Journal of Quantitative Finance and Economics
Volume 4; Number 2; 2022; pp : 179-196
https://DOI: 10.47509/JQFE.2022.v04i02.02

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Evolutionary Game Analysis of Corporate Carbon Reduction Strategies under Carbon Emission Rights Auction

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ARTICLEINFO

Received: 29 April 2022

Revised: 30 May 2022

Accepted: 22 June 2022

Online: 16 November 2022

To cite this paper:

Guoshun Ma & Jing Zhao (2022). Evolutionary Game Analysis of Corporate Carbon Reduction Strategies under Carbon Neutral Targets. *Journal of Quantitative Finance and Economics.* 4(2), 179-196. https://DOI: 10.47509/JQFE.2022.v04i02.02

***Abstract**: As the world's largest emitter of greenhouse gases, China is actively exploring the best way to address climate change. 2021 marks the official opening of China's carbon emission trading market. In order to investigate the evolutionary game relationship between carbon emission reduction by enterprises and carbon regulation by the government under the carbon emission rights auction, the article constructs an evolutionary game model between enterprises and the government, and analyzes the influence of carbon penalty, carbon subsidy and carbon emission rights revenue on the behavior of the government and enterprises. The results of the model show that the government's active carbon regulation measures can effectively promote the energy saving and emission reduction of enterprises, and the carbon emission trading market can play the role of market regulation to promote the goal of "double carbon" and the coordinated development of the region.*

Keywords: Carbon credits auction; carbon reduction; evolutionary game; numerical simulation

1. Introduction

With the continuous development of human society and industry, the climate issue has become a serious test that the world needs to face together in the 21st century. China, as the world's largest emitter of greenhouse gases, is actively exploring the best ways to address climate change. General Secretary Xi Jinping announced at the United Nations General Assembly that "China will increase its independent national contribution, adopt more vigorous policies and measures, strive to peak CO2 emissions by 2030, and work hard to achieve carbon neutrality by 2060." In 2011, the National Development and Reform Commission (NDRC) officially approved seven provinces, including Beijing, to carry out carbon emissions trading pilot projects, and officially launched the carbon emissions trading pilot project in 2013. The carbon trading market in the pilot areas was officially launched in 2013. With the official opening of the national carbon emission trading market in 2021, it is worth studying whether a national carbon emission trading market can effectively promote energy saving and emission reduction by enterprises and help achieve the "double carbon" target.

Liu *et al* [1] argue that carbon trading, carbon tax, and carbon subsidies are the main government measures for carbon regulation.J Asafu-Adjaye *et al* [2] argue that implementing a carbon trading scheme can effectively promote carbon emission reduction. Xu Jianzhong [3] *et al*. argued that both green innovation input subsidies and carbon taxes can promote breakthrough green innovation activities of enterprises. Zhu Qinghua[4] *et al*. explored the game relationship between local governments and manufacturing firms under carbon emission reduction policies, and concluded that the model has four equilibrium points when the government implements dynamic rewards and penalties. Wei Shengxiang[5] analyzed from the perspective of WTO and concluded that carbon tax is a better policy management tool than carbon emissions trading. Yingying Xu *et al* [6] construct a game model based on two models of open innovation and closed innovation of low-carbon technologies. Yin-Yin Wu *et al* [7] analyzed the actual effect of carbon market on carbon emission reduction based on the systematic role perspective of market mechanism and administrative intervention, and concluded that the market mechanism has limited effect on promoting carbon emission reduction, and the administrative intervention of government is crucial to the carbon emission reduction effect. Lu Qiuqin *et al* [8] used a combination of system dynamics and evolutionary game model to establish a static mixed strategy evolutionary game model between government and heavy polluting enterprises. In the process of carbon emission reduction, scholars at home and abroad have used evolutionary game models and empirical studies to investigate the game relationship between enterprises and the government, and have achieved certain results. However, the research on government carbon regulation policies is not comprehensive enough, and most of them only consider carbon tax and carbon subsidy without considering the efficiency of government's own carbon regulation.

Based on this, this paper establishes an evolutionary game model of the carbon emission reduction strategy of enterprises and the carbon regulation strategy of the government, and comprehensively analyzes the impact of government carbon penalty, carbon subsidy, carbon tax, carbon regulation efficiency and carbon emission right auction strategy on the carbon emission reduction strategy of enterprises, so as to provide a theoretical basis for the development of low-carbon economy in China.

2. Modeling the evolutionary game between businesses and governments

2.1. Model Assumptions

2.1.2 Behavioral strategies of both sides of the game

In the evolutionary game, only two groups of companies and governments play the game of interests, and both sides of the game have limited rationality. The assumptions and explanations of the cost-benefit parameters of the game between enterprises and the government are shown in Table 1.

