

Evolutionary Game Analysis on Production and Emissions Reduction of Manufacturing Enterprises under Different Carbon Policies

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Abstract. This paper is to analyze the game behaviors of production and emission reduction between government and manufacturing enterprise under different carbon emission policies. To start with, based on different enterprises' behaviors of production and emission reduction under carbon policies of carbon tax and carbon cap and trade, cost-benefit functions for the enterprise and government are constructed respectively. Through the dynamic replication method, an evolutionary game model between enterprises and the government based on limited rationality is built. After that, the problem how participants' behaviors affect evolutionary stable strategies has been discussed. At last, the game analysis results show that both emission reduction cost of enterprise and government penalties on over emission as well as carbon cap would affect not only the government choice of carbon policy, but also the implementation of enterprises' production and emissions reduction.

1. Introduction

With the advance of industrialization, rapid economic growth happens constantly all over the world, meanwhile, however, greenhouse gases like carbon dioxide has been emitted extravagantly, which is a real and urgent threat to human survival. Therefore, a consensus to control carbon emission has been reached, in which carbon tax as well as carbon cap and trade is widely acceptable as the effective emission control measure ^[1]. On the one hand, as known to be the major emission source of greenhouse gases, manufacturing enterprises have to take responsibility to compliance with the government policy of energy saving and emission reduction. On the other hand, government regulations should also make appropriate and differential adjustment on the specific enterprise type and feature, such as different emissions policies, emissions punishments and carbon quotas ^[2]. That is to say, the development of low carbon economy is inseparable from the joint effort of enterprises and government. Therefore, studying the game behaviors between the government and manufacturing enterprises on carbon emission and reduction has important theoretical and practical significance.

Regarding game theory as an effective tool, many researchers have studied some conflict and cooperation problems of carbon emissions and other environmental protection among different economic entities. Based on the classical game theory, Forgo et.al (2005) ^[3] built an expanded model under perfect information to get general equilibrium conditions on emission reduction of greenhouse gases. The pricing strategy of environmental regulation was found by Chen and Sheu (2009) ^[4] through establishing a differential game model. Under EU carbon-trading scheme, Jaehn (2010) ^[5]

analyzes the influential factors and downturn reasons of carbon price through a cooperate game model. Zhao (2012) ^[6] using the game theory to analyze the decision-making process of reducing environmental risk and carbon emissions under the background of green supply chain management. Based on multiple traditional game models, Stephen and Anders (2013) ^[7] analyzed the effects of clean technology on energy conservation and emission reduction in different countries. Chen and Wang (2016) ^[8] utilized dynamic evolution to analyze how to design a reasonable environmental regulation mechanism so as to effectively urge firms to control pollution. Recently, some scholars introduced evolutionary game mode to discuss strategy selection behaviors of the government or environmental protection department and the enterprises, and then provided scientific suggestions according to the analysis results of evolutionary stable strategy to promote the effective implementation of production reduction, such as Wang et al. (2015) ^[9], Luo and Ruan (2015) ^[10], Fu et al. (2016) ^[11].

Considering the significance of carbon policies in guiding production and emission reduction, this paper constructs an evolutionary game model between a manufacturing enterprise and government to analyze corresponding equilibrium conditions under different policies of carbon tax and emissions trading. Moreover, findings do help not only to make practicable carbon emission policies for government but also to disclose the theoretical mechanism of the manufacturing enterprise's strategy choice on production and emission reduction.

2. The Evolutionary Model

To seek maximum profit is the priority of each enterprise under market competition, which indicates a conflict between the social goal of energy saving and emission reduction and the private goal of making profit. Therefore, government has a responsibility to make balance through implementing effective policies and regulations. Due to limited rationality and information asymmetry, the government and enterprise only take game strategies that will maximize their gains. In other words, the enterprise's decision that whether to reduce emissions depends on the game results with government. In order to demonstrate game process visually and formulate evolutionary game model, we put forward three hypotheses as follows:

H1: As the regulatory agency government has two options for enterprises, which are carbon tax (imposing on quantity) and carbon cap and trade (trade carbon quota freely).

H2: Under different carbon emission policies, the enterprise plays the game by maximizing profit. There are two possible response actions for the enterprise: ① purification production, namely, the enterprise produce with purification technics to reduce carbon emissions; ② no purification production, that is to say the enterprise achieve the maximum profit through reducing production cost.

