DOI: 10.23977/cpcs.2023.070105
ISSN 2371-8889 Vol. 7 Num. 1

Evolution and Equilibrium of Collaborative Innovation System of Low-Carbon Technology: Simulation of a Multi-stakeholders Game Model

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Keywords: Low-carbon technology, evolutionary game, collaborative innovation

Abstract: Low-carbon technology innovation is different from ordinary technology research, which has high investment, high risk and great uncertainty. It is very hard for enterprises and research institutions to succeed independently, and almost impossible for them to cooperate actively. Due to the different objective of participants, the expectation of innovation is reflected in the initial collaborative intention, which is a pivotal factor influencing the stability of collaborative innovation. On the premise of bounded rationality, this paper constructs multiple stakeholders evolutionary game model involving government, enterprises and scientific institutions. The influence of initial strategy probabilities of three participants is analysed in detail through simulation. The findings are as follows: (1) The evolution of government strategy is not affected by the initial collaboration probabilities of enterprises and research institutions. Eventually government strategies evolve into stimulation and support. (2) The strategy evolution of enterprises and research institutions is significantly affected by the initial strategy probabilities of three participants. The higher the initial probability of government support, the higher the possibility of enterprises and scientific institutions participating in collaboration. At the same time, the initial collaboration probabilities of enterprises and research institutions have a significant impact on each other, and the higher initial collaboration probability of one participant, the higher the probability of the other participating in collaboration. (3) Through the scenario simulation of two extreme probabilities, it is found that enterprises, compared with research institutions, play a more decisive role in collaborative low-carbon technology innovation under the support of the government. Therefore, if the government wants to realize the low-carbon technology collaborative innovation, the essential point is to stimulate collaboration enthusiasm of enterprises.

1. Introduction

Human beings' excessive dependence on non-renewable energy in production leads to excessive greenhouse gas emissions. According to the Statistical Yearbook of World Energy (2019), the global carbon emissions increased by 2% in 2018, a historically high [1]. To deal with various environmental problems caused by greenhouse gas emissions, low-carbon technology innovation has become an essential solution [2]. Low-carbon technology can not only alleviate the fossil energy crisis, provide green technologies for mankind, but also promote the improvement of the ecological environment and realize the sustainable development of human society and economy. However, low-carbon technology is different from ordinary technology, which has high investment, high risk and benefits uncertain, so it is very difficult for enterprises or research institutions to conduct independently. Therefore, collaborative low-carbon technology innovation is the radical measure to achieve green technology breakthrough.

In the process of the construction of low-carbon technology collaborative innovation system, the government, enterprises and research institutions, as stakeholders, have different expectations. The government expects to maximize the public interest through collaborative innovation of low-carbon technology. As the major low-carbon technology innovation subjects, enterprises and research institutions expect to maximize their own interests. Participants' expectation of innovation is reflected in the initial collaborative intention, which is an important factor affecting the formation of collaborative innovation situation and the success rate of low-carbon technology innovation. On the premise of bounded rationality, this paper establishes a dynamic evolutionary game model involving government, scientific institutions and enterprises, studying the equilibrium and stability of the game model through deep analysis on the interest conflicts and strategic interactions among three participants. On this basis, the initial strategy probability represents the initial cooperative intention, and numerical simulation is used to reflect the influence of the probability change of participants' initial strategies on the evolution trend, and targeted suggestions are provided to promote the collaborative innovation of low-carbon technology.

2. Literature Review

From the previous literature, it can be found that the research on collaborative innovation of low-carbon technology is mainly carried out from two aspects. One aspect is to discuss influencing factors of low-carbon technology innovation. Rothenberg [3] believed that enterprises are the dominant players in low-carbon technology innovation activities, and the driving force of low-carbon technology innovation is influenced by the innovation atmosphere of enterprises and the working enthusiasm of employees. Crawford and French [4] studied influencing factors of low-carbon technology innovation, which include government policies, enterprise regulations and technology research capability. Quan Guo [5] analysed the impact of environmental regulation and green credit on low-carbon technology innovation. The research results show that the stronger the environmental regulation, or the more perfect the green credit mechanism, the more conducive to promoting low-carbon technology innovation. Mingyue Wang et al. [6] believed that the more efforts enterprises make for low-carbon technology innovation, the higher the benefit of system emission reduction will be under the scenario of centralized decision-making. Parayil G. [7] believed that low-carbon technology innovation system involves many aspects, including the government, enterprises and the public. Then the joint efforts of many parties are an effective way for the system to achieve its goals.