Table 1: Parameter assumptions and explanations for the cost-benefit of both sides of the game

Parameters	*Meaning*
S_1	Benefits for companies when they reduce emissions negatively
S_2	Benefits for companies when they actively reduce carbon emissions
S_3	Subsidies from the government's active carbon regulation when companies actively reduce carbon emissions and revenues from companies through carbon emissions trading
S_g	Potential benefits to government when companies actively reduce carbon emissions
C	The cost of technological innovation when companies actively reduce carbon emissions
C_g	Total cost to government when actively regulating carbon
B_1	Carbon emissions when companies reduce their carbon emissions negatively
B_2	Carbon emissions when companies actively reduce carbon emissions
P	Penalty of government's positive carbon regulation when enterprises reduce carbon emissions negatively
P_g	The cost of environmental remediation due to the government's negative carbon regulation that does not regulate companies with excessive emissions
η	The ratio of carbon emissions from positive carbon emission reduction by enterprises to carbon emissions from negative carbon emission reduction by enterprises when the government is actively regulating carbon reflects the efficiency of active carbon emission reduction by the government, i.e. the lower the value of α, the higher the efficiency of government carbon regulation
λ	Carbon tax rates in the case of active government carbon regulation

In the evolutionary game, only two groups, enterprises and the government, play the game of interest, and both sides of the game have limited rationality. The behavioral strategy set of enterprises A = {positive carbon reduction, negative carbon reduction}, and the behavioral strategy set of government B = {positive carbon regulation, negative carbon regulation}. Under the dual mechanism of carbon subsidy and carbon tax, the government will give a certain subsidy to the enterprises that actively and positively implement carbon emission reduction strategies, and at the same time, each enterprise will pay a certain tax on the carbon emissions it produces according to a certain percentage, both of which aim to motivate each enterprise to actively implement carbon emission reduction strategies. Under the carbon auction mechanism, enterprises that actively implement carbon emission reduction strategies will not only receive subsidies from the government, but also earn additional income through carbon trading. If the government is active in carbon regulation, there will be regulatory costs, but if the enterprises are active in carbon emission reduction, the government will have a good image among the public and gain potential revenue; if the government is passive in carbon regulation, the government will lose its reputation when the enterprises are passive in carbon emission reduction. The assumptions and explanations of the cost-benefit parameters of the game between enterprises and the government are shown in Table 1.

2.1.2. Basic assumptions

Hypothesis 1: When companies actively implement carbon reduction strategies, the benefits of positive carbon reduction are assumed to be smaller than those when negative carbon reduction is implemented because of the increase in technological innovation inputs and related management costs, i.e. $R_1 > R_2$.

Hypothesis 2: It is assumed that the carbon emissions generated by a firm when it adopts a positive carbon reduction strategy are lower than those when it adopts a negative carbon emission strategy, i.e. $Q_1 > Q_2$.

Hypothesis 3: The probability that a firm chooses a positive carbon reduction strategy is x ,and the probability that a firm chooses a negative carbon reduction strategy is $(1-x)$. The probability that the government chooses positive carbon regulation is y, and the probability that the government chooses negative carbon regulation is $(1-y)$.

2.2. Evolutionary game modeling

The revenue function of the enterprise: when the government adopts an aggressive carbon regulation strategy, the benefit of enterprises adopting an aggressive carbon reduction strategy is $S_2 + S_3$-C-$\lambda\eta B_1$; the benefits of a firm adopting a negative carbon reduction strategy are $S_1 - \lambda B_1 - P$; when the government adopts a negative carbon regulation strategy, the benefits to firms of adopting an aggressive carbon reduction strategy are

$S_2 - C - \lambda B_2$; the benefits of a firm adopting a negative carbon reduction strategy are S_1. The government's revenue function:when firms adopt an aggressive carbon reduction strategy, the benefits of aggressive carbon regulation by the government are $S_g + \lambda\eta B_1 - C_g - S_3$; the benefits of adopting negative carbon regulation are S_g; when firms adopt a negative carbon reduction strategy, the benefits of aggressive carbon regulation by the government are $\lambda B_1 - C_g + P$; the benefits of adopting negative carbon regulation are $-P_g$. This results in the benefit matrix benefits of the firm-government game, as shown in Table 2.

Table 2: Enterprise and government game revenue matrix

	Game parties	*Government*	
		Positive Carbon Regulation	*Negative carbon regulation*
Enterprise	Active carbon reduction	$S_2 + S_3$-C-$\lambda\eta B_1$; $S_g + \lambda\eta B_1 - C_g - S_3$	$S_2 - C - \lambda B_2$; S_g
	Negative carbon reduction	$S_1 - \lambda B_1 - P$; $\lambda B_1 - C_g + P$	S_1; $-P_g$

Since both enterprises and governments are finite rational groups, they cannot judge each other's chosen strategies completely rationally, so the replicator dynamic equations of behavioral strategies of enterprises and governments are constructed according to evolutionary game theory.