H3: The market demand as well as product price is given as constant under all game strategies.

As a result, the game model has four different strategy combinations, which are demonstrated in **Table. 1.**

Table 1: Strategy combinations between government and manufacturing enterprise

		Government	
		Carbon tax (CT)	Carbon cap and trade (CCT)
Enterprise	Purification (P)	(P, CT)	(P, CCT)
	Non-purification (N-P)	(N-P, CT)	(N-P, CCT)

Similar to the studies of Yuan and Gen (2010) ^[12], Bai and Ma (2015) ^[13], parameter settings on the revenue and cost of the government and enterprise are given as follows: R_m is the sales revenue of the enterprise; in the strategy of non-purification with government policies, manufacturing cost is c_m while carbon emission is E_m ; in the strategy of purification with government policies, an incremental cost of manufacturing cost c_a (namely purification cost) occurs, which decreases carbon emissions to

E_r ($E_m > E_r$); when the government implements carbon tax policy, the corresponding tax rate is T ; in the strategy of carbon cap and trade, carbon price is P_c while carbon cap is E_0 ; the economic loss caused by atmospheric pollution is proportional to carbon emission, which is taken by the government, and damage value to environment from one-unit carbon emission is δ . Based on all above, the payoff matrix between the government and enterprise is shown as **Table. 2**.

Table 2: The payoff matrix between the government and manufacturing enterprise

		Government	
		Carbon tax	Carbon cap and trade
Enterprise	Purification	$R_m - (c_m + c_a) - T(E_m - E_r),$ $(T - \delta)(E_m - E_r)$	$R_m - (c_m + c_a) - P_c(E_m - E_r - E_0),$ $P_c(E_m - E_r - E_0) - \delta(E_m - E_r)$
	Non- purification	$R_m - c_m - T \cdot E_m,$ $(T - \delta)E_m$	$R_m - c_m - P_c(E_m - E_0),$ $P_c(E_m - E_0) - \delta \cdot E_m$

3. The Game Strategy Analysis

Evolutionary game theory is a combination of rational economics and evolutionary biology, which is widely used to seek game balance and analyze stability. With the assumption of limited rationality for players, the game decision is made through constant emulation and learning^[14].

3.1. Expected Return Function Formulation

For government, the fraction to adopt carbon tax is x , while $(1-x)$ shows the possibility to choose carbon cap and trade. Similarly, for the enterprise we set y as the possibility of purification production, where $(1-y)$ is the fraction of no purification production. Then U_{1T} , U_{1C} and U_1 are government expected returns for the adoption of carbon tax, carbon cap and trade, and the average return, which can be written as:

$$U_{1T} = y(T - \delta)(E_m - E_r) + (1 - y)(T - \delta)E_m$$

$$= -y(T - \delta)E_r + (T - \delta)E_m \quad (1)$$

$$U_{1C} = y[P_c(E_m - E_r - E_0) - \delta(E_m - E_r)] + (1 - y)[P_c(E_m - E_0) - \delta \cdot E_m]$$

$$= -y(P_c - \delta) \cdot E_r + P_c(E_m - E_0) - \delta \cdot E_m \quad (2)$$

$$U_1 = x \cdot U_{1T} + (1 - x) \cdot U_{1C}$$

$$= xy(P_c - T)E_r + x[T \cdot E_m - P_c(E_m - E_0)] - y(P_c - \delta) \cdot E_r + P_c(E_m - E_0) - \delta \cdot E_m \quad (3)$$

The enterprise expected return of purification production and no purification production under different carbon policies (U_{2Y} , U_{2N}) as well as average expected return (U_2) can be written as:

$$U_{2Y} = x[R_m - (c_m + c_a) - T(E_m - E_r)] + (1 - x)[R_m - (c_m + c_a) - P_c(E_m - E_r - E_0)]$$

$$= x[P_c(E_m - E_r - E_0) - T(E_m - E_r)] + R_m - (c_m + c_a) - P_c(E_m - E_r - E_0) \quad (4)$$

$$U_{2N} = x(R_m - c_m - T \cdot E_m) + (1 - x)[R_m - c_m - P_c(E_m - E_0)]$$

$$= x[P_c(E_m - E_0) - T \cdot E_m] + R_m - c_m - P_c(E_m - E_0) \quad (5)$$

$$U_2 = y \cdot U_{2Y} + (1 - y) \cdot U_{2N}$$

$$= xy(T - P_c)E_r + y(P_c E_r - c_a) + x[P_c(E_m - E_0) - T \cdot E_m] + R_m - c_m - P_c(E_m - E_0) \quad (6)$$