The other aspect is to analyse strategy interaction and equilibrium among the participants of collaborative technology innovation [8]-[16]. Liew et al. [9] distinguished the roles of technology innovation participants, and believed that the innovation project leader handled the problems arising in the cooperation process, guided the communication among members, constantly revised the research direction in the cooperation, and played a prime part in the stability of the cooperation. Hanjie Xiao et al. [10] believed that collaborative innovation has high risk and uncertain. Then they added the government and financial institutions into the game model and revealed that the crucial factor of low-carbon technology innovation success is government guiding and financial institutions leverage. Hedong Liu [11] included the government as a direct beneficiary in the game model. So, the cooperation between game participants is usually conducted under the guidance and supervision of the government, but if the government considers its own benefits, the stability of collaborative innovation will be reduced. Liu Yueting [12] added financial institutions into the collaborative innovation model. Through simulation analysis, she found that the system evolution is mainly affected by one member’s loss due to the withdrawal of the other. Zigang Yang [13] added government variables into the game model to analyse the impact of government intervention on technology transfer and cooperative development. He found that government intervention increases the upper limit of technology transfer price, which can enhance the cooperation willingness of industry, university and research institute. Ruguo Fan and Lili Dong [14] constructed a low-carbon technology market model with the participation of enterprises and consumers, analysed the influence of four kinds of government subsidies on technology diffusion, and believed that only when the proportion of enterprises with low-carbon strategies is relatively high, government subsidies effectively promote innovation. Etzkowitz et al. [15] used the triple helical model to analyse the cooperation process among universities, enterprises and governments, and believed that tripartite cooperation could improve their respective social values. Wu Jie et al. [16] constructed a collaborative innovation model of government, universities and enterprises. Through simulation analysis, they believed that the influence of government incentive policies is different between universities and enterprises, and enterprises are more sensitive to punishment and income distribution.

Through analysis of relevant literatures, it can be found that although some scholars put the government into the collaborative innovation system and analysed the role of the three participants, the influence of the initial collaborative intention of the government, enterprises and research institutions on the game equilibrium was not analysed. Because low-carbon technology is different from ordinary technological innovation, the research process has high investment, high risk and great uncertainty, so it is difficult to achieve technological breakthrough unilaterally [17]. As collaborative innovation participants, the government, enterprises and research institutions have different objective function in the process of game. These three participants have different expectations for the results of collaborative innovation, thus at the beginning of the game they will show different initial willingness to cooperate, which may be the crucial factor affecting the formation of collaborative innovation situation. It is necessary to conduct analysis in detail on how the enterprises initial collaborative willingness and research institutions affects the equilibrium at the beginning of collaborative innovation of low-carbon technology, and how the government simulates enterprises and institutions when they have different collaborative probabilities.

On the premise of bounded rationality, this paper constructs a dynamic evolutionary game model involving enterprises government and research institutions, analyses in detail the interest conflicts and strategic interactions among the participants, and clarifies the dynamic evolution process of strategy and the stability of equilibrium. On this basis, we use initial strategy probabilities to reflect three participants’ initial collaborative intention. Through the game simulation, the influence of the three participants initial strategy probabilities on the evolution is analysed deeply, which provides effective theoretical support for exploring the realization approach of low-carbon technology innovation.

3. Hypothesis and Construction of Collaborative Innovation Model of Low Carbon Technology

3.1. Connotation of Collaborative Innovation of Low Carbon Technology

Collaborative innovation refers to the cooperation of multiple stakeholders to complete the activities for the purpose of innovation. In the process of cooperation, the behaviours of each participant influence each other. Low-carbon technology is different from ordinary technology, which has high risk, great difficulty and uncertainty for individual innovation. Collaboration is the crucial approach to realize low-carbon technology innovation. By breaking the cooperation barriers, the flow of resource elements such as knowledge, technology, manpower and information can be realized. Collaborative innovation is a new and effective organization, which can form interactive and mutually beneficial collaborative innovation relationship and contribute to maximizing economic and social benefits.