Let the expected benefit of adopting a positive carbon reduction strategy is u_{11}, and the expected benefit of choosing a negative carbon reduction strategy is u_{12}, and the average expected benefit is $\bar{u}_1$, then we have:

$$\begin{aligned} u_{11} &= y(S_2 + S_3 - C - \lambda\eta B_1) + (1-y)(S_2 - C - \lambda B_2) \\ &= y(S_3 - \lambda\eta B_1 + \lambda B_2) + (S_2 - C - \lambda B_2) \end{aligned} \tag{1}$$

$$\begin{aligned} u_{12} &= y(S_1 - \lambda B_1 - P) + (1-y)S_1 \\ &= y(-\lambda B_1 - P) + S_1 \end{aligned} \tag{2}$$

$$\bar{u}_1 = xu_{11} + (1-x)u_{12} \tag{3}$$

This leads to a replicator dynamic equation for the probability of a firm choosing an aggressive carbon reduction strategy:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(u_{11} - \bar{u}_1) \\ &= x[u_{11} - xu_{11} - (1-x)u_{12}] \\ &= x(1-x)(u_{11} - u_{12}) \\ &= x(1-x)\{y(S_3 + (1-\eta)\lambda B_1 + \lambda B_2 + P) + (S_2 - S_1 - C - \lambda B_2)\} \end{aligned} \tag{4}$$

Let the expected benefit of the government adopting a positive carbon regulation strategy is u_{21}, and the expected benefit of choosing a negative carbon regulation strategy is u_{22}, and the average expected benefit is $\bar{u}_2$, then we have:

$$\begin{aligned} u_{21} &= x(S_g + \lambda\eta B_1 - S_g - S_3) + (1-x)(\lambda B_1 - S_g + P) \\ &= x[S_g + (\eta - 1)\lambda B_1 - S_3 - P] + (\lambda B_1 - S_g + P) \end{aligned} \tag{5}$$

$$\begin{aligned} u_{22} &= xS_g + (1-x)(-P_g) \\ &= x(S_g + P_g) - P_g \end{aligned} \tag{6}$$

$$\bar{u}_2 = yu_{21} + (1-y)u_{22} \tag{7}$$

This leads to a replicator dynamic equation for the probability of the government choosing an aggressive carbon regulation strategy:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(u_{21} - \bar{u}_2) \\ &= y(1-y)(u_{21} - u_{22}) \\ &= y(1-y)\{x[(\eta - 1)\lambda B_1 - S_3 - P - P_g] + \lambda B_1 - S_g + P + P_g\} \end{aligned} \tag{8}$$

3. Stability analysis of business-government evolutionary game model

3.1. Analysis of the stability of corporate unilateral strategies

Based on the above replicator dynamic equations for corporate carbon emission reduction and government carbon regulation, we can see that the replicator dynamic equations for corporate.

$$F(x) == x(1-x)\{y(S_3+(1-\eta)\lambda B_1+\lambda B_2+P)+(S_2-S_1-C-\lambda B_2)\} \tag{9}$$

If $y=\frac{-S_2+S_1+C+\lambda B_2}{S_3+(1-\eta)\lambda B_1+\lambda B_2+P}$, regardless of the value of *x*, the firm has a steady state, indicating that the firm's steady state at this time is independent of its probability of actively reducing carbon emissions.

If $y\neq\frac{-S_2+S_1+C+\lambda B_2}{S_3+(1-\eta)\lambda B_1+\lambda B_2+P}$, let $F(x)=0$, then $x=0$ and $x=1$ are two stable points of the replicator dynamic equation of the firm's carbon reduction strategy. The partial derivative of $F(x)$ with respect to x gives:

$$\frac{\partial F(x)}{\partial x}=(1-2x)\{y(S_3+(1-\eta)\lambda B_1+\lambda B_2+P)+(S_2-S_1-C-\lambda B_2)\} \tag{10}$$

From evolutionary game theory, it is known that the system is evolutionarily stable strategy only when $\frac{\partial F(x)}{\partial x}<0$. Since $\frac{-S_2+S_1+C+\lambda B_2}{S_3+(1-\eta)\lambda B_1+\lambda B_2+P}>0$, it can be divided into the following two cases according to the magnitude of *y*: when $y>\frac{-S_2+S_1+C+\lambda B_2}{S_3+(1-\eta)\lambda B_1+\lambda B_2+P}$, $x=1$ is an evolutionary stabilization strategy, i.e., the firm chooses an aggressive carbon reduction strategy; when $y<\frac{-S_2+S_1+C+\lambda B_2}{S_3+(1-\eta)\lambda B_1+\lambda B_2+P}$, $x=0$ is an evolutionary stabilization strategy. Based on the above analysis, a dynamic phase diagram of replicators of corporate carbon reduction strategy behavior can be drawn, as shown in Figure 1.

