Will Enterprises Choose Low-carbon Production Technology? Evolutionary Game Model Considering Consumers’ Environmental Protection Moral and Market Clearing

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Abstract. Considering that manufacturing enterprises have two production strategies, one is traditional production strategy, and the other is low-carbon production strategy. Consumers have environmental protection moral, they are composed of green consumers and non-green consumers. In addition, enterprises are bounded rational. Based on this, we constructed an evolutionary game model of low-carbon production strategy selection, and analyzed the conditions for achieving the evolutionary stable equilibrium (ESS). Furthermore, the co-evolution of the proportion of companies adopting low-carbon strategy and the proportion of green consumers is also analyzed.

Keywords: Low-carbon; Carbon Emission; Consumers’ environmental protection moral; Evolutionary game model.

1. Introduction

With the rapid development of economy, manufacturing enterprises gradually produce more and more products to ensure that they can occupy a part of market share in the competitive market environment. However, in the production process of products, manufacturing enterprises will simultaneously emit a large amount of carbon dioxide into the atmosphere. Carbon dioxide is the main component of greenhouse gases. A large number of carbon emissions have led to serious global environmental deterioration, aggravating global climate change gradually, causing global warming, increasing greenhouse effect and environmental pollution. Global warming has brought severe challenges to human survival and development.

Due to the strong impact of environmental problems on society and economy, in order to help developing countries to reduce the emission of pollutants without damaging economic development. The low-carbon development pattern has gradually attracted more attention. Developing low-carbon economy is very important for every country to improve the environment and achieve sustainable economic development. Changing the way of production and life of human beings and realizing the sustainable development of low-carbon economy are becoming the focus of global attention. In order to reduce carbon emissions and make the economy sustainable, the government issued a number of policies to promote the development of low-carbon economy, including carbon cap-and-trade policy, low-carbon subsidy policy and carbon tax policy.

In different industrial sectors, manufacturing is often the largest contributor to carbon emissions in most developing and developed countries [1]. Considering the low-carbon environmental protection policies formulated by the government and the increasing environmental protection moral of consumers, more
and more manufacturing enterprises begin to use carbon emission reduction technology to produce green products. In order to achieve more sustainable consumption and production, low-carbon manufacturing has gradually become an important research area. Low-carbon manufacturing is generally referred to as the production and manufacturing process of producing low-carbon emission intensity through effective and efficient use of energy and resources [2]. Although the low-carbon development mode is accepted by more and more people, the cost and risk of inventing low-carbon technology and products and using low-carbon technology in production are relatively high for enterprises, which tend to avoid risks. In addition, the price of low-carbon products is usually higher than that of ordinary products. In the case of weak consumer awareness of environmental protection, enterprises manufacturing low-carbon products face less market demand. Therefore, in the absence of low-carbon policies, enterprises do not have enough motivation to overcome their own interests and reduce carbon emissions. The government is willing to encourage more enterprises to adopt low-carbon strategy through various subsidies.

In actual operation process, the decision-makers of enterprises may not be completely rational, but bounded rational. In the enterprise alliance, enterprises interact with each other. The decision-making of enterprises in production and operation not only depends on their own risk preference, but also depends on the mutual observation, continuous imitation and learning among enterprises in the alliance. Evolutionary game is more suitable to describe the dynamic decision-making process between enterprises.

Compared with traditional manufacturing technology, low-carbon manufacturing technology is not only a transformation, but also an innovation. The transition to low-carbon manufacturing will require innovation and investment in a series of low-carbon technologies. Only when technology is popularized and widely applied can innovation affect economic and social development [3]. The diffusion of green (low-carbon) manufacturing technology supports the development of low-carbon path, thus enhancing the ability to mitigate climate change [4]. Therefore, only when low-carbon manufacturing technology is widely used among enterprises, can the whole society realize the transformation to low-carbon economy.

2. Literature Review

There are many previous studies on low-carbon production, low-carbon policies, diffusion of innovative technologies, evolutionary games [5,6], evolutionary games on complex networks and diffusion on complex networks. Tapiero CS(2005) studies the evolutionary game of environmental quality control [7]. Cohen MC et al. (2015) pointed out that when making policy, policymakers usually consider average market demand and tend to ignore the uncertainty of demand [8]. Further, the author studied three questions, namely, i) How should the government design green subsidy when facing uncertain consumer market; ii) How do uncertain market demand and subsidy policies affect suppliers' prices and production volumes; iii) How does the subsidy policy affect consumers? The optimal subsidy level is obtained under the condition of the minimum government expenditure and the given green adoption target level. And another model in the article is to maximize the total social welfare of the government, taking into account subsidies, emission reduction and social welfare.