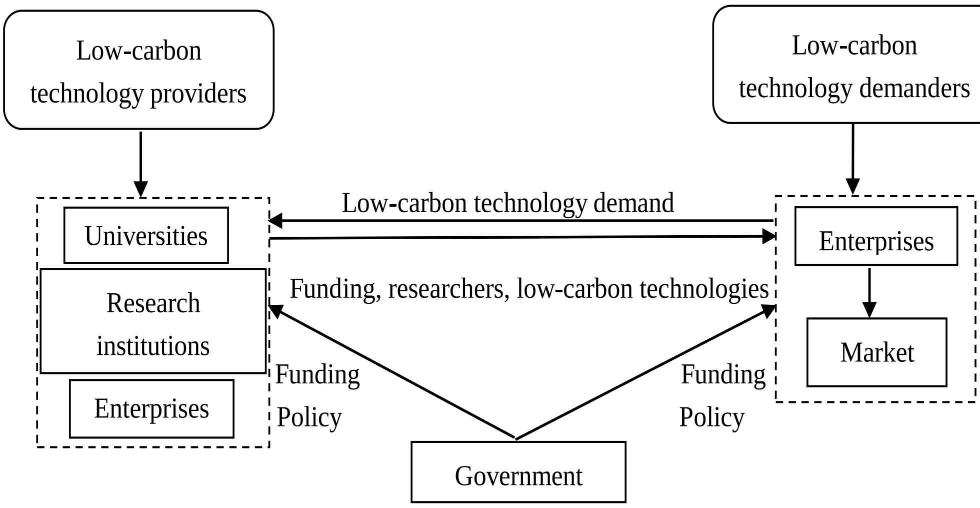

Figure 1: Supply-demand relationship of low-carbon technology innovation.

Collaborative innovation is a complicated organic system, as shown in Figure 1. Enterprises are the demanders for low-carbon technologies. Due to the direct contact with the market, enterprises can fully understand the market demand and technology application effect, timely provide information resources and effective suggestions on the direction of low-carbon technology innovation in the collaborative system. The main suppliers of low-carbon technologies are research institutions and enterprises, both of which have their own advantages. Research institutions have many researchers who have professional knowledge, understand the frontiers of low-carbon technology, and have enough research and development energy and time to focus on innovation. Starting with application and practice, the enterprises are more targeted in development of low-carbon technology. Therefore, low-carbon technology innovation can make full use of the advantages of participants, reduce the difficulty of innovation, disperse innovation risks and improve the probability of success. On the other hand, the government should play the role of guidance and macro-control in collaborative innovation, who creates an environment for innovation, provides policy support through financial input, enterprise subsidies, tax incentives, etc., unclogs communication channels, and coordinates cooperation between the scientific institutions and enterprises [18]. Low-carbon technology collaborative innovation is an effective organizational mode, which can form an interactive and mutually beneficial collaborative innovation network, help to maximize social and economic benefits, fundamentally change the status of high carbon economy, and achieve the dual goals of meeting market demand and realizing environmentally friendly production.

3.2. Hypothesis of the Model

Evolutionary game theory is originally applied to the study of biological genetic evolution, which takes bounded rationality as its premise and regards the change of various factors as a dynamic process. In the dynamic change process, the initial evolution state of behaviour subject is the crucial factor. The agent constantly makes its own strategy judgment through the strategy choice of other participants, corrects the wrong behaviour, and finally finds the most favourable strategy [19]. In the process of collaborative innovation, the government, enterprises and scientific institutions are bounded rational. The evolutionary game model of collaborative innovation is established to analyse the strategy evolution process in repeated learning. In order to analyse the strategy evolution and equilibrium of low-carbon technology innovation, the following assumptions are set:

(1) In the process of low-carbon technology collaborative innovation, the government can choose to provide policy and financial support for enterprises and research institutions. Therefore, the government's strategy choices set is {stimulate; not stimulate}, and the strategies set of enterprises and scientific research institutions is {collaborate, not collaborate}.

(2) "R" denotes the benefits obtained by the government when it chooses the strategy of "stimulate". While the government chooses the "not stimulate" strategy, the benefit brought by low-carbon technological innovation is cR, and "c" represents the proportion of the government benefit to the whole profit in the low-carbon technology collaborative innovation, which is a number between 0 and 1.

(3) When enterprises and scientific research institutions do not participate in collaborative innovation, their initial benefits are A and B respectively. And when they carry out collaborative innovation, the expenditure costs are a_1 and a_2 respectively. If the government supervises the cooperative behaviours of scientific institutions and enterprises, the supervision cost will be G. The government gives financial reward of G_1 for enterprises participating in collaborative innovation; For the scientific institutions participating, the financial support provided by the government is G_2. If enterprises or scientific research institutions do not take part in collaborative innovation, the government's reward is 0.

(4) When enterprises join in collaborative innovation, profit obtained is s, and due to the spill over effect of enterprises' low-carbon technological innovation, the additional income obtained by scientific research institutions is t. When scientific institutions involve in collaborative innovation, the profit obtained is m, and additional income obtained by enterprises due to low-carbon technological innovation carried out by scientific and technological institutions is n. Therefore, when enterprises and scientific institutions jointly involve in collaborative innovation, their total benefits are s+n and m+t respectively.