3.2. Analysis of the stability of the government's unilateral strategy

According to equation (8), the replicator dynamic equation of the government carbon regulation strategy can be found as shown in equation (11).

$$F(y)=(1-2y)\{x[(\eta-1)\eta B_1-S_3-P-P_g]+\eta B_1-C_g+P+P_g\} \tag{11}$$

If $x=\frac{\lambda B_1-C_g+P+P_g}{(1-\eta)\lambda B_1+S_3+P+P_g}$, the government has a steady state

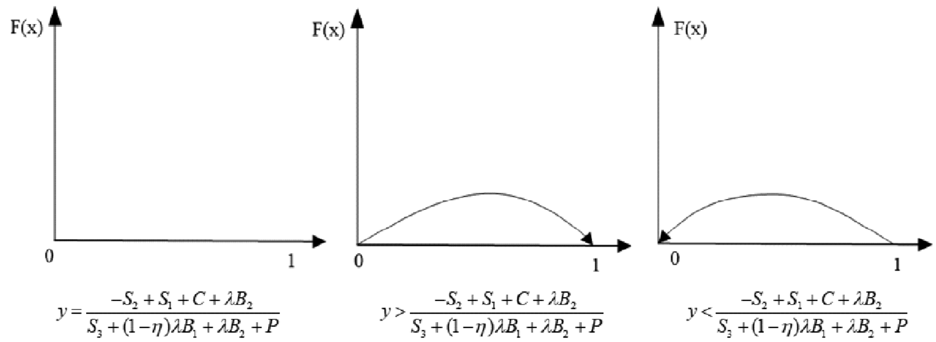

Figure 1: Dynamic phase diagram for replicating the behavior of corporate carbon reduction strategies

regardless of the value, indicating that the steady state of the government at this time is independent of the probability of its active carbon regulation.

If $x \neq \frac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g}$, let $F(y)=0$, then $y=0$ and $y=1$ are the two stable points of the replicator dynamics equation of the government carbon regulation strategy, and the partial derivative of $F(y)$ with respect to y yields:

$$\frac{\partial F(y)}{\partial y} = (1-2y)\{x[(\eta-1)\lambda B_1 - S_3 - P - P_g] + \lambda B_1 - C_g + P + P_g\} \tag{12}$$

The evolutionary stabilization strategy occurs for the government when $\frac{\partial F(y)}{\partial y} < 0$. Therefore, a discussion of the sign of $\lambda B_1 - C_g + P + P_g$ is required.

When $\lambda B_1 - C_g + P + P_g < 0$, $\frac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g} < 0$, therefore x is constantly greater than $\frac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g} < 0$, i.e., $y=1$ is an evolutionary stable strategy. When $\lambda B_1 - C_g + P + P_g > 0$, it is necessary to discuss and analyze two cases according to the magnitude of x value: when $x > \frac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g}$, $y=1$ is the evolutionary stable strategy; when

$x < \dfrac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g}$, $y = 0$ is the evolutionary stable strategy. Based on the above analysis, a phase diagram of the replicator dynamics of government carbon regulation strategy behavior can be drawn, as shown in Figure 2.

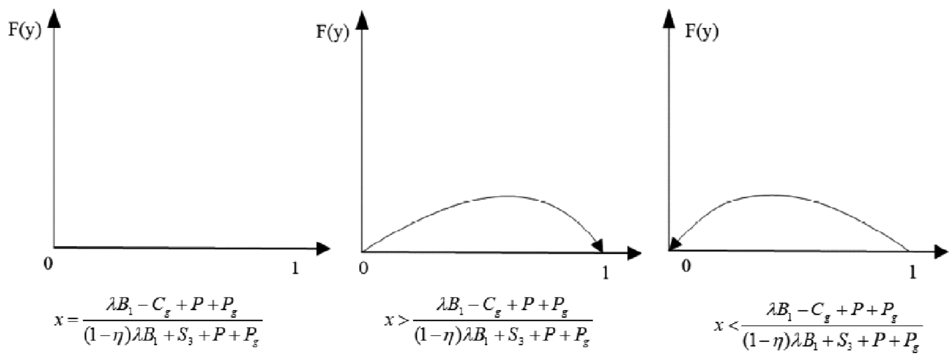

Figure 2: Dynamic phase diagram of replication of government carbon regulation strategy behavior

3.3. Stability analysis of the mixed evolutionary game between business and government

Based on the above analysis, it is clear that the firm has two evolutionary stabilization strategies, $x = 1$ and $x = 0$. The government has two evolutionary stabilization strategies, $y = 1$ and $y = 0$, when $\lambda B_1 - C_g + P + P_g > 0$, i.e., when the total cost of active government carbon regulation is less than the sum of carbon taxes, government penalties, and government environmental governance costs. Letting $F(x) = 0, F(y) = 0$ yields five Nash equilibrium points for this replicator dynamic system, which are $(0,0)$ ` $(0,1)$ ` $(1,0)$ ` $(1,1)$ ` (x^*, y^*), where x^* and y^* are shown below.

$$\begin{cases} x^* = \dfrac{\lambda B_1 - C_g + P + P_g}{(1-\eta)\lambda B_1 + S_3 + P + P_g} \\ y^* = \dfrac{-S_2 + S_1 + C + \lambda B_2}{S_3 + (1-\eta)\lambda B_1 + \lambda B_2 + P} \end{cases}$$

According to Friedman's proposed method of analyzing local stability using Jacobi matrices, the stability of the equilibrium point of the evolutionary game can be derived. The corresponding Jacobi matrices are obtained from the replicator dynamic equations of the evolutionary game of the firm and the government as shown in equation (14).

