profitable similarly with low unit carbon emission for implementing green technology.

Even though some results have been obtained, due to the complexity of the problem, several follow-up studies can be conducted. First of all, joint emission reduction between two manufacturers can be studied. Considering when they implement green technology together, and how they share the cost. Secondly, different impacts of government policies, such as emission allowance, on the game among supply chain members can be investigated. Lastly, a retailer can be added to analyze whether the retailer would share the cost of green technology and what is the cost-sharing mechanism.

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