(5) Under the supervision of the government, when either the enterprises or scientific research institutions withdraws from collaborative innovation activities, this participant will be punished with P. It is assumed that when scientific research institutions withdraw from collaborative innovation alone, the loss suffered by enterprises is b_1. Similarly, when enterprises withdraw from collaborative innovation alone, the loss suffered by research institutions is b_2.

(6) In the game model, it is assumed that the probability of the government choosing the "stimulate" strategy is x, and the government "not stimulate" strategy probability is 1-x. The probability of enterprises choosing to participate in the collaborative innovation strategy is y, and the probability of enterprises choosing not to participate in is 1-y. In the same way, the probability of institutions in the collaborative innovation is z, and then the complementary probability is 1-z.

According to the above assumptions, the payoff matrix can be obtained, as shown in Table 1 and

Table 2.

Table 1: Payoff matrix when government chooses "stimulate" strategy.

		Research institutions	
		Collaborate (z)	Not collaborate ($1-z$)
Enterprises	Collaborate (y)	$R-G-G_1-G_2$, $A+s+n+G_1-a_1$, $B+m+t+G_2-a_2$	$R-G-G_1$ $A+s+G_1-a_1-b_1$ $B+t-P$
	Not collaborate ($1-y$)	$R-G-G_2$ $A+n-P$ $B+m+G_2-a_2-b_2$	$R-G$ A B

Table 2: Payoff matrix when government chooses "not stimulate" strategy.

		Research institutions	
		Collaborate (z)	Not collaborate ($1-z$)
Enterprises	Collaborate (y)	cR $A+s+n-a_1$, $B+m+t-a_2$	cR $A+s-a_1-b_1$ $B+t-P$
	Not collaborate ($1-z$)	cR $A+n-P$ $B+m-a_2-b_2$	cR A B

3.3. The Participants Replicate Dynamic Equations

According to Malthusian dynamic equation, the change speed of government dynamic strategy is expressed by dynamic differential equation. The replication dynamic equation of the government can be calculated as follows:

$$F(x)=dx/dt=x(1-x)[(1-c)R-G-yG_1-zG_2]$$

For the convenience of discussion, let $y^*=[(1-c)R-G-zG_2]/G_1$:

(1) If $y=y^*$, $F(x)=0$. For any $x\in(0,1)$, $F(x)$ is in a stable state, indicating that when enterprises participate in collaborative innovation of low-carbon technology at the level of $[(1-c)R-G-zG_2]/G_1$, the government will get the same benefits no matter which strategy chosen.

(2) If $y\neq y^*$, two quasi-stable points, $x=0$ and $x=1$, can be obtained under $F(x)=0$. Because $dF(x)/dx=(1-2x)[(1-c)R-G-yG_1-zG_2]$, three cases need to be discussed:

(a) If $(1-c)R-G-zG_2<0$, we can get $y^*<0$. For $y\in(0,1)$, there is always $y>y^*$, then plug in $x=0$, $x=1$, we can get $\frac{dF(x)}{dx}|_{x=0}<0$, $\frac{dF(x)}{dx}|_{x=1}>0$. The government is in a stable evolutionary state when $x=0$, which means no matter whether enterprises and scientific institutions in or not, the government will eventually choose the strategy of not motivating collaborative innovation due to the lack of profit in the process of evolution because the cost is greater than the actual benefit.

(b) If $(1-c)R-G-zG_2>G_1$, we can get $y^*>1$. For $y\in(0,1)$, there is always $y<y^*$, then $\frac{dF(x)}{dx}|_{x=0}>0$, $\frac{dF(x)}{dx}|_{x=1}<0$. When $x=1$, the government is in a stable evolutionary state which means whether the enterprises and institutions take part in collaborative innovation, the government chooses the stimulation strategy because for government the benefits brought by low-carbon technology collaborative innovation activities will outweigh the costs invested.

(c) If $0<(1-c)R-G-zG_2<G_1$, then $(1-c)R<G_1+G+zG_2$. And two scenarios should be discussed. If $y>y^*$,we can get $\frac{dF(x)}{dx}|_{x=0}<0$, $\frac{dF(x)}{dx}|_{x=1}>0$, and if $y<y^*$,the result is $\frac{dF(x)}{dx}|_{x=0}>0$, $\frac{dF(x)}{dx}|_{x=1}<0$.

There is a high correlation between the government and the enterprises choices. Only when the enterprises' collaborative intention satisfies the relevant conditions, the government will choose to stimulate collaborative innovation.