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} \tag{14}$$

where n_{11}, n_{12}, n_{21}, n_{22} are shown below.

$$n_{11} = (1-2x)\{y(S_3 + (1-\eta)\lambda B_1 + \lambda B_2 + P) + (S_2 - S_1 - C - \lambda B_2)\}$$
$$n_{12} = x(1-x)[S_3 + (1-\eta)\lambda B_1 + \lambda B_2 + P]$$
$$n_{21} = y(1-y)[(\eta - 1)\lambda B_1 - S_3 - P - P_g]$$
$$n_{22} = (1-2y)\{x[(\eta-1)\lambda B_1 - S_3 - P - P_g] + \lambda B_1 - C_g + P + P_g\}$$

The Jacobi matrix reflects the optimal linear approximation of the differential equation to a given point. The equilibrium point among the five Nash equilibria analyzed above that satisfies the following two conditions is the evolutionary stabilization strategy.

$$(1)\, trJ = n_{11} + n_{22} < 0$$
$$(2)\det J = n_{11}n_{22} - n_{12}n_{21} > 0$$

As a result, the specific values of a_{11}, a_{12}, a_{21}, a_{22} at the local equilibrium point can be obtained, as shown in Table 3. From the table, we can see that at the equilibrium point (x^*, y^*), its $trJ = 0$, does not satisfy the condition of $trJ < 0$, so only four points of $(0,0)$ `$(0,1)$ `$(1,0)$ and $(1,1)$ need to discuss the stability.

Table 3: Specific values of n_{11}, n_{12}, n_{21}, n_{22} at local equilibrium points

Equilibrium points	n_{11}	n_{12}	n_{21}	n_{22}
(0,0)	$S_2 - S_1 - C - \lambda B_2$	0	0	$\lambda B_1 - C_g + P + P_g$
(0,1)	$S_3 + (1-\eta)\lambda B_1 + P + S_2 - S_1 - C$	0	0	$-\lambda B_1 + C_g - P - P_g$
(1,0)	$-S_2 + S_1 + C + \lambda B_2$	0	0	$\eta\lambda B_1 - S_3 - C_g$
(1,1)	$-S_3 - (1-\eta)\lambda B_1 - P - S_2 + S_1 + C$	0	0	$-\eta\lambda B_1 + S_3 + C_g$
(x^*, y^*)	0	*	*	0

According to the analysis above, the government has two evolutionary stable strategies at $y=1$ and $y=0$ when $\lambda B_1 - C_g + P + P_g > 0$, so the discussion focuses on the stability of the mixed strategy of the firm and the government under $\lambda B_1 - C_g + P + P_g > 0$. Depending on the specific value of $n_{11}, n_{12}, n_{21}, n_{22}$ at the local equilibrium, the stability of the equilibrium can be discussed in four cases.

Scenario 1: When $\lambda B_1 - C_g + P + P_g > 0$, $S_3 + (1-\eta)\lambda B_1 + P + S_2 > S_1 + C$ and $\eta\lambda B_1 > S_3 + C_g$. Scenario 2: When $\lambda B_1 - C_g + P + P_g > 0$, $S_3 + (1-\eta)\lambda B_1 + P + S_2 > S_1 + C$ and $\eta\lambda B_1 < S_3 + C_g$. The results of local stability analysis for the four equilibrium points are shown in Table 4.

Table 4: Local stability analysis under scenarios 1 and 2

Equilibrium points	*det J*	*Situation 1* *tr J*	*Results*	*det J*	*Scenario 2* *tr J*	*Results*
(0,0)	-	+/-	Saddle Point	-	+/-	Saddle Point
(0,1)	-	+/-	Saddle Point	-	+/-	Saddle Point
(1,0)	+	+	Instability point	-	+/-	Saddle Point
(1,1)	+	-	ESS	-	+/-	Saddle Point

As can be seen from Table 4, in Scenario 1, $(1,1)$ is the local stability point of the evolutionary game. That is, when the total cost of positive government carbon regulation is smaller than the sum of carbon tax, government penalty and government environmental governance cost, the sum of the benefits of negative carbon emission reduction and the cost of technological innovation in positive carbon emission reduction is smaller than the sum of government subsidy, carbon tax, government penalty and the benefits of positive carbon emission reduction of enterprises, and the sum of the total cost of government subsidy and positive government carbon regulation is smaller than carbon tax, the comprehensive benefits obtained by enterprises implementing positive carbon emission reduction strategy Therefore, enterprises tend to implement positive carbon reduction strategies. At this point, the government's combined benefits of implementing active carbon regulation are greater, so the government tends to implement an active carbon regulation strategy. The evolutionary game in Scenario 2 has no local stability point.