Zhu QH, Geng Y et al. (2010) investigated the implementation, performance improvement and driving factors of green supply chain management through a survey of nine large Japanese manufacturing enterprises [9]. It is found that large enterprises can build a win-win relationship with their small suppliers and consumers so as to make the whole supply chain green and realize the sustainable development of the supply chain. In addition, the research have shown that the government's formulation of appropriate regulations and policies can help green supply chain management spread from leading enterprises to small enterprises. Cao KY et al. (2017) studied the impact of carbon cap-and-trade policy (CTP) and low carbon subsidy policy (LCSP) on the production and carbon emission reduction level of manufacturing enterprises, and then explored which policy was better for the society [10]. This paper explored the optimal production strategy and carbon emission reduction level of manufacturing enterprises under the two policies, as well as the government's optimal decision on carbon quota and low carbon allowance per unit. To provide insights for policy makers in the government and
production decision of manufacturing enterprises. The results show that when the price of carbon trading increases, the level of carbon emission reduction increases. Carbon trading price is not always bad for manufacturers' profits. Monopoly, externality and information asymmetry lead to insufficient resource allocation in energy and low-carbon markets. Therefore, the government often uses taxes, subsidies and other measures to compensate for market failure [11]. Therefore, the government's policy tools are crucial to achieve the strategic goal of low-carbon economy [12]. Zhang LP (2019) constructed an evolutionary game model of green (low-carbon) technology diffusion among enterprises under the complex network environment, simulating the influence of carbon trading market, environmental tax and subsidy on the diffusion of green manufacturing technology in China's manufacturing enterprises in the BA scale-free network (Barabási-Albert model) [13,14]. The results show that: improving the carbon trading market, raising the environmental tax standard and strengthening the input subsidy can help the green manufacturing technology to be fully spread in the whole enterprise alliance; excessive environmental tax will limit the diffusion of green manufacturing technology in the inter-enterprise alliance; excessive subsidy does not promote the diffusion of green manufacturing technology in the inter-enterprise alliance.

In the consumer market, consumers' demand for ordinary products and green low-carbon products not only depends on the price and function of products, but also depends on consumers' awareness of environmental protection [15]. Tian YH et al. (2014) studied how subsidy policies promote the diffusion of green supply chain management (GSCM) in China by establishing system dynamics (SD) model. Using evolutionary game theory, the paper analyzed the relationship among the government, enterprises, consumers and other stakeholders [16]. Finally, taking Chinese automobile manufacturing industry as an example, the model is used to simulate the diffusion process of GSCM. The results show that subsidies to manufacturers are more conducive to promoting the diffusion of green supply chain than subsidies to consumers, and another key factor affecting the diffusion of green supply chain is environmental protection awareness. Guo Benhai et al. (2012) established a mechanism for high energy consuming industries to withdraw from the market by using evolutionary game theory, and obtained that whether high energy consuming enterprises withdraw from the market mainly depends on the government's incentive measures [17]. Wang Lu et al. (2018) put the factors of industry network topology, consumer environmental protection awareness and enterprise heterogeneity into the modeling analysis of low-carbon strategy diffusion, and put forward the network evolution game model of low-carbon production strategy diffusion [18]. Based on the complex network, the spread of low-carbon production strategy is studied, and the influence of statistical characteristics of complex network on the diffusion is also considered.

Wang's research is quite significant, but we think there is one deficiency, the proportion of green consumers and brown consumers in the consumer market does not change with the proportion of green low-carbon products and traditional products in the product market, that is, the balance between the consumer market and the product market has not been achieved, and the market has not been cleared. When $\beta$ exceeds $\beta^*$, the evolution result is that all enterprises adopt low-carbon strategy. We assume that the $\beta$ equals 0.7, the evolutionary stability strategy is: 70% of consumers in the market choose low-carbon products, 30% choose traditional products. But at this time, the evolutionary stable equilibrium is $x=1$. That is all enterprises produce low-carbon products, so when the supply of low-carbon products exceeds the demand, enterprises are still producing, which cannot achieve the market clearing. Therefore, the proportion of green consumers should be the same as the proportion of enterprises choosing low-carbon strategies. That is, $\beta = x$.

