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RESEARCH ON THE CARBON EMISSION REGULATION AND OPTIMAL STATE OF MARKET STRUCTURE: BASED ON THE PERSPECTIVE OF EVOLUTIONARY GAME OF DIFFERENT STAGES

Hao Sun* and Guangkuo Gao

Abstract. In the background of green and low-carbon development, many enterprises still have illegal emission behaviors to obtain excess revenue. Therefore, it is an urgent problem to restrain the illegal emission behaviors of enterprises through external supervision. This paper mainly studies the regulatory system composed of government and enterprises. We divide the regulation into two phases: loose regulation and strict regulation, analyzed the impact of government regulatory intensity on carbon emission behavior enterprises and industry market structure through the evolutionary game model. The results show that with the increase of the intensity of government supervision, leading enterprises will gradually complete the transformation and upgrading from low carbon to compliant production. The leading enterprises with low carbon technology have strengthened their dominant position in the market, while the enterprises without low carbon technology are constrained by carbon emissions and can only continue to stay in the industry market by buying carbon emission rights or exiting the market. The industry market structure gradually changed from a decentralized competition structure to a centralized oligopoly structure.

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1. Introduction

It is well known that enterprises' carbon emissions have a significant impact on the global climate. To reduce the carbon emission of enterprises, many countries have promulgated various regulations on carbon emission to restrain the carbon emission behavior of enterprises [19]. In the long term, low-carbon production can promote enterprises to reduce the risk cost of environmental punishment, thus offsetting the input cost of enterprises, and finally achieving a win–win situation between environmental governance and profit objectives [1, 21, 22]. However, in the short term, low-carbon investment by enterprises will increase the production cost of enterprises, since enterprises prefer to determine profits and economic benefits, it is difficult for them actively to the low-carbon investment of low short-term economic benefits and uncertain future returns with their limited financial resources [8, 30]. Therefore, in the absence of external supervision, it is difficult to control carbon emissions and optimize market structure only through the adjustment of internal interests and the promotion of social

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Business School, University of Shanghai for Science and Technology, Shanghai 200093, P.R. China.
*Corresponding author: 705143946@qq.com

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responsibility consciousness. However, excessive supervision will restrict the development and production of enterprises, thus affecting economic development.

The government, leading enterprises, and following enterprises have new characteristics and evolution rules under the condition of government supervision. In the process of carbon regulation, the choice of enterprise behavior strategy is inevitably influenced by the horizontal division of enterprise and the vertical decision of the government. For example, in the carbon emission supervision system composed of the government, the leading enterprise, and the following enterprise, the production strategy of the leading enterprise will be affected by the strategy of the government and the following enterprise. In turn, the government's regulatory strategy will also be affected by the strategy of enterprises. Therefore, exploring the interaction and behavior decision between government and enterprises in the process of government regulation is of great significance for economic development and market structure optimization.

Due to the complexity of the decision-making environment and the difference in cognitive ability, the government and enterprise show certain irrational characteristics in the decision-making process. With respect to the typical game theory model's assumption of perfect rational, the evolutionary game can relax the rational assumption of game participants. It effectively makes up for the deficiency of traditional game theory [5,17], so we choose the evolutionary game method for analysis.

Under the carbon peaking and carbon neutrality goals, many local governments have increased their efforts to regulate carbon emissions of enterprises. In order to control carbon emissions, some local governments have implemented mandatory regulatory measures, such as "power rationing", which has seriously affected the production of enterprises and the normal life of residents. China's Ministry of Ecology and Environment pointed out that green and low-carbon development should be promoted in an orderly manner, and economic development and environmental protection should be coordinated. Carbon emission reduction is a gradual process, which requires enterprises to be given time to transform, rather than adopting one-size-fits-all regulatory measures.

Therefore, based on the above analysis, considering the change of carbon emission regulation intensity, we divide carbon emission regulation into two stages: loose regulation and strict regulation, and dynamically connects the two stages. Using evolutionary game model, we analyze the strategic choices of government and enterprises in the stage of loose regulation and the strategic choices of leading enterprises and following enterprises in the stage of strict supervision. Finally, we carry out numerical simulation analysis.

The main contributions of this paper are as follows: (1) We divide carbon emission regulation into two stages: loose regulation and strict regulation. In the first stage, we analyze the dynamic game relationship between government regulation intensity and enterprise behavior. The second stage analyzes the evolution of the industry market under the strict supervision of the government. (2) Considering the irrationality of government and enterprise in the process of carbon emission regulation, this paper uses an evolutionary game model to analyze the strategic choice of government and enterprises. (3) Based on the exposure rate of the public and the third party, we constructed a carbon emission regulation intensity function, and determined the scope of loose regulation and strict regulation, so that the two stages can be dynamically linked.

The research structure of this paper is as follows. The second part reviews the relevant literature. The third part analyzes the loose regulation stage evolutionary game model between government and enterprises. The fourth analyzes the strict regulation stage evolutionary game model between leading enterprises and the following enterprises. The fifth part is numerical simulation. The sixth part is the conclusion, discussing the results and proposing policy suggestions.

2. Literature review

In order to effectively control the carbon emission behavior of enterprises, many scholars have studied the regulation of carbon emission. Yang *et al.* [28] studied the impact of carbon emission regulation on energy structure, they found that overly strict carbon regulation is not conducive to the optimization of energy structure. Li *et al.* [13] studied the impact of regulation intensity on the carbon emission of unit product and the total production quantity. In addition, Wang *et al.* [23] proposed that it is necessary to set up a special regulatory department to conduct unified management of carbon emission supervision. Chen [2] studied the regulatory legal system of China's carbon emissions from the aspects of carbon emission monitoring and carbon emission permits.