Scenario 3: When $\lambda B_1 - C_g + P + P_g > 0$, $S_3 + (1-\eta)\lambda B_1 + P + S_2 < S_1 + C$ and $\eta\lambda B_1 > S_3 + C_g$. Scenario 4: When $\lambda B_1 - C_g + P + P_g > 0$, $\eta\lambda B_1 < S_3 + C_g$

and $S_3+(1-\eta)\lambda B_1+P+S_2<S_1+C$. The local stability analysis is shown in Table 5.

Table 5: Local stability analysis under scenarios 3 and 4

Equilibrium points	Scenario 3 det J	tr J	Results	Scenario 4 det J	tr J	Results
(0,0)	-	+/-	Saddle Point	-	+/-	Saddle Point
(0,1)	+	-	ESS	+	-	ESS
(1,0)	+	+	Instability point	-	+/-	Saddle Point
(1,1)	-	+/-	Saddle Point	+	+	Instability point

As can be seen from Table 5, in scenarios 3 and 4, (0,1) is the local stability point of the evolutionary game. That is, when the total cost of positive government carbon regulation is less than the sum of carbon tax, government penalty and government environmental governance costs, and the sum of the benefits of technological innovation when enterprises reduce carbon emissions negatively and when enterprises reduce carbon emissions positively is greater than the sum of government subsidies, carbon tax, government penalty and the benefits of enterprises reducing carbon emissions positively, the comprehensive benefits obtained by enterprises implementing the strategy of negative carbon reduction are greater, so enterprises tend to reduce carbon emissions negatively. At this time, the comprehensive benefits of positive carbon regulation by the government are greater, so the government tends to implement positive carbon regulation strategy

4. Numerical simulation analysis

4.1. Evolutionary game analysis in multiple scenarios

1. Based on the above theoretical analysis basis, numerical simulation analysis of the behavioral strategies of firms and governments is conducted using MATLAB software using constraints and replicator dynamic equations. Combined with the theoretical analysis, the following simulation constraints are set for each parameter: $S_1>S_2, B_1>B_2, 0\le\eta\le 1$; the rest of the parameters are positive. In case 1, i.e., when $\lambda B_1-C_g+P+P_g>0$, $S_3+(1-\eta)\lambda B_1+P+S_2>S_1+C$ and $\eta\lambda B_1>S_3+C_g$, the parameters are set as shown in Table 6. Figure 3 shows the dynamic evolution process of the probability of decision making between enterprise and government behavior under different initial values.

Table 6: Parameter value settings for the business-government game

Parameters	*Assignment*	*Parameter*	*Assignment*
S_1	8	B_2	30
S_2	6	P	12
S_3	4	P_g	1
C	14	η	0.3
C_g	5	λ	0.8
B_1	50	—	—

It can be seen from the figure that the evolutionary game between enterprises and the government will evolve to the stable point of (1,1) with the increase of the number of iterations under different initial values, indicating that the different initial values do not affect the evolutionary results. From the evolutionary results, when the benefit of negative carbon emission reduction is lower than the cost of technological innovation in positive carbon emission reduction, the probability of enterprises choosing positive carbon emission reduction strategy will keep increasing, while the probability of the government choosing positive carbon regulation will also keep increasing.

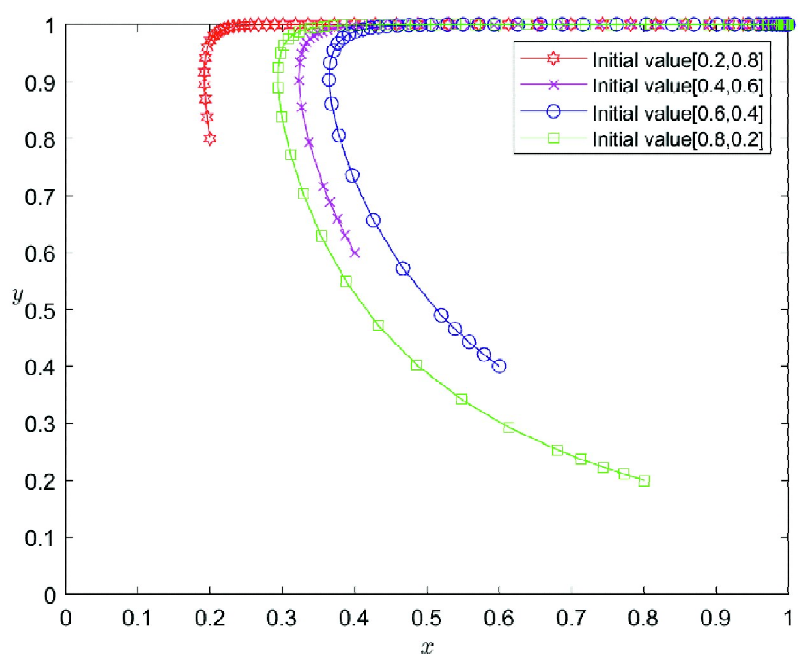

Figure 3: Results of the dynamic evolution of political enterprises with different initial values

2. Through the above analysis, $(0,1)$ is an evolutionary stable strategy for the evolutionary game between the firm and the government in case 3 and 4 above. Therefore, Case 3 and Case 4 are grouped together, i.e., when $\lambda B_1 - C_g + P + P_g > 0$ and $S_3 + (1-\eta)\lambda B_1 + P + S_2 < S_1 + C$. Set the parameters as shown in Table 7.