Similarly, the enterprises replication dynamic equation is as follows:

$$F(y)=dy/dt= y(1-y)\ [z(P+b_1) +xG_1+s-a_1-b_1]$$

For the convenience of discussion, let $z^*=\frac{a_1+b_1-(s+xG_1)}{P+b_1}$:

(1) If $z=z^*$, then $F(y)=0$. This indicates that no matter whether scientific institutions participate in or not, enterprises are in a stable strategic state of participating in collaborative innovation, which will not change.

(2) If $z\neq z^*$, two quasi-stable points, $y=0$ and $y=1$, can be obtained under $F(y)=0$. Because $dF(y)/dy= (1-2y)\ [z(P+b_1) +xG_1+s-a_1-b_1]$ and $z(P+b_1)+xG_1-s+a_1+b_1$ can’t be judged the magnitude, three cases need to be discussed:

(a) If $a_1+b_1<s+xG_1$, $z^*<0$. So, for any z in the range from 0 to 1 there's $z>z^*$. Then plug in $y=0$， $y=1$, we can get $\frac{dF(y)}{dy}|_{y=0}>0$, $\frac{dF(y)}{dy}|_{y=1}<0$. It shows that when the benefits brought by enterprises' participation in collaborative innovation are greater than the costs incurred, enterprises will choose to actively participate in low-carbon technology collaborative innovation. And the enterprises are in a stable evolutionary state when $y=1$.

(b) If $P+b_1< a_1+b_1-(xG_1+s)$, we can get $z^* >1$. For $z\in(0,1)$, there is always $z<z^*$, $\frac{dF(y)}{dy}|_{y=0}<0$, $\frac{dF(y)}{dy}|_{y=1}>0$. When the sum of the benefits obtained by enterprises and the financial support from the government is far less than the cost of enterprises' participation in, enterprises tend to give up the collaborative innovation strategy in the end under the action of time evolution pressure.

(c) If $0<a_1+b_1-(xG_1+s)<P+b_1$, two scenarios should be discussed. When $z>z^*$, then $\frac{dF(y)}{dy}|_{y=0}>0$, $\frac{dF(y)}{dy}|_{y=1}<0$, and when $z<z^*$, then $\frac{dF(y)}{dy}|_{y=0}<0$, $\frac{dF(y)}{dy}|_{y=1}>0$. This means that the strategy choice of enterprises is affected by the strategy of scientific research institutions and the government. When the government is more willing to encourage, at the same time the scientific institutions are more willing to choose collaboration, the enterprises are more willing to choose to participant in collaborative innovation, and vice versa.

In the same way, the replication dynamic equation of research institutions is:

$$F(z)=dz/dt= z(1-z)[m-a_2+ yP+xG_2 -(1-y)b_2]$$

For the convenience of discussion, let $y^{**}=\frac{a_2+b_2-(m+xG_2)}{P+b_2}$:

(1) If $y=y^{**}$, $F(z)=0$. This indicates that scientific institutions choose to participate in collaborative innovation of low-carbon technology as a stable strategic state, not changing over time.

(2) If $y\neq y^{**}$, two quasi-stable points, $z=0$ and $z=1$, can be obtained under $F(z)=0$. Because $dF(z)/dz= (1-2z)[m-a_2+yP-(1-y)b_2]$ and $a_2+b_2-(m+xG_2)$ can’t be judged the magnitude, three cases need to be discussed:

(a) If $a_2+b_2-(m+xG_2)>P+b_2$, $y^{**}>1$. So, for any y in the range from 0 to 1, there's $y<y^{**}$. Then plug in $z=0$， $z=1$, we can get $\frac{dF(z)}{dz}|_{z=0}<0$, $\frac{dF(z)}{dz}|_{z=1}>0$. It means that when the benefits obtained by research institutions and the financial support from the government is far less than the cost of enterprises, research institutions tend to give up the collaborative innovation strategy in the end under the action of time evolution pressure.

(b) If $a_2+b_2-(m+xG_2)<0$, $y^{**}<0$. So, for any y in the range from 0 to 1 there's $y>y^{**}$. Then plug in z=0, z=1, we can get $\frac{dF(z)}{dz}|_{z=0}>0$, $\frac{dF(z)}{dz}|_{z=1}<0$. The research institutions are in a stable evolutionary state when z=1, which means that when the benefits brought by research institutions are greater than the costs incurred, research institutions will choose to participate in low-carbon technology collaborative innovation.

(c) If $0<a_2+b_2-(m+xG_2)<P+b_2$, two scenarios should be discussed. When $y>y^{**}$, $\frac{dF(z)}{dz}|_{z=0}>0$, $\frac{dF(z)}{dz}|_{z=1}<0$, and when $y<y^{**}$, $\frac{dF(z)}{dz}|_{z=0}<0$, $\frac{dF(z)}{dz}|_{z=1}>0$. This means that the strategy choice of research institutions is affected by the enterprises and the government strategy. If the government is more willing to encourage, and the enterprises are more willing to choose collaboration, the research institutions are more willing to choose to participant in collaborative innovation, and vice versa.