Game theory is an effective tool to analyze the interactive relationships and the optimization problems. Some scholars have used game theory to explore the interaction between government and enterprise in carbon regulation. He *et al.* [9] analyzed the game of carbon emission reduction of fashion supply chain composed of suppliers and manufacturers. Haghighi *et al.* [6] using game theory to study government regulation of carbon emissions from power plants, and conducted sensitivity analysis on carbon tax and government subsidy. Halat *et al.* [7] studied the influence of carbon emission regulation on the inventory cost of enterprises in the multi-level supply chain. Combined with carbon tax regulation, Zhang *et al.* [29] studied the relationship between government regulation and manufacturers' low-carbon strategy choice under three power structures. Lyu *et al.* [16] studied manufacturers' strategies of carbon emission reduction and recycling under different regulation strategies of the government.

The above scholars have conducted research on the regulation of carbon emissions from different perspectives, but the game models proposed above are under the assumption that the participators are completely rational, which is not consistent with the reality. Unlike traditional game theory, evolutionary game theory focuses on the behaviors of bounded rational players, where the strategies of players are based on the continuous trial and error [25].

In recent years, more and more researchers have started to build evolutionary game models to study the regulation of carbon emissions [4,11,12,20]. In the area of pluralistic governance system, Wu *et al.* [26] analyze the government's carbon emission regulation behavior by evolutionary game theory under a dual governance system. Jiang *et al.* [10] conducted an evolutionary game analysis on the implementation of a multi-agent environmental regulation strategy under fiscal decentralization in China. Liu *et al.* [15] analyzed the strategy selection of enterprise carbon emissions under the dual governance system from the perspective of initial intention. Wang *et al.* [24] studied the regulation of carbon emissions under the dual governance system of China by constructing an evolutionary game model between the central government, local government, and emission enterprises. In area of third-party regulation, Pan *et al.* [18] found that when the government adopts positive regulatory strategy, the collusive behavior of enterprises and third-party supervision institutions can be reduced. Xu *et al.* [27] studied the dynamic relationship of the government and enterprises in the process of carbon emission regulation under the influence of third-party regulation. In other respects, Chen *et al.* [3] elaborated the impact of a carbon tax on enterprise behavior by constructing the evolutionary game model between the government and enterprises.

The above researches applied evolutionary game theory to analysis the strategic choice of enterprises and government from dynamic and bounded rational perspectives. Nevertheless, they fail to consider the stage of carbon regulation and the evolution of market structures. Different from the above research, this paper studied the change of carbon emission regulation intensity, divided carbon emission regulation into two stages: strict regulation and loose regulation, and analyzed the interaction between government and enterprises and market evolution in different stages.

3. Evolutionary game analysis of loose regulation stage

In the loose regulation stage, the two sides of the game are government and enterprise. The government's regulation will be changed according to the production strategy of enterprises, and to guide enterprises to carry out low-carbon production. Enterprises will choose low-carbon production or traditional production according to the principle of utility maximization.

3.1. Model hypothesis and related parameters description

To analyze the production strategy of the enterprise under different supervision intensities, we propose the following hypothesis. The model parameters are shown in Table 1.

Table 1. Model parameter description.

Notation	Meaning
x	Represents the probability that the government chooses positive regulation strategy
$1-x$	Represents the probability that the government chooses passive regulatory strategy
V	Represents the revenue of the government when the enterprise chooses low carbon production
V'	Represents the revenue of the government when the enterprise chooses traditional production ($V > V'$)
k	Represents the amount of penalty imposed by the government on the enterprise for traditional production
t	Represents the government's loss when the enterprise chooses traditional production is exposed ($t > k$)
y	Represents the probability that the enterprise chooses low-carbon production
$1-y$	Represents the probability that the enterprise chooses traditional production
U	Represents the revenue of enterprise when the enterprise chooses low carbon production
U'	Represents the revenue of enterprise when the enterprise chooses traditional production ($U' > U$)
C	Represents the cost of the government when the government adopts a strategy of positive regulation
w	Represents the probability of exposure of traditional production behavior by the third parties and public

Hypothesis 1. We assumed that both government and enterprise are bounded rational in the game process. Since assuming bounded rationality of government and enterprise would bring uncertainty to the model analysis, for the sake of simplification, we assume that the government and enterprises are rational at the beginning, and then gradually relax the rationale after obtaining the basic results.

Hypothesis 2. Both government and enterprise have two alternative strategies. The enterprise can choose the low carbon production strategy or the traditional production strategy. Government can choose positive regulation or passive regulation strategy. Both sides do not have the optimal strategy at the beginning, they reach the optimal strategies through constant learning and trial and adjust in the game process.

Hypothesis 3. In the mixed Nash equilibrium strategy, the probability that the government chooses positive regulation is $x(0 \le x \le 1)$, then the probability that the government chooses passive regulation is $1-x$; the probability of the enterprise choosing the low carbon production strategy is $y(0 \le y \le 1)$, the probability of the enterprise choosing the traditional production strategy is $1-y$.

Hypothesis 4. When the government chooses the positive regulation strategy, they can quickly find the traditional production behavior of the enterprise and then punish them, meanwhile, the government needs to pay a regulation cost C. When the government chooses passive regulation, the traditional production behavior of the enterprise cannot be detected, but the cost of regulation is 0.

Hypothesis 5. When the government chooses passive regulation and the enterprise chooses traditional production, the production behavior of the enterprise may be exposed by the public or the third party, and the probability is $w(0 \le w \le 1)$. The third parties and the public do not know each other's strategies at the same stage and they make independent decisions. Their strategy choices are affected by the results of the previous stage of the game (Tab. 1).

3.2. Pure strategy Nash equilibrium analysis

Based on the above assumptions, we construct the pure strategy Nash equilibrium matrix between the governments and enterprises, as shown in Table 2 [31].