Table 7: Parameter value setting of the game between the lower enterprise and the government

Parameters	*Assignment*	*Parameters*	*Assignment*
S_1	10	B_2	30
S_2	6	P	12
S_3	4	P_g	1
C	30	η	0.7
C_g	5	λ	0.8
B_1	40	—	—

The evolution of the game between enterprises and the government at different initial values is shown in Fig. 4. From the figure, it can be seen that the stable point of $(0,1)$ evolves at different initial values. The probability of enterprises choosing to implement negative carbon reduction strategy will keep decreasing when the benefits of enterprises' negative

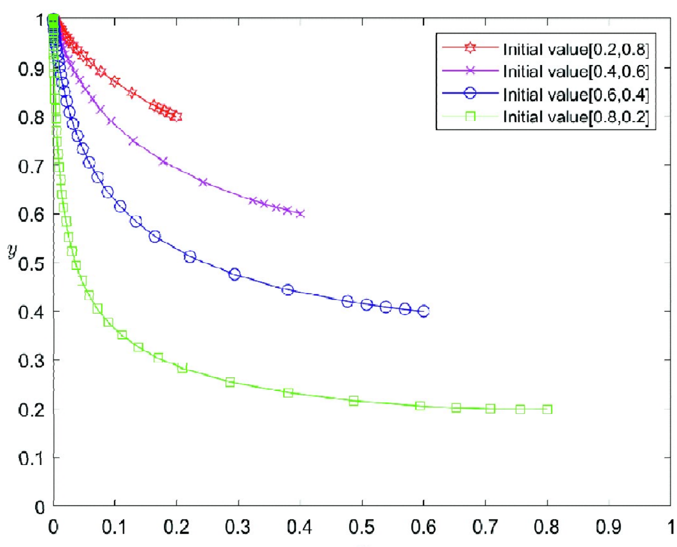

Figure 4: Results of the dynamic evolution of political enterprises with different initial values

carbon reduction are higher than the costs of technological innovation when they are positive carbon reduction, while the probability of the government choosing positive carbon regulation will keep increasing.

Through the analysis of the above two scenarios, it is found that for enterprises, when the benefits of negative carbon emission reduction and the costs of technological innovation required for positive carbon emission reduction are low, enterprises will tend to implement positive carbon emission reduction strategies; when the benefits of negative carbon emission reduction and the costs of technological innovation required for positive carbon emission reduction are high, enterprises will tend to implement negative carbon emission reduction strategies. For the government, when the carbon tax rate and carbon penalty are large, the government will tend to positive carbon regulation; when the carbon tax rate and carbon penalty are small, the government will tend to negative carbon regulation.

4.2. Analysis of the impact of parameters on the evolutionary game of corporate government

4.2.1. The effect of government punishment intensity on evolutionary outcomes

In order to investigate the effect of collecting penalties on firms' behavioral strategies when the government actively regulates carbon, numerical simulations were conducted by varying the magnitude of P-values under the parameter settings of Case 1. Figure 5 shows the simulation results. From the figure, it can be seen that when the government's penalty is small, firms are more inclined to implement negative carbon emission reduction strategies, and when the government increases the penalty, firms will

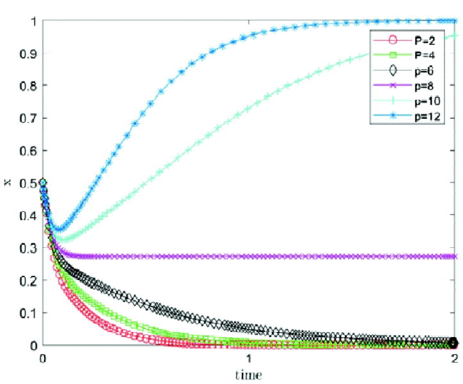

Figure 5: Impact of carbon penalty on the evolutionary path of corporate strategy

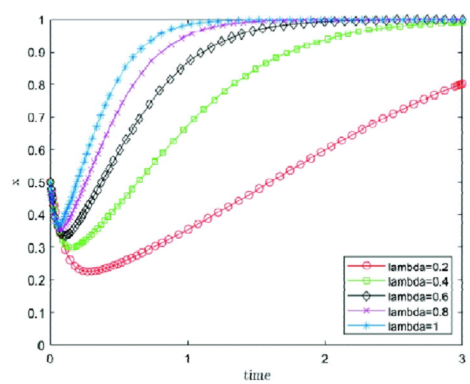

Figure 6: Impact of carbon tax on the evolutionary path of corporate strategy

gradually tend to implement positive carbon emission reduction strategies. Therefore, the government can increase the penalty to promote the implementation of positive carbon reduction strategies.