From the analysis, it shows that the stimulation of government for collaborative innovation and the punishment for the withdrawal have an important impact on the enterprises strategic choice. The greater stimulation and punishment, the more likely the enterprises choose the collaborative strategy in the evolutionary game. Moreover, the benefits obtained by enterprises are greater than the costs, which also has an incentive effect on the strategic choice. Therefore, when enterprises choose whether to adopt collaborative innovation strategy, the main factors to be considered include the benefits gained from cooperation, the government support and subsidies, as well as the input cost and the risks. For research institutions when the benefits in the collaborative innovation exceed costs, research institutions will actively participate in collaborative innovation. In addition, the institutions strategic choice is also affected by the rewards and punishments from government and the strategic choice of enterprises.

3.4. Solution Method for the Model

According to Friedman's method, the Jacobian matrix J is obtained by taking partial derivatives of the replicating dynamic equation. In terms of the local stability evaluation method of evolutionary games, the equilibrium points are determined whether to be evolutionarily stable strategy (ESS).

There are nine equilibrium in this system, they are: $EQ_1(0,0,0)$, $EQ_2(0,0,1)$, $EQ_3(0,1,0)$, $EQ_4(0,1,1)$, $EQ_5(1,0,0)$, $EQ_6(1,0,1)$, $EQ_7(1,1,0)$, $EQ_8(1,1,1)$, $EQ_9(x_0, y_0, z_0)$. Since EQ_9 belongs to the non-asymptotically stable state, only the local stabilities from EQ_1 to EQ_8 are analysed. In order to judge the sign of eigenvalues under different conditions, it is assumed $(1-c)R-G-G_1-G_2>0$, $P+s-a_1>0$, $m-a_2+P>0$.

Under the condition that the hypothesis is satisfied, the tripartite evolutionary stable equilibrium strategy has two points, EQ_5 (1,0,0) and EQ_8(1,1,1). It means that no matter whether the government stimulates or not, only when the benefits of enterprises and research institutions outweigh the costs, the collaborative strategy can be chosen. And when the government, as an economic participant, is included in the evolutionary game of collaborative innovation, its strategic behaviour of choosing stimulation will improve the possibility of collaborative innovation cooperation between enterprises and scientific research institutions.

4. Numerical Simulation Analysis

Enterprises and scientific research institutions cooperate to carry out low-carbon technological innovation, dispersing risks and achieving win-win economic benefits. The government encourages and supervises collaborative innovation to provide the stable policy environment for the realization of innovation, and at the same time, to obtain more benefits from low-carbon innovation [20]. In order to deeply analyze the sensitivity and relevance of relevant parameters of collaborative innovation, this paper conducts data simulation. According to the above analysis and the basic assumptions of the model, the initial assignments of the set parameters are shown in Table 3:

Table 3: Parameters assignment.

Parameters	A	B	R	c	s	m	G	G_1	G_2	a_1	a_2	b_1	b_2	P
Assignment	10	8	32	0.5	34	27.5	3	4	4	22	19	28	25	5

According to the calculation of parameter assignment, the relevant parameter values can be obtained: $y^*\approx2.75$, $z^*=0.42$, $y^{**}=0.48$. The probability of strategic choice of the government, enterprises and scientific research institutions are simulated to analyse the evolution process of the two equilibrium points under the condition of different willingness of the participants.

4.1. Influence of Initial Probability of Government on Strategy Evolution

If other conditions remain unchanged, y=z=0.5 and the value of x is changed, the influence of the change of the probability value of government strategy choice on the evolution stability of the three participants is studied. Let x be 0.3 and 0.4 respectively, and the game evolution process is shown in Fig. 2.