(1) If the enterprise chooses traditional production strategy, the government has two strategies to choose, when $V' - C + k < V' - wt + wk$, the government will choose the strategy of passive regulation, the pure

TABLE 2. Government and enterprises pure strategy game model.

		Enterprise	
		Low-carbon production	Traditional production
Government	Positive regulation	$V-C;U$	$V'-C+k;U'-k$
	Passive regulation	$V;U$	$V'-wt+wk;U'-wk$

TABLE 3. Government and enterprise mixed strategy game model.

		Enterprise	
		Low carbon production y	Traditional production $1-y$
Government	Positive regulation x	$V-C;U$	$V'-C+k;U'-k$
	Passive regulation $1-x$	$V;U$	$V'-wt+wk;U'-wk$

strategy Nash equilibrium solution of the evolutionary game model is $\{V'-wt+wk, U'-wk\}$. When $V'-C+k > V'-wt+wk$, the government will choose the strategy of positive regulation, the pure strategy Nash equilibrium solution of the evolutionary game model is $\{V'-C+k, U'-k\}$.

(2) If the enterprises choose low-carbon production strategy, the government has two strategies to choose, due to $V > V-C$, the government will choose the passive regulation strategy, so the pure Nash equilibrium solution of the game model is $\{V, U\}$.

(3) If the government chooses positive regulation, the enterprise has two strategies to choose. when $U > U'-k$, enterprise will choose low carbon production, and the pure strategy Nash equilibrium solution is $\{V-C, U\}$. When $U < U'-k$, enterprise will choose traditional production, and the pure strategy Nash equilibrium solution is $\{V'-C+k, U'-k\}$.

(4) If the government chooses passive regulation strategy, the enterprise also has two strategies to choose. When $U > U'-wk$, enterprise will choose low-carbon production, and the pure strategy Nash equilibrium solution is $\{V, U\}$. When $U < U'-wk$, the enterprise will choose traditional production, and the pure strategy Nash equilibrium solution is $\{V'-wt+wk, U'-wk\}$.

3.3. Mixed strategy Nash equilibrium analysis

In practice, the pure strategy Nash equilibrium solution may not exist, then the two sides of the game can only adopt a mixed strategy. Based on the above assumptions, we constructed the mixed strategy game matrix of governments and enterprises, as shown in Table 3.

1. Analysis of government regulation strategy.

When the government implements the positive regulation strategy, the expected revenue of the government is E_{11}; on the contrary, when the government implements the passive regulation strategy, the expected revenue of the government is E_{12}. The corresponding formula is as follows.

$$E_{11} = y(-C+V) + (1-y)(V'-C+k) \tag{3.1}$$

$$E_{12} = yV + (1-y)(V'-wt+wk). \tag{3.2}$$

The average revenue of government E_1 is:

$$E_1 = xE_{11} + (1-x)E_{12}. \tag{3.3}$$

The replicating dynamic equation of government strategy in the game process is:

$$F(x) = x(E_{11}-E_1) = x(1-x)[-y(k+w(t-k)) - C + k + w(t-k)]. \tag{3.4}$$

From $F(x) = 0$, we can get:

$$x_1 = 0; x_2 = 1; y^* = \frac{-C + k + w(t-k)}{k + w(t-k)}.$$

The derivative of $F(x)$ can be obtained as follow:

$$F'(x) = (1 - 2x)[-y(k + w(t-k)) - C + k + w(t-k)]. \tag{3.5}$$

According to the evolutionary game theory, when $F(x) = 0$ and $F'(x) < 0$, x is an evolutionary stable point. However, the positive or negative of the $F'(x)$ is depends on the size of the relationship between y and y^*. We can analyze the system evolution in the following situations [14].

(1) $y^* < 0$.
Because of $k + w(t-k) > 0$, we can get $-C + k + w(t-k) < 0$, so we have $w \in \left(0, \frac{C-k}{t-k}\right)$. When $y = 0$, we have $F(0) = 0$, $F'(0) < 0$. Therefore, when $w \in (0, \frac{C-k}{t-k})$, we have the government's regulatory strategies tend to be passive regulation.

(2) $0 < y^* < 1$.
From $-C + K + w(t-k) < k + w(t-k)$, we can get $-C + k + w(t-k) > 0$. At this point, we have $w \in \left(\frac{C-k}{t-k}, 1\right)$. When $y < y^*$, we have $F(1) = 0$, $F'(1) < 0$, the regulatory strategy of government tends to be positive regulation. When $y = y^*$, we have $F(y) = 0$. At this point, the government's decision-making is in equilibrium. When $y > y^*$, we have $F(0) = 0$, $F'(0) < 0$, the government's evolving strategy is passive regulation.

(3) $y^* > 1$.
Due to $-C + k + w(t-k) < k + w(t-k)$, so this situation does not exist.

To sum up, we can get that when $w \in \left(0, \frac{C-k}{t-k}\right)$, the government adopted a passive regulatory strategy, this is a stage of loose regulation. When $w \in \left(\frac{C-k}{t-k}, 1\right)$, if $y < y^*$, the intensity of government regulation changes from passive regulation to positive regulation, this is a stage of strict regulation.