4.2.2. Impact of carbon taxes on evolutionary outcomes

Controlling the other parameters constant, the carbon tax rate at the time of active government carbon regulation b is set to 0.2, 0.4, 0.6, 0.8 and 1, respectively, and Figure 6 shows the numerical simulation results. From the figure, it can be seen that as the carbon tax rate continues to rise, x converges to 1 faster and faster, i.e., the probability of enterprises choosing to implement active carbon emission reduction strategies converges to 1 faster and faster, indicating that appropriately increasing the carbon tax rate β can substantially increase the probability of enterprises implementing active carbon emission reduction.

4.2.3. Impact of government carbon regulation efficiency on evolutionary outcomes

In order to investigate the influence of the efficiency of active government carbon regulation on the behavioral decision of enterprises, the proportion of carbon emissions reduced by the time of active government carbon regulation α is set to 0.1, 0.2, 0.3, 0.4 and 0.5, respectively, controlling other parameters constant, and Figure 7 shows the numerical simulation results. From the figure, it can be seen that, with the increasing efficiency of government active carbon regulation, the probability of government active carbon regulation x converges to 1 faster and faster, i.e., the probability that enterprises choose to implement active carbon emission reduction strategy becomes larger and larger, indicating that improving the efficiency when government active carbon regulation can effectively promote enterprises' active carbon emission reduction.

4.2.4. The influence of government subsidies on the behavioral strategies of enterprises

In order to investigate the influence of government subsidies on enterprises' behavioral decisions, the subsidies S_3 by the government to enterprises implementing active carbon emission reduction strategies are set to 4, 8, 12, 16 and 20, controlling other parameters constant, and Figure 8 shows the numerical simulation results.

From the figure, it can be seen that when the government subsidy R_3 to the active carbon emission reduction enterprises is set to 4 and 8, the probability of enterprises choosing to implement the active carbon emission reduction strategy converges to 1. However, with the increase of the subsidy, the probability of enterprises choosing the active carbon emission reduction

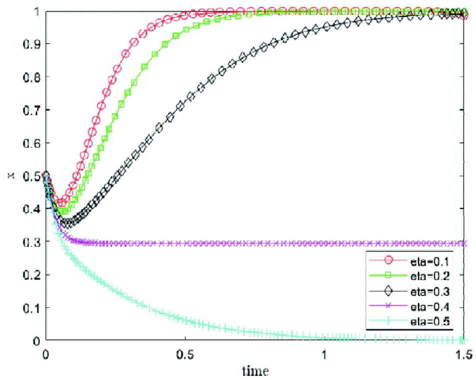

Figure 7: Effect of government carbon efficiency on the evolutionary path of corporate strategies

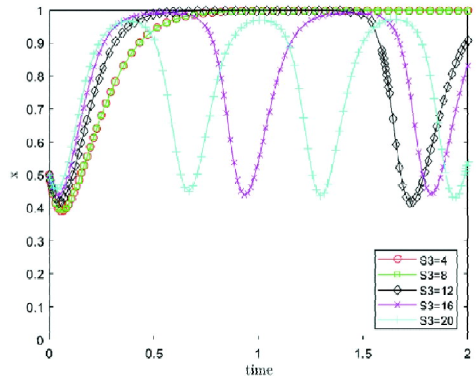

Figure 8: Effect of carbon subsidies on the evolutionary path of corporate strategies

strategy appears a cyclical behavior pattern and there is no longer an evolutionary stable strategy. It can be seen that setting appropriate carbon emission reduction subsidies can significantly increase the probability of enterprises to actively reduce carbon emissions. The optimal range of carbon emission reduction subsidies R_3 is $4 \leq S_3 \leq 8$, and increasing carbon emission reduction subsidies within this range can improve the probability of enterprises to implement carbon emission reduction, and too high carbon subsidies instead make the probability of enterprises to choose active carbon emission reduction unstable.

5. Conclusion

Through the simulation analysis of the evolutionary game of carbon emission reduction between government and enterprises under different scenarios, and the influence of four parameters on the evolutionary game path of government and enterprises, namely, the intensity of government penalties, the carbon tax rate, the efficiency of government carbon regulation, and the revenue from government subsidies and carbon emission rights auctions, we can draw the following conclusions:

(1) When the cost of technological innovation is low or the overall benefit of negative carbon reduction enterprises is low, enterprises will actively implement carbon reduction strategies in the expectation of higher benefits

(2) For the government, when carbon tax rates and carbon penalties are high, the government will adopt an aggressive carbon regulation strategy.

(3) Carbon subsidies given by the government to enterprises and the carbon emission rights auction mechanism can effectively promote enterprises to actively reduce carbon emissions. Under the carbon emission trading mechanism, enterprises will actively research and innovate to reduce carbon emissions, improve their production technology, reduce carbon emissions, and earn extra income in the carbon emission trading market.

Acknowledgement

This research was financially supported by the National Nature Science Foundation of China (Grant NO.12061065 and Grant NO.12061066)

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