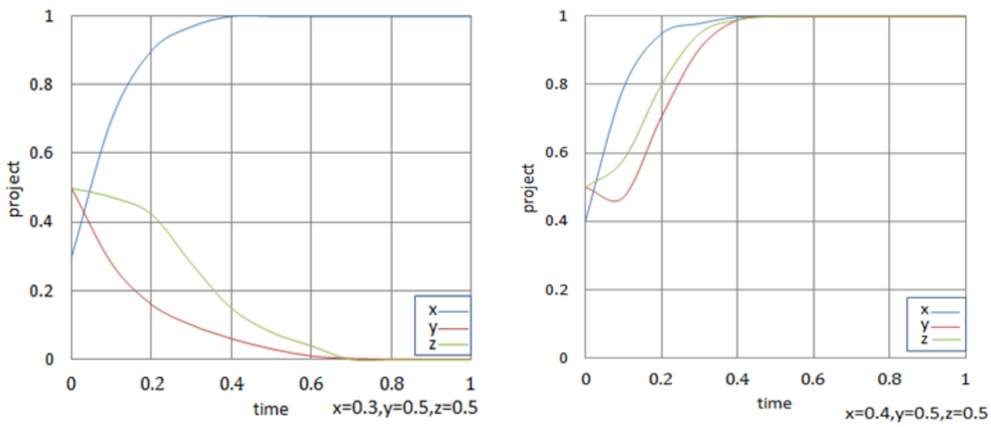

Figure 2: Evolution paths of x, y, z when x=0.3 or 0.4.

According to the evolution results, when the government's initial stimulation probability is lower than 0.375, x tends to 1, and both y and z tend to 0, that is to say, the final result of the evolutionary game tends to (1,0,0). With the gradual increase of X value, the probability of enterprises collaborative intention tends to 0 faster than that of scientific research institutions. When the government's initial stimulation probability is higher than 0.375, x, y, z all tend to 1, which means that the final result of the evolutionary game tends to (1,1,1). As can be seen, with the x value increase, the speed of y and z approaching equilibrium value will be faster and faster, and the evolution speed of z will be higher than y.

4.2. Influence of Initial Collaboration Probability of Research Institutions on Evolution

From the strategy stability analysis of the enterprise, the critical value z * can be calculated as 0.42. Therefor if the probability of scientific research institutions choosing collaborative innovation is greater than 0.42, then enterprises will choose to join in collaborative innovation. If the probability is less than 0.42, the enterprises will choose not to. The government's optimal strategy is still to encourage collaborative innovation and will not change. Keep x=y=0.5 and set the initial values of z equal to 0.3 and 0.6 respectively to observe the influence of the change of z initial value on the evolutionary stability. The game evolution process is shown in Fig. 3.

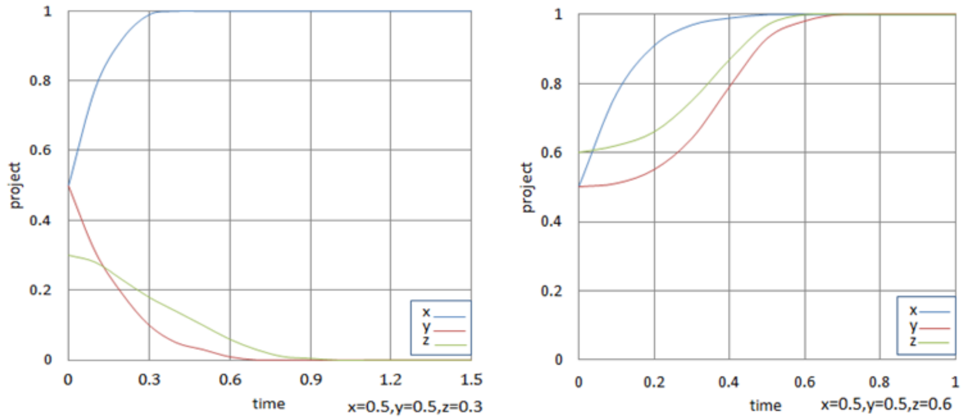

Figure 3: Evolution paths of x, y and z when z=0.3 or 0.6.

From the game evolution process, when the initial value of z is lower than the critical value of 0.42, the x value tends to 1, and the y value and z value both tend to 0. And the enterprises evolution speed is faster than scientific institutions, and the evolutionary game tends to the equilibrium point (1,0,0). This evolutionary process indicates that the evolution of enterprises strategy is affected by the initial collaborative intention of research institutions. When research institutions show a high willingness of collaborative innovation at the initial stage of the game, it can directly drive the enthusiasm of enterprises to join in collaboration.

4.3. Initial Probability of Enterprises Collaboration Influence

The institutions strategy evolution is affected by the initial collaborative intention of enterprises, and the critical value of its strategic stability is y^{**}. According to the assumed conditions and initial assignment, $y^{**}=0.48$. This means that if the initial probability of enterprises is greater than 0.48, strategy evolution of institutions is to join in collaborative innovation. If initial collaboration probability of enterprises is less than 0.48, strategy evolution of research institutions is not to act. The government's optimal strategy is still to encourage collaborative innovation. Set $x=z=0.5$, and the initial value of y as 0.3 and 0.6 respectively, to analyse the initial value of y influence on the stability of strategy evolution of the three participants. The evolution paths are shown in Fig. 4.