2. Analysis of enterprise production strategy.

When the enterprise chooses low-carbon production, the expected revenue of enterprise is E_{21}; when they choose traditional production, their expected revenue is E_{22}; the average revenue of enterprise is E_2. The specific formula is as follows:

$$E_{21} = xU + (1-x)U \tag{3.6}$$

$$E_{22} = x(U' - k) + (1-x)(U' - wk) \tag{3.7}$$

$$E_2 = yE_{21} + (1-y)E_{22}. \tag{3.8}$$

The replicating dynamic equation of the evolutionary game of enterprise as:

$$F(y) = y(E_{21} - E_2) = y(1-y)[x(k - wk) + U - U' + wk]. \tag{3.9}$$

By taking the derivative of $F(y)$, we can get:

$$F'(y) = (1 - 2y)[x(k - wk) + U - U' + wk]. \tag{3.10}$$

From $F(y) = 0$, we can get $y_1 = 0$, $y_2 = 1$, $x^* = \frac{(U' - U - wk)}{k - wk}$.
Similarly, according to the evolutionary game theory, when $F(y) = 0$ and $F'(y) < 0$, y is an evolutionary stable point.

TABLE 4. Analysis of local stability results.

Equilibrium point	$\det(J)$	$\mathrm{tr}(J)$
$O(0,0)$	$[-C+k+w(t-k)](U-U'+wk)$	$[-C+k+w(t-k)]+(U-U'+wk)$
$A(0,1)$	$C(U-U'+k)$	$-C-(U-U'+k)$
$B(1,0)$	$-[-C+k+w(t-k)](k+U-U')$	$-[-C+k+w(t-k)]+(k+U-U')$
$C(1,1)$	$-C(k+U-U')$	$C-(k+U-U')$
$D(x^*,y^*)$	–	0

(1) When $x=x^*$, $F(y)=0$, $F'(y)=0$, all values of y are in a stable state. This means that when the probability of the government regulation is $(U'-U-wk)/(k-wk)$, the enterprise chooses traditional production or low-carbon traditional production will obtain the same revenue.

(2) When $x<x^*$, $y_1=0$ and $y_2=1$ are two possible stable state points. Due to $F(0)=0$, $F'(0)<0$, we have $y_1=0$ is the evolutionary stable point. It indicates that when the probability of government regulation is less than $(U'-U-wk)/(k-wk)$, the enterprise will tend to choose traditional production strategy. Similarly, when $x>x^*$, we have $y_2=1$ is the evolutionary stable strategy. It shows that when the probability of government regulation is higher than $(U'-U-wk)/(k-wk)$, the enterprise will tend to choose low-carbon production strategy.

3. Government and enterprise evolutionary game analysis.

According to the replicating dynamic equation, we can get the Jacobian matrix as follow:

$$J=\begin{bmatrix}(1-2x)[-y(k+w(t-k))-C+k+w(t-k)] & -x(1-x)(k+w(t-k))\\ y(1-y)(1-w)k & (1-2y)[x(k-wk)+U-U'+wk]\end{bmatrix}.$$

The corresponding determinant of the Jacobian matrix is:

$$\begin{aligned}\det(J)=\frac{\partial F(x)}{\partial x}\cdot\frac{\partial F(y)}{\partial y}-\frac{\partial F(x)}{\partial y}\cdot\frac{\partial F(x)}{\partial x}&=(1-2x)[-y(k+w(t-k))\\ &-C+k+w(t-k)](1-2y)[x(k-wk)+U-U'+wk]\\ &+y(1-y)(1-w)kx(1-x)(k+w(t-k)).\end{aligned}$$

The trace of Jacobi matrix is:

$$\begin{aligned}\mathrm{tr}(J)=\frac{\partial F(x)}{\partial x}+\frac{\partial F(y)}{\partial y}&=(1-2x)[-y(k+w(t-k))-C+k\\ &+w(t-k)]+(1-2y)[x(k-wk)+U-U'+wk].\end{aligned}$$

When $\det(J)>0$, and $\mathrm{tr}(J)<0$, the evolutionary game matrix is in a stable state. Therefore, according to Jacobi matrix, we can obtain the local stability points of the game system, as shown in Table 4.

The dynamic change relationship between government and enterprise game is shown in Figure 1. The horizontal axis represents government strategy and the vertical axis represents enterprise strategy. Where $O(0,1)$, $A(0,1)$, $B(1,0)$, $C(1,1)$ represent the local equilibrium point of the game, and $D(x^*,y^*)$ represents the saddle point.

Corollary 3.1. *When $[-C+k+w(t-k)](U-U'+wk)>0$ and $[-C+k+w(t-k)](U-U'+wk)<0$, the game system reaches a stable equilibrium at $x=0$, $y=0$. In this case, the revenue of government positive regulation is lower than the cost of regulation, while the revenue of traditional production of enterprise is higher than the penalty fine. Therefore, the government tend to choose passive regulation, and the enterprise tend to choose traditional production, as shown in Figure 1(I).*

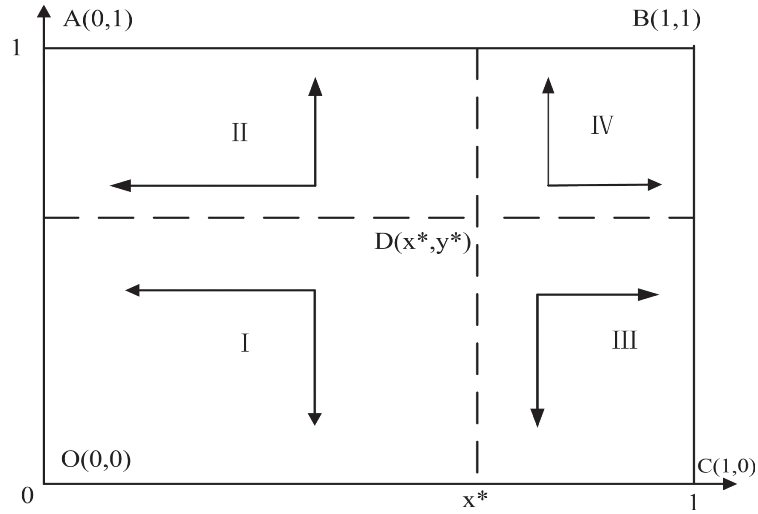

FIGURE 1. Evolution game trajectory of government and enterprise.