Based on this literature, we improve the model and assume that the proportion of green consumers in the consumption market is the same as that of green and low-carbon products in the product market. In other words, when considering the market clearing, the proportion of companies adopting low-carbon production strategy co-evolved with the proportion of green consumers. we constructed an evolutionary game model of low-carbon production strategy selection, and analyzed the conditions for achieving the evolutionary stable equilibrium (ESS).
3. Model Description
The companies in the alliance are the players in this game model, enterprises have two production strategy choices in the production process. One is to choose the traditional strategy with relatively low product price and production cost. The products they produce are called traditional products. However, in the production process of such products, a large amount of carbon dioxide will be emitted into atmosphere. The emission of such greenhouse gas will have a certain negative impact on the environment and accelerate global warming. The other is to choose low-carbon strategy with relatively high product price and production cost, and this kind of product is called low-carbon product. Compared with the traditional strategy, the amount of carbon dioxide emitted into the air during the production process of per unit product is lower, so the production of such products will reduce the pollution degree to the environment. Because the low-carbon strategy needs to upgrade the original production technology or additional purchase the corresponding low-carbon production equipment, the enterprises that choose the low-carbon strategy have high cost and high risk. In order to encourage enterprises to change their production strategy from traditional strategy to low-carbon strategy, the government will formulate subsidy policy for enterprises that choose the low-carbon strategy, and provide certain subsidies according to the low-carbon degree of the products. The consumers in the market are composed of green consumers and non green consumers. Green consumers refer to those who are willing to actively buy low-carbon products; non green consumers refer to those who only buy traditional products. The demand of green consumers is met by enterprises producing low-carbon products, and the demand of non green consumers is met by enterprises that produce traditional products. When the market clears, the proportion of green consumers should be the same as that of companies adopting low-carbon production strategy. Therefore, the model also describes the co-evolution of the proportion of companies adopting low-carbon production strategy and that of green consumers.

4. Assumptions
(1) The industry of the enterprise is the perfectly competitive industry;
(2) Enterprises are homogeneous;
(3) The government subsidizes low-carbon products according to the low-carbon degree of per unit product;
(4) Consumers are composed of green consumers and non green consumers;
(5) Consumer demand is met by all incumbent companies on average. The product demand of green consumers is only satisfied by the enterprises that choose low-carbon strategy, while the demand of non green consumers is only satisfied by the enterprises that choose traditional strategy;
(6) \( p^l > p^r \geq 0 \), per unit price of low carbon products is higher than that of traditional products;
(7) \( c^l > c^r \geq 0 \), per unit cost of low carbon products is higher than that of traditional products;
(8) \((p^l - c^l + gs)q > I\), When choosing low-carbon strategy, the profit of enterprises is greater than the total investment of low-carbon technology;
(9) \((p^r - c^r)q > I\), When choosing the traditional strategy, the profit of enterprises is also greater than the investment of low-carbon technology.

Based on the above assumptions, the evolutionary game model of low-carbon strategy selection is established.

Symbols and definitions are shown in Table 1.

The \( l^c \) means manufacture enterprise adopts the low-carbon product strategy, while the \( l^r \) represents manufacture enterprise adopts the traditional product strategy.

When the proportion of green consumers is the same as that of enterprises adopting low-carbon strategy, the market will clear up. The percentage of companies adopting low-carbon production strategy \( x \) can also be interpreted as the probability of single enterprise adopting low-carbon strategy \( x \). The probability of adopting the traditional strategy is \((1-x)\).
Table 1. Symbols and definitions.

| symbols | Descriptions                                      | symbols | Descriptions                                      |
|---------|---------------------------------------------------|---------|---------------------------------------------------|
| $p^l$   | Price of low-carbon products                      | $p^t$   | Price of traditional products                     |
| $c^l$   | Cost of low-carbon products                        | $c^t$   | Cost of traditional products                      |
| $g$     | Low carbon degree of products                      | $s$     | Subsidies for low-carbon products                  |
| $x$     | Proportion of enterprises choosing low-carbon strategies | $1-x$   | Proportion of enterprises choosing traditional strategies |
| $u^l$   | The expected profit of enterprise choosing low-carbon strategies | $u^t$   | The expected profit of enterprises choosing traditional strategies |
| $-u$    | Average profit of enterprises with different strategies | $I$     | Investment in low carbon technology               |
| $x$     | Proportion of green consumers                      | $1-x$   | Proportion of non green consumers                 |
| $n$     | Total number of enterprises in the industry        | $Q$     | Total demand in the market                         |
| $q$     | Average demand of enterprises, $q=Q/n$             |         |                                                   |

The payoff matrix is as follows Table 2:

Table 2. Payoff matrix.

| Green consumers $x$ | Non green consumers $(1-x)$ |
|---------------------|-----------------------------|
|                     | Low carbon $x$ | Traditional $(1-x)$ | Low carbon $x$ | Traditional $(1-x)$ |
|                     | $p^l - c^l + gs)q - I$ | $2(p^l - c^l + gs)q - I$ | $-I$ | $-I$ |
|                     | $(p^t - c^t + gs)q - I$ | $0$ | $-I$ | $2(p^t - c^t)q$ |
| Enterprise $x$       |                     | | | |
| Traditional $1-x$   | $0$ | $2(p^t - c^t)q$ | $(p^t - c^t)q$ | $(p^t - c^t)q$ |