3.2. Replicated Dynamic Equation of Government

According to Malthusian formula ^[15], the replicated dynamic equation of the adoption of carbon tax can be written as:

$$F(x) = \frac{dx}{dt} = x(U_{1T} - U_1) = x(x-1)\{y(T-P_c)E_r - [T \cdot E_m - P_c(E_m - E_0)]\} \quad (7)$$

When $y = [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$, then $F(x) \equiv 0$, which is a stable condition anyhow.

When $y \neq [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$, once $F(x) = 0$, two balance points exist that are $x = 0$ and $x = 1$. Taking the derivation of $F(x)$:

$$\frac{dF(x)}{dx} = (2x-1)\{y(T-P_c)E_r - [T \cdot E_m - P_c(E_m - E_0)]\} \quad (8)$$

As $dF(x)/dx < 0$ is the inevitable requirement of evolutionary stable strategy, all possibility of $(T - P_c)$ should be analyzed:

(1) If $T > P_c$, that is $(T - P_c)E_r > 0$, considering $E_m > E_r$, so $T \cdot E_m - P_c(E_m - E_0) > (T - P_c)E_r > 0$, namely $[T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r] > 1$. Therefore $y < [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$ exists anyhow, which indicates $x = 1$ is an evolutionary stable strategy.

(2) If $T < P_c$, that means $(T - P_c)E_r < 0$, then we need to analyze all possibilities of $[T \cdot E_m - P_c(E_m - E_0)]$:

① If $T \cdot E_m - P_c(E_m - E_0) > 0$, namely $[T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r] < 0$, then there always exists $y > [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$, which means $x = 1$ is an evolutionary stable strategy.

② If $T \cdot E_m - P_c(E_m - E_0) < (T - P_c)E_r < 0$, namely $[T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r] > 1$, then $y < [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$ exists anyhow, which means $x = 0$ is an evolutionary stable strategy.

③ If $(T - P_c)E_r < T \cdot E_m - P_c(E_m - E_0) < 0$, namely $0 < [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r] < 1$, then there exist two different conditions:

When $y > [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$, $x = 1$ is an evolutionary stable strategy;

When $y < [T \cdot E_m - P_c(E_m - E_0)] / [(T - P_c)E_r]$, $x = 0$ is an evolutionary stable strategy.

3.3. Replicated dynamic equation of the manufacturing enterprise

The same as last sub-section, the replicated dynamic equation of purification production can be written as:

$$F(y) = \frac{dy}{dt} = y(U_{2Y} - U_2) = y(y-1)[x(P_c - T)E_r - (P_cE_r - c_a)] \quad (9)$$

When $x = (P_cE_r - c_a) / [(P_c - T)E_r]$, then $F(y) \equiv 0$, which is a stable condition anyhow.

When $x \neq (P_cE_r - c_a) / [(P_c - T)E_r]$, once $F(y) = 0$, two balance points exist that are $y = 0$ and $y = 1$. Taking the derivation of $F(y)$:

$$\frac{dF(y)}{dy} = (2y-1)[x(P_c - T)E_r - (P_cE_r - c_a)] \quad (10)$$

(1) If $T > P_c$ that means $(P_c - T)E_r < 0$, then all possibilities of $(P_cE_r - c_a)$ should be analyzed:

① If $P_c E_r - c_a > 0$, namely $(P_c E_r - c_a)/[(P_c - T)E_r] < 0$, then there always exists $x > (P_c E_r - c_a)/[(P_c - T)E_r]$, which means $y = 1$ is an evolutionary stable strategy.

② If $P_c E_r - c_a < (P_c - T)E_r < 0$, that is $(P_c E_r - c_a)/[(P_c - T)E_r] > 1$, then $x < (P_c E_r - c_a)/[(P_c - T)E_r]$ exists anyhow, which means $y = 0$ is an evolutionary stable strategy.