Corollary 3.2. *When $C(U - U' + k) > 0$ and $-C - (U - U' + k) < 0$, the game system reaches a stable equilibrium at $x = 0$, $y = 1$. In this case, the cost of the positive regulation of government is higher than the revenue, while the penalty fine of traditional production of enterprise is greater than the revenue. Therefore, the government tend to choose passive regulation, and the enterprise tend to choose low-carbon production, as shown in Figure 1(II).*

Corollary 3.3. *When $-[-C + k + w(t - k)](k + U - U')$ and $-[-C + k + w(t - k)] + (k + U - U')$, the game system reaches a stable equilibrium at $x = 1$, $y = 0$. The revenue of positive regulation of government is higher than the cost, and the revenue of traditional production enterprise is higher than the penalty fine. Therefore, the government tends to choose positive regulation and the enterprise tends to choose traditional production, as shown in Figure 1(III).*

Corollary 3.4. *When $-C(k+U-U') > 0$ and $C-(k+U-U')$, the game system reaches a stable equilibrium at $x = 1$, $y = 1$. In this case, the revenue of positive regulation of government are greater than the cost, while the penalty fine of traditional production of enterprise is greater than the revenue. Therefore, the government tends to choose positive regulation and enterprise tends to choose low-carbon production, as shown in Figure 1(IV).*

Through the evolutionary game results, we found that in the stage of loose regulation, the governments and enterprise are constantly adjusting their strategies to maximize profits. With the development of green economy and the improvement of public awareness of low carbon. The government will gradually increase the intensity of regulation, and it is transformed from loose regulation to strict regulation.

4. Evolutionary game analysis of strict regulation stage

In the stage of strict regulation, it is the evolutionary game between leading enterprises and following enterprises. The leading enterprise with abundant capital and development capabilities will gradually complete the low-carbon upgrade, it can choose market maintenance strategy and market expansion strategy. However, the following enterprise without low-carbon production technology, and it can only buy carbon emission rights to stay in the market or quit the market.

TABLE 5. Leading enterprise and following enterprise pure strategy game model.

		Following enterprise	
		Stay market	Exit market
Leading enterprise	Market expansion	$R_1 + \Delta R_1 - C_1 - C_1'; R_2' - C_2$	$R_1' + \Delta R_1 - C_1' - C_1; 0$
	Market maintenance	$R_1 - C_1'; R_2 - C_2$	$R_1' - C_1'; 0$

According to 3.1 analysis, when $w \in \left(\frac{C-k}{t-k}, 1\right)$, if $x < x^*$, the intensity of government regulation enters the stage of strict regulation. In this stage, we analyze the evolutionary game between leading enterprise and following enterprise.

4.1. Game model hypothesis

Hypothesis 1. There are two types of carbon emission enterprise. The first type is the leading enterprise, which has the capital and technology to carry out low-carbon production. The second type is the following enterprise, which is constrained by technology and capital and have no capacity for low-carbon production, they can only purchase carbon emission rights through the carbon trading market to maintain production.

Hypothesis 2. Enterprise have no opportunity to traditional production under strict regulation of government. Leading enterprise will choose low-carbon production, which requires paying costs of low-carbon C_1', and the following enterprise require to pay the cost of carbon emission rights C_2.

Hypothesis 3. The leading enterprise can choose the market maintenance strategy or the market expansion strategy, and the following enterprise can choose to stay in the market or exit the market. The probability of the leading enterprise choosing market expansion strategy is $p(0 < p < 1)$, and the probability of choosing market maintenance strategy is $1-p$. The probability of the following enterprise choosing to stay in the market is $q(0 < q < 1)$, and the probability of the following enterprise choosing to exit the market is $1 - q$.

Hypothesis 4. R_1 is the basic revenue of the leading enterprise when both the leading enterprises and the following enterprise exist; R_1' is the basic revenue of the leading enterprises in the market alone; ΔR_1 is the expected revenue when the leading enterprise choosing market expansion strategy, C_1 is the cost of market expansion of the leading enterprise.

Hypothesis 5. When the leading enterprise chooses the market maintenance strategy, the revenue of the following enterprise stay in the market is R_2; when the leading enterprise chooses the market expansion strategy, the revenue of following enterprise stay in the market is ΔR_1; the cost of purchasing carbon emission right by the following enterprise is C_2.

4.2. Pure strategy Nash equilibrium analysis

Based on the above assumptions, we can construct a pure strategy Nash equilibrium matrix between leading enterprise and following enterprise, as shown in Table 5.

(1) If the leading enterprise chooses the market expansion strategy, there are two strategic options for the following enterprise. When $R_2' - C_2 > 0$, the following enterprise will choose to stay in the market. The pure strategy Nash equilibrium solution of the game model is $\{R_1 + \Delta R_1 - C_1' - C_1, R_2' - C_2\}$. When $R_2' - C_2 < 0$, the following enterprise will choose to exit market, the pure strategy Nash equilibrium solution of the game model is $\{R_1' + \Delta R_1 - C_1' - C_1, 0\}$.

(2) If the leading enterprise chooses the market maintenance strategy, there are also two strategic options for the following enterprise. When $R_2 - C_2 > 0$, the following enterprise will choose to stay in the market strategy, the pure Nash equilibrium solution of the game model is $\{R_1 - C_1', R_2 - C_2\}$. When $R_2 - C_2 < 0$,

Table 6. Leading enterprise and following enterprise mixed strategy game model.

		Following enterprise	
		Stay market q	Exit market $(1-q)$
Leading enterprise	Market expansion p	$R_1+\Delta R_1-C_1'-C_1; R_2'-C_2$	$R_1'+\Delta R_1-C_1'-C_1; 0$
	Market maintenance $(1-p)$	$R_1-C_1'; R_2-C_2$	$R_1'-C_1'; 0$

the following enterprise will choose to exit the market strategy, the pure Nash equilibrium solution of the game model is $\{R_1'-C_1', 0\}$.