When the initial value of y is less than 0.48, the values of y, z tend to 0 and x tend to 1 gradually, so the local equilibrium point is (1,0,0), and the z value decreases a little faster than the y value. When the initial value of y is greater than the critical value of 0.48, the values of y and z gradually get close to 1. At this time, the evolutionary game eventually approaches the equilibrium point (1,1,1), and the growth rate of the value of y is similar to z. In this condition, in the initial change of y value, there is a stage of decreasing variation. When y value decreases to around 0.5, z value starts to rise synchronously until 1.

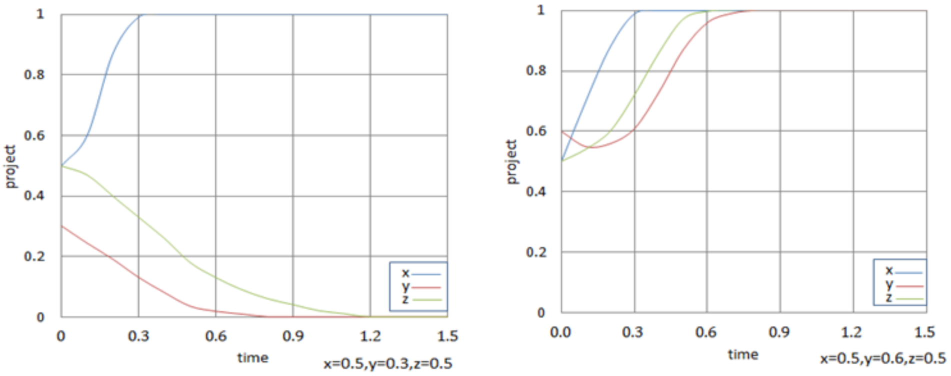

Figure 4: Evolution paths of x, y and z when y=0.3 or 0.6.

4.4. Influence of Initial Probabilities of Both Enterprises and Research Institutions on Evolution

The comprehensive analysis of the evolution path characteristics of the participants in the above three situations shows that the state of the government tends to be stable, and the final equilibrium result of its evolution is the implementation of stimulation strategy. At the same time, it can also be found that the collaborative probabilities of enterprises and scientific research institutions change with each other. Then, in the case of government support, which participant is more decisive in the formation of collaborative innovation situation between enterprises and scientific institutions? In order to explore the participant who plays a leading role in the final evolution, two extreme cases are set. Assume x initial value is 0.5, and y=0.9, z=0.1. The other case is y=0.1, z=0.9. Observe the strategy evolution trajectories of government, enterprises and research institutions, and the results are shown in Fig. 5.

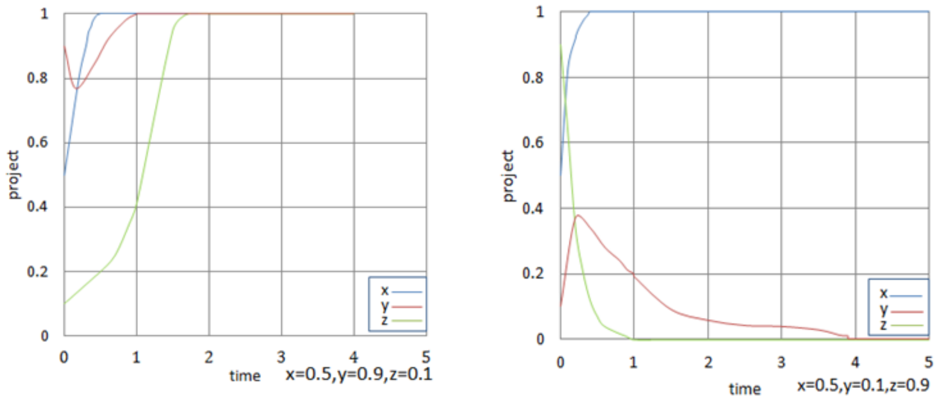

Figure 5: Evolution paths when y=0.9, z=0.1 or y=0.1, z=0.9.

If enterprises initial collaboration probability is very high and the that of research institutions is relatively low, the final result of game evolution is that enterprises and research institutions eventually evolve into collaborative low-carbon technological innovation under the government support. In Fig.5, if the initial collaboration probability of enterprises is very low and that of research institutions is relatively high, the final result of game evolution is that enterprises and scientific research institutions cannot form collaborative innovation in the end, even under government's incentive policies.

5. Conclusions

In this paper, the evolutionary game analysis method is used to establish the payment matrix of collaborative innovation game involving enterprises, government and research institutions, and the decision-making evolution process and local equilibrium points are systematically analysed. Combined with numerical simulation, the influence of the initial collaboration