③ If $(P_c - T)E_r < P_c E_r - c_a < 0$, that is $0 < (P_c E_r - c_a)/[(P_c - T)E_r] < 1$, then there exist two different conditions:

When $x > (P_c E_r - c_a)/[(P_c - T)E_r]$, $y = 1$ is an evolutionary stable strategy;

When $x < (P_c E_r - c_a)/[(P_c - T)E_r]$, $y = 0$ is an evolutionary stable strategy.

(2) If $T < P_c$, that is $(P_c - T)E_r > 0$, all possibilities of $(P_c E_r - c_a)$ should be analyzed:

① If $P_c E_r - c_a < 0$, namely $(P_c E_r - c_a)/[(P_c - T)E_r] < 0$, then there always exists $x > (P_c E_r - c_a)/[(P_c - T)E_r]$, which means $y = 0$ is an evolutionary stable strategy.

② If $P_c E_r - c_a > (P_c - T)E_r > 0$, that is to say $(P_c E_r - c_a)/[(P_c - T)E_r] > 1$, then $x < (P_c E_r - c_a)/[(P_c - T)E_r]$ exists anyway, which means $y = 1$ is an evolutionary stable strategy.

③ If $0 < P_c E_r - c_a < (P_c - T)E_r$ that is $0 < (P_c E_r - c_a)/[(P_c - T)E_r] < 1$, then there exist two different conditions: When $x > (P_c E_r - c_a)/[(P_c - T)E_r]$, $y = 0$ is an evolutionary stable strategy, while $x < (P_c E_r - c_a)/[(P_c - T)E_r]$, $y = 1$ is an evolutionary stable strategy.

4. The evolution results analysis

To be more visible, **Figure 1** shows replicator dynamic trends of the government and manufacturing enterprise under different circumstances, where we can obtain different balance points.

(1) When the initial state of the game located in **Figure 1** (i) zone I, **Figure 1** (ii) zone II and **Figure 1**(ii) zone IV, the game will converge to balance point of (1,1), that is to say (Carbon tax, Purification production) is the inevitable choice between two game groups of the government and manufacturing enterprise.

(2) When the initial state located in **Figure 1** (i) zone III, **Figure 1** (i) zone IV and **Figure 1** (ii) zone I, the game will converge to balance point of (1,0), which indicates (Carbon tax, No purification production) is the inevitable choice between two game groups of the government and manufacturing enterprise.

(3) When the initial state located in **Figure 1** (ii) zone II, the game will converge to balance point of (0,0), which means (Carbon cap and trade, No purification production) is the inevitable choice between two game groups of the government and manufacturing enterprise.

(4) When the initial state located in **Figure 1** (ii) zone III, the game will converge to balance point of (0,1), that is to say (Carbon cap and trade, Purification production) is the inevitable choice between two game groups of the government and manufacturing enterprise.

As can be seen from **Figure 1**, $(x, y) = (0, 1), (1, 0), (1, 1), (0, 0)$ are all the saddle points when $T < P_c$, which indicates there exists no evolutionary stable strategy. When $T > P_c$, $(x, y) = (1, 0)$ is still the saddle point while $(x, y) = (1, 1)$ evolves to the stationary point, and $(x, y) = (0, 1), (0, 0)$ are unstable points.

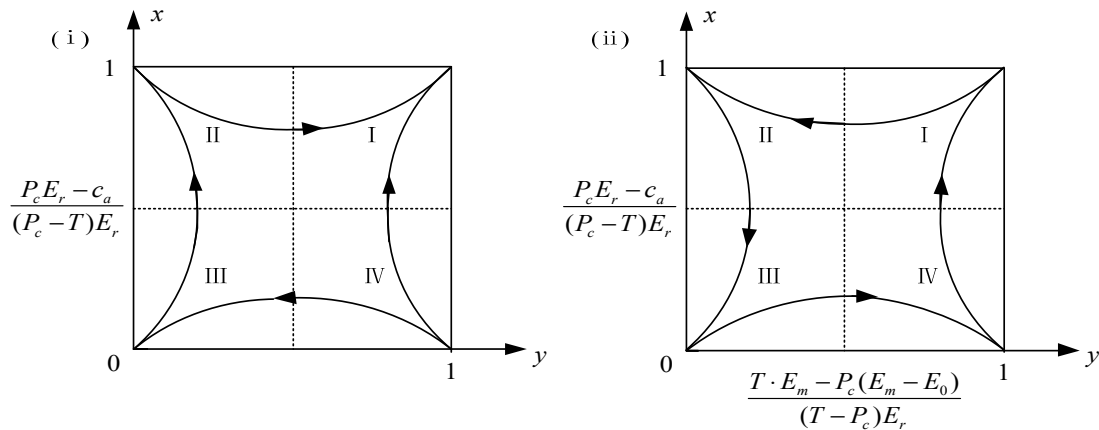


Figure 1: The evolutionary game route under scenarios of (i) $T > P_c$ and (ii) $T < P_c$