(3) If the following enterprise chooses to stay in the market, there are two strategic options for the leading enterprise. When $R_1+\Delta R_1-C_1'-C_1 > R_1-C_1'$, the leading enterprise will choose the market expansion strategy, the game model has the pure strategy Nash equilibrium solution is $\{R_1+\Delta R_1-C_1'-C_1, R_2'-C_2\}$. When $R_1+\Delta R_1-C_1'-C_1 < R_1-C_1'$, the leading enterprise will choose the market maintenance strategy, the game model has the pure strategy Nash equilibrium solution $\{R_1-C_1', R_2'-C_2\}$.

(4) If the following enterprise chooses an exit market strategy, the leading enterprise also has two strategies to choose. When $R_1+\Delta R_1-C_1'-C_1 > R_1-C_1'$, the leading enterprise will choose the market expansion strategy, the pure strategy Nash equilibrium solution of the game model is $\{R_1+\Delta R_1-C_1'-C_1, 0\}$. When $R_1+\Delta R_1-C_1'-C_1 < R_1-C_1'$, the leading enterprise will choose the market maintenance strategy, the pure strategy Nash equilibrium solution of the game model is $\{R_1-C_1', 0\}$.

4.3. Mixed strategy Nash equilibrium matrix

Based on the above assumptions, we constructed a mixed strategy Nash equilibrium game matrix, as shown in Table 6.

1. The leading enterprise strategy analysis.

Assume that the expected revenue of market expansion of leading enterprise is E_{31}, the expected revenue of market maintenance is E_{32}, and the average expected revenue is E_3. The specific formula is as follows:

$$E_{31} = q(R_1+\Delta R_1-C_1-C_1') + (1-q)(R_1'+\Delta R_1-C_1-C_1') \tag{4.1}$$

$$E_{32} = q(R_1-C_1') + (1-q)(R_1'-C_1') \tag{4.2}$$

$$E_3 = pE_{11} + (1-p)E_{12}. \tag{4.3}$$

The replication dynamic equation is:

$$F(p) = p(E_{31}-E_3) = p(1-p)(\Delta R_1 - C_1). \tag{4.4}$$

Taking the derivative of $F(p)$ with respect to p, we get:

$$F'(p) = (1-2p)(\Delta R_1 - C_1). \tag{4.5}$$

According to Freidman's evolutionary game theory, when $F(p)=0$ and $F'(p)<0$, we have p is an evolutionary stability strategy.

When $\Delta R_1 > C_1$, $p_1 = 0$ and $p_2 = 1$ are two possible evolutionary stability points. Because of $F(1)=0$, $F'(1)<0$, we have $p_1 = 1$ is the evolutionary stable strategy, which means that the leading enterprise will choose the market expansion strategy at this time. Similarly, when $\Delta R_1 < C_1$, $p_1 = 0$ is the evolutionary stable strategy, which means that the leading enterprise will choose the market maintenance strategy at this time.

TABLE 7. Analysis of local equilibrium results.

Equilibrium point	det(J)	tr(J)
$O(0,0)$	$(\Delta R_1 - C_1)(R_2 - C_2)$	$(\Delta R_1 - C_1) + (R_2 - C_2)$
$A(0,1)$	$(\Delta R_1 - C_1)(C_2 - R_2)$	$(\Delta R_1 - C_1) - (R_2 - C_2)$
$B(1,0)$	$(C_1 - \Delta R_1)(R_2' - C_2)$	$(C_1 - \Delta R_1) + (R_2' - C_2)$
$C(1,1)$	$(C_1 - \Delta R_1)(C_2 - R_2')$	$(C_1 - \Delta R_1) + (C_2 - R_2')$
$D(x^*, y^*)$	+	0

2. The following enterprise strategy analysis.

Similarly, we can obtain the replication dynamic equation of the enterprise:

$$F(q) = q(1-q)[p(R_2' - R_2) + R_2 - C_2] \tag{4.6}$$
$$F'(q) = (1-2q)[p(R_2' - R_2) + R_2 - C_2]. \tag{4.7}$$

Let $F(q) = 0$, we have $q_1 = 0$, $q_2 = 1$, $p^* = (C_2 - R_2)/(R_2' - R_2)$; when $F(q) = 0$ and $F'(q) < 0$, we have q is an evolutionary stability strategy.

(1) When $p = p^*$, we have $F(q) = 0$, $F'(q) = 0$, this means that when the probability of the leading enterprise choosing to market expand strategy is $(C_2 - R_2)/(R_2' - R_2)$, the following enterprise choose exits the market or stay in the market will have the same revenue.
(2) When $p < p^*$, $p_1 = 0$ and $p_2 = 1$ are two possible evolutionary stability strategies. Due to $F(0) = 0$, $F'(0) < 0$, therefore, we have $q_1 = 0$ is the evolutionary stable strategy, this means that the following enterprise will choose market exit strategy. Similarly, when $p > p^*$, $q_2 = 1$ is the evolutionary stable strategy, this means that the following enterprise will choose to stay in the market.

3. Evolutionary game analysis of leading enterprise and following enterprise.

The Jacobian matrix can be obtained from the above repeated dynamics equation, as follow:

$$J = \begin{bmatrix} (1-2p)(\Delta R_1 - C_1) & 0 \\ q(1-q)(R_2' - R_2) & (1-2q)[p(R_2' - R_2) + R_2 - C_2] \end{bmatrix}.$$

The determinant and trace of the matrix can be obtained as follows:

$$\det(J) = (1-2p)(\Delta R_1 - C_1)(1-2q)[p(R_2' - R_2) + R_2 - C_2]$$
$$\operatorname{tr}(J) = (1-2p)(\Delta R_1 - C_1) + (1-2q)[p(R_2' - R_2) + R_2 - C_2].$$

When $\det(J) > 0$ and $\operatorname{tr}(J) < 0$, the evolutionary game system is in an equilibrium state. The states of local equilibrium point of the Jacobian matrix are analyzed in Table 7.