When the consumers in the market are green consumers: If both enterprises choose the low-carbon production strategy, at this time, the enterprises in the market share the demand of the product market equally. Therefore, the profits of the enterprises that choose the low-carbon production strategy are $(p^l - c^l + gs)q - I$. The first represents the price of low-carbon products, the second represents the
cost of producing low-carbon products, the third represents the government's subsidy to enterprises according to the green degree of products, and the last represents the investment cost of enterprises to low-carbon production technology; If one enterprise chooses the low-carbon production strategy and the other chooses the traditional production strategy, at this time, because the green consumers only buy low-carbon products, the market demand of the consumers for the green low-carbon products in the market is met by the enterprises that choose the low-carbon production strategy, and the market demand of the enterprises that choose the traditional production strategy is 0. Therefore, the profit of enterprise that choose low-carbon production strategy is 2\((p^{lc} - c^{lc} + gs)q - I\); the profit of enterprise that choose traditional production strategy is 0. If both enterprises choose the traditional production strategy, since the consumers are green consumers, at this time, the market demand of both enterprises is 0. Therefore, the profit of both enterprises is 0. Similarly, when the consumers in the market are non green consumers, the analysis on the right side of the payoff matrix is the same as above.

The expected profit of enterprise choosing low-carbon strategy is as follows:

\[
u^{lc} = (x - 1 - x) \left( \begin{pmatrix} p^{lc} - c^{lc} + gs \\ 2(p^{lc} - c^{lc} + gs)q - I \\ 2(p^{lc} - c^{lc} + gs)q - I - I \end{pmatrix} \right) \begin{pmatrix} x \\ 1 - x \end{pmatrix}.
\]

It can be simplified as follows:

\[
u^{lc} = (p^{lc} - c^{lc} + gs)(2 - x)qx - I
\]

The expected profit of enterprise choosing traditional strategy is as follows:

\[
u^{u} = (x - 1 - x) \left( \begin{pmatrix} 0 \\ 2(p^{u} - c^{u})q \\ (p^{u} - c^{u})q \end{pmatrix} \right) \begin{pmatrix} x \\ 1 - x \end{pmatrix}.
\]

It can be simplified as follows:

\[
u^{u} = (p^{u} - c^{u})(x + 1)q(1 - x)
\]

The average expected profit of low carbon strategy and traditional strategy is as follows:

\[
\bar{u} = xu^{lc} + (1 - x)u^{u}
\]

The replication dynamic equation is:

\[
F(x) = \frac{dx}{dt} = x(u^{lc} - \bar{u}) = x(1 - x)(A - Bx)
\]

And,
\[ A = 2(p^c - c^c + gs)qx - (p^r - c^r)(1-x)q-I. \]  

(7)

\[ B = (p^c - c^c + gs)qx + (p^r - c^r)(1-x)q. \]  

(8)

When \( F(x) = 0 \), namely, \( \frac{dx}{dt} = 0 \), we can get three kinds of stable states as follows:

(9)

\[ z x_1^* = 0. \]

\[ x_2^* = 1. \]  

(10)

\[ x_3^* = \frac{p^c - c^c + gs}{p^c - c^c + gs + p^r - c^r} \pm \sqrt{\frac{(p^c - c^c + gs)^2}{(p^c - c^c + gs + p^r - c^r)^2} + \frac{(p^r - c^r)q-I}{(p^c - c^c + gs + p^r - c^r)q}.} \]  

(11)

5. The ESS Analysis

(i) When \( A \leq 0 \),

\[ 0 \leq x \leq A_1 = \frac{(p^r - c^r)q + I}{[2(p^c - c^c + gs) + (p^r - c^r)q]q} < 1. \]  

(12)

\[ x_1 = \frac{(p^r - c^r)q + I}{[2(p^c - c^c + gs) + (p^r - c^r)q]q} < 1. \]  

(13)

The phase diagram is as follows Figure 1:

\[ ESS: x_1^* = 0, 0 < x < x_1 \]

Figure 1. Phase diagram.

When the initial state is \( x < x_1 \), the ESS is \( x_1^* = 0 \). Namely, in this situation, there is no enterprise is willing to adopt low-carbon strategy. Correspondingly, the proportion of green consumers is also 0.