Based on analyses above, conclusions are made as follows:

(1) For two game groups of the government and manufacturing enterprise, $(x, y) = (1, 1)$ is the only stationary point when $T > P_c > c_a / E_r$, which means the corresponding evolutionary stable strategy is (Carbon tax, Purification production). The possible explanation for this is that when carbon price is lower than tax rate, the implementation of carbon cap and trade policy will make the manufacturing enterprise have more some space for carbon emissions besides carbon quotas, which is definitely not conducive to promoting purification production. For the manufacturing enterprise, they will definitely select purification production when the carbon cost savings is higher than purification cost. Therefore, under the premise of economic development, government could force enterprises to implement low-carbon production through increasing carbon tax as well as carbon price properly.

(2) Two kinds of evolutionary stable strategies exist for government when $T < P_c$: ① $x = 1$ as the stationary point when $E_0 > (P_c - T)E_m / P_c$, which means carbon tax will be the policy choice once carbon quota exceeds a certain value; ② $x = 0$ as the stationary point when $E_0 < (P_c - T)(E_m - E_r) / P_c$, which means carbon cap and trade will be the policy choice once carbon quota is less than a certain value. The result shows that when carbon cap and trade policy is implemented, the carbon quotas directly influence the development of low-carbon economy. Although the increase of the carbon price would increase the carbon emission cost, carbon quota also determines the production strategy of the enterprise. Therefore, the government should provide scientific carbon quotas according to the environmental tolerance of carbon dioxide and other greenhouse gases and carbon emissions of the enterprise, and actively guides the manufacturing enterprise to develop low-carbon production.

(3) For the enterprise, when $T > P_c$ or $T < P_c$, there always exist two kinds of evolutionary stable strategies $y = 0$ and $y = 1$, which depends mostly on carbon emission cost and purification cost. The result shows that when $P_c E_r > c_a$ or $T \cdot E_r > c_a$, that is to say carbon emission cost is larger than purification cost, then $y = 1$ is the evolutionary stable point, which indicates the enterprise will select purification production to reduce carbon emissions to achieve maximum profit. However, under the scenario of $P_c E_r < c_a$ or $T \cdot E_r < c_a$, as purification cost is larger than carbon emission cost, it is better for the profit-seeking enterprise to take measures to reduce manufacturing cost other than carbon emission cost, where $y = 0$ is the stationary point. To sum up, there are two specific measures to promote enterprises emission reduction: on the one hand, the government could exact strict punishments on over emissions enterprises, which is aimed to increase carbon emission cost; on the other hand, the government and enterprise should work together to introduce and develop advanced

purifying techniques to decrease unit cost of emission reduction, which could encourage enterprises to select purification production to achieve a win-win situation.

(4) There is no evolutionary stable strategy when $T < P_c < c_a/E_r$ and $E_0 < (P_c - T)(E_m - E_r)/P_c$, which indicates a periodic behavior in the game process between the government and enterprise. In the sight of public choice theory, as the government is also an economic man, the emergence of such periodic behavior during the implementation of public policies is nothing strange in real economic life.

5. Conclusions and Future Research

Based on evolutionary game theory, this paper has analyzed the game behaviors between the government and manufacturing enterprises under different carbon emission policies. By decomposing evolutionary stable strategies, we found that emission reduction cost plays a key role to the purification production of manufacturing enterprises. In addition, besides the key role that advanced carbon emission technique plays in emissions reduction, the emissions punishments and carbon cap could also affect strategy choices of the government and manufacturing enterprises.

What we have done in this paper is to discover the mechanism that how carbon tax policy as well as carbon cap and trade policy affects enterprises choice on production and emission reduction, while what we have not studied is the essential difference of those two policies, such problems as implementation cost difference between different carbon emission policies. In addition, we can further study the effect of government subsidy on the evolutionary stable strategies. Last but not least, it also deserves future study to verify the conclusions of this paper through empirical analysis.

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