Corollary 4.1. *When $(\Delta R_1 - C_1)(R_2 - C_2) > 0$ and $(\Delta R_1 - C_1) + (R_2 - C_2) < 0$, the system reaches equilibrium at $(0,0)$. This situation indicates that the industry market is in the stage of contraction. The leading enterprise have no intention to expand the market share, while the following enterprise choose to gradually quit the market due to the high operating costs.*

Corollary 4.2. *When $(\Delta R_1 - C_1)(C_2 - R_2) > 0$ and $(\Delta R_1 - C_1)(C_2 - R_2) < 0$, the system reaches equilibrium at $(0,1)$. This situation indicates that the industry operation in a stable stage. At this point, the leading enterprise*

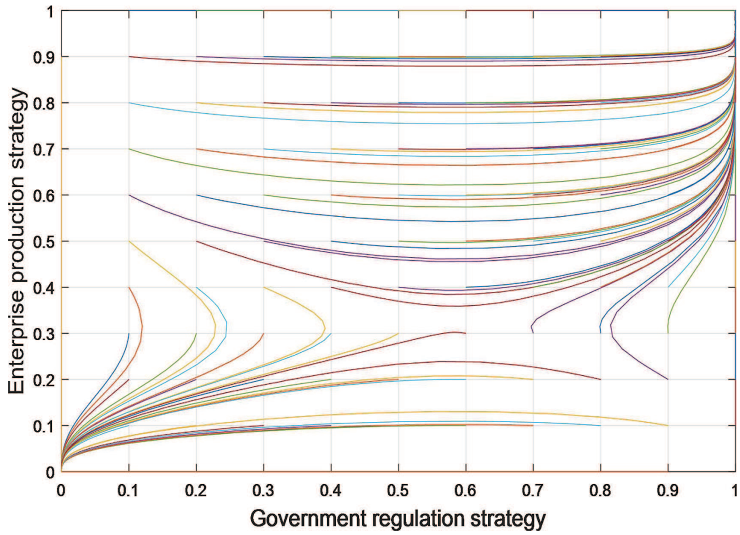

FIGURE 2. Evolutionary path of government and enterprise mixed strategy.

has no incentive to expand market share, while the following enterprise continue to operate in the market, and the whole market is in a stable state.

Corollary 4.3. *When* $(C_1 - \Delta R_1)(R_2' - C_2) > 0$ *and* $(C_1 - \Delta R_1)(R_2' - C_2) < 0$*, the system reaches equilibrium at* $(1, 0)$*. This situation indicates that the industry market is in the stage of competitive. Compared with the following enterprise, the leading enterprise has more abundant technical and financial support, when they choose the market expansion strategy, they are likely to get more revenue. At this time, it is difficult for the following enterprise to get revenue in the market competition, so it will choose to quit the market.*

Corollary 4.4. *When* $(C_1 - \Delta R_1)(C_2 - R_2') > 0$ *and* $(C_1 - \Delta R_1) + (C_2 - R_2') < 0$*, the system reaches equilibrium at* $(1, 1)$*. This situation belongs to the stage of market development, the market demand is large. When the leading enterprise chooses the market expansion strategy, it is more likely to obtain the expected revenue, and the following enterprise can also obtain expected revenue in the market operation.*

5. NUMERICAL ANALYSIS

Taking China's manufacturing industry as an example, numerical simulation is carried out. We set relevant parameters by analyzing government supervision mechanism and enterprise operation mechanism and try to make the parameters conform to the actual situation. The basic parameters are set as follow:

$$C = 15, \quad w = 0.45, \quad t = 40, \quad U = 4.6, \quad U' = 10, \quad k = 7.$$

The dynamic game evolution path diagram of government and enterprise can be obtained by using Matlab software simulation, as shown in Figure 2.

Under the initial parameters, due to $x^* = \frac{U'-U-wk}{k-wk}$, $y^* = \frac{-C+k+w(t-k)}{k+w(t-k)}$, we can get the saddle point $x^* = 0.584$, $y^* = 0.313$.

The dynamic evolutionary path of the game between government and enterprise is obtained through simulation, as shown in Figure 2. Each curve in the figure represents an evolutionary path of the mixed strategy between government and enterprise. From Figure 2, we can see that the mix strategies of government and enterprise converges to $(0, 0)$ in the lower left region of saddle point. That is the evolution trend of government and

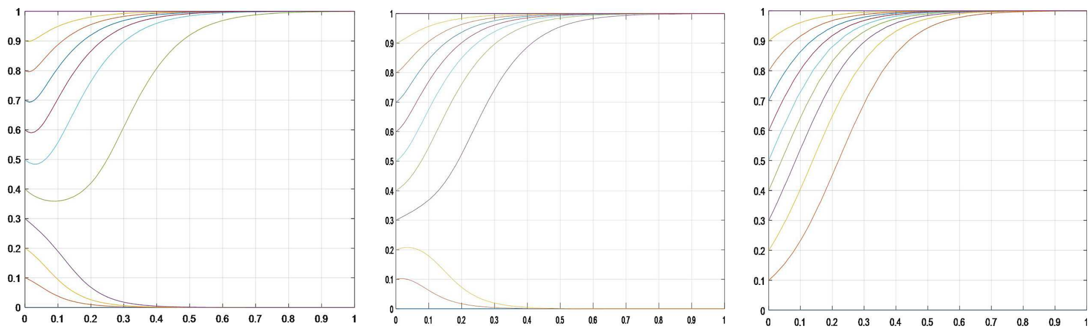

FIGURE 3. Evolution trend of low-carbon production under initial parameters.