(ii) When \( 0 < A < B \), \( x_1 < x < x_2 \),
\[ x_2 = \frac{2(p^r_c - c^r_c)q + I}{[(p^l_c - c^l_c + gs) + 2(p^r_c - c^r_c)]q}. \]  

(14)

Namely,

\[ \frac{(p^r_c - c^r_c)q + I}{2(p^l_c - c^l_c + gs) + (p^r_c - c^r_c)]q} < x < \frac{2(p^r_c - c^r_c)q + I}{[(p^l_c - c^l_c + gs) + 2(p^r_c - c^r_c)]q}. \]  

(15)

Because \((p^r_c - c^r_c)q > I\), the equation (11) takes ‘+’ sign, then, the \(x^*_3\) is as follows,

\[ x^*_3 = \frac{p^l_c - c^l_c + gs}{p^l_c - c^l_c + gs + p^r_c - c^r_c} + \frac{(p^r_c - c^r_c + gs)^2}{(p^l_c - c^l_c + gs + p^r_c - c^r_c)^2} + \frac{(p^r_c - c^r_c)q - I}{(p^l_c - c^l_c + gs + p^r_c - c^r_c)q}. \]  

(16)

The phase diagram is as follows Figure 2:

\[ \frac{dx}{dt} \quad ESS: x^*_3 = -\, x_1 < x < x_2 \]

\[ x_3 \]

\[ 1 \]

\[ x \]

\[ 0 \]

Figure 2. Phase diagram.

When the initial state is \(x_1 < x < x_2\), the ESS is equation (16). Correspondingly, the proportion of green consumers is also equation (16).

(iii) When \(A \geq B, x_2 \leq x < 1\)

The phase diagram is as follows Figure 3:

\[ \frac{dx}{dt} \quad ESS: x^*_2 = 1, x_2 \leq x \leq 1 \]

\[ 0 \]

\[ 1 \]

\[ x \]

Figure 3. Phase diagram.

When the initial state is \(x \geq x_2\), the ESS is \(x^*_2 = 1\). Namely, in this situation, all enterprises adopt low-carbon strategy. Correspondingly, the proportion of green consumers is also 1.

The proportion of enterprises adopting low-carbon strategy has co-evolved with the proportion of green consumers.
6. Conclusion
Considering the consumers’ environmental protection moral, based on Wang's model, we consider the clearing of product market. Based on this, we establish an evolutionary game model for the production strategy selection of enterprises. Furthermore, the evolutionary stable equilibrium of the model is analyzed. We get that when the proportion of enterprises that initially choose low-carbon production strategy is small, it is not conducive to the diffusion of low-carbon production strategy. Finally, enterprises in the market do not choose low-carbon production strategy. Correspondingly, the proportion of green consumers is also 0. The proportion of the initial selection of low-carbon production strategy is affected by the price and cost of traditional products, the price and cost of low-carbon products, government subsidies for low-carbon products and the investment cost of low-carbon production technology. When \( x_1 < x < x_2 \), the evolutionary stable equilibrium is \( x_3^* \). That is to say, enterprises with \( x_3^* \) proportion choose low-carbon production strategy, while the rest choose traditional production strategy. Accordingly, the percentage of green consumers in the market is \( x_3^* \), and the proportion of non green consumers is \( 1 - x_3^* \). Through sensitivity analysis, we find that the higher the price of low-carbon products, the lower the cost of low-carbon products, the more conducive to the spread of low-carbon production strategy. Similarly, the lower the price of low-carbon products, the higher the production cost of low-carbon products, and the more unfavorable the spread of low-carbon production strategy. The lower the price of traditional products, the higher the cost of traditional production strategy, and the more conducive to the spread of low-carbon production strategy. In addition, the higher the government subsidies for low-carbon products, the more conducive to the diffusion of low-carbon production strategy; the higher the investment cost of low-carbon production technology, the less conducive to the diffusion of low-carbon production technology. When the percentage of companies that initially choose low-carbon production strategy is large, it can also be explained that the larger the proportion of green consumers in the market, the more conducive to the diffusion of low-carbon production strategy. Finally, all enterprises choose low-carbon production strategy. At this time, the proportion of green consumers is also 1.

The market power is not considered in this model, and the evolutionary game of low-carbon strategy choice of enterprises with market power can be considered in further research. In this model, it is assumed that the enterprise is risk neutral. In the actual operation process, the enterprise may also be risk averse. In addition, we can also consider the evolutionary game problem of enterprise production strategy selection under the government's carbon tax policy, and how the government makes incentive mechanism to promote the spread of low-carbon technology. Furthermore, the government can make policies that minimize the cost of environmental pollution without interfering with the market as far as possible. In the future, we can consider different situations of market structure.

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