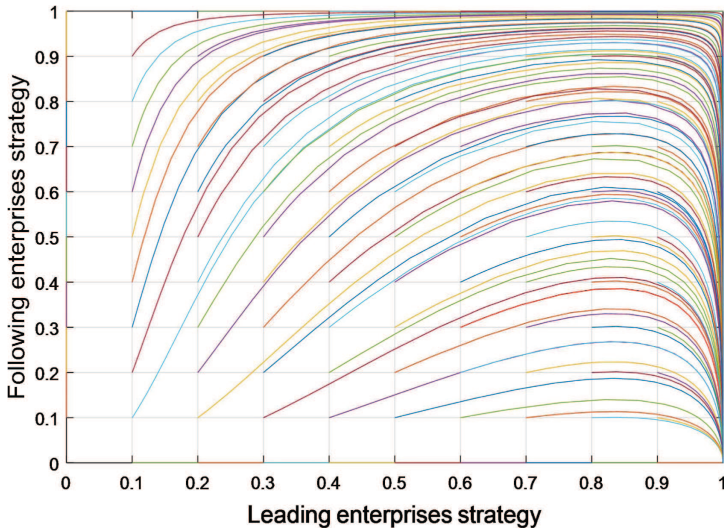

FIGURE 4. Evolutionary path of leading enterprise and following enterprise.

enterprise is {passive regulation, traditional production}. Similarly, the system converges to $(1, 1)$ in the upper right region of the saddle point. That is the evolution trend of government and enterprise is {positive regulation, low-carbon production}. Since the saddle point located in the middle of the graph, the evolution trend of the two sides is not obvious under the initial parameter state. We can see that the government regulation is in the stage of loose regulation.

To clearly observe the evolution trend of government and enterprise under the initial parameters. Let's assume that the regulatory intensity as 0.4, 0.7, 1, we observe the evolutionary trend of low-carbon production of enterprises, as shown in Figure 3.

The curve in Figure 3 represents the evolutionary trend of low-carbon production behavior of enterprises under different supervision intensities government. As can be seen from Figure 3, with the increase of intensity of regulation, the probability of enterprises choosing low-carbon production gradually increases. When the probability of government strict supervision reaches $x = 1$, all enterprises will choose low-carbon production.

In the strict regulation stage, we set the parameter as $R_1 = 70$, $R_1' = 110$, $\Delta R_1 = 40$, $C_1 = 30$, $R_2' = 10$, $R_2 = 30$, $C_2 = 15$. The evolution trend of leading enterprises and following enterprises can be obtained through numerical simulation with MATLAB software, as shown in Figure 4.

The curve in Figure 4 represents the evolutionary trend of mixed strategy of leading and following enterprise under the initial parameters. As can be seen from Figure 4, under the initial parameters, the game trend of both sides is consistent with the conclusion in Corollary 4.3. The evolutionary strategy of leading enterprise and following enterprise eventually tends to {market expansion, exit market}. This means that with the development of national green economy, it is an inevitable trend for enterprise to carry out low-carbon production. If enterprise does not update their production technology in time, they will eventually be eliminated by the market.

6. Conclusions

In this paper, we analyze a carbon emissions regulation system consisting of government and enterprise in the context of green development. Different from the previous research, we divide the process of government regulation into two stages to analyze the enterprises' production behavior and market structure under different regulatory intensities of government. The main conclusions are the following:

(1) The supervision cost and revenue of governments, the revenue of low-carbon production and traditional production of enterprises, the public attention, and the penalty fine amount of the enterprise's traditional productional are the important factors affecting the behavior of both the government and the enterprise. When the revenue of government positive regulation is higher than the costs, and the penalty fine imposed on enterprises for traditional production is higher than the revenue, the government will reduce the traditional production behaviors of enterprises by strengthening supervision, and then optimize the market structure of the industry.
(2) Green transformation of enterprise is a gradual process, which requires the joint efforts of the government, enterprise, and the public. In the process of low-carbon transformation, the leading enterprise with low-carbon technologies constantly obtain positive benefits under the government's low-carbon policy, and their market share will gradually increase, while the following enterprises without low-carbon production technologies will continue to shrink their market share, and eventually exit the market or transform and upgrade.
(3) It is difficult for enterprise to consciously invest in low-carbon technology because investment in low-carbon technology will reduce their operating efficiency. Therefore, it is necessary for government to urge enterprise to carry out low-carbon production through compulsory regulation and gradually improve the carbon emission problem.

Based on the above analysis, this paper proposes the following policy suggestions for future development:

(1) The government should formulate systematic regulation strategies based on the actual production status of enterprises and the local economic development level. At the initial stage of transformation, the government adjusts the intensity of regulation and gives enterprises some time for transformation, when the green transformation reaches a certain level, then the government strengthen regulation and phase out unqualified enterprises.
(2) Improve the carbon market trading system. The government sets reasonable total carbon emission and carbon quota, guides enterprises to actively reduce emissions through carbon market trading, gives play to the regulating role of carbon market, and constantly optimizes the industrial market structure.
(3) Introduce the public supervision mechanism. The government encourages the public and industry associations to supervise the efficiency of government regulation and the behavior of enterprises, to form an external regulation mechanism.

This study has the following limitations. In this paper, hypothetical parameters are used for simulation analysis, and the final actual effect needs to be verified by actual data. The influence of carbon trading is not considered in the model construction. All these need to be further deepened in future research. These are all directions that we need to further study in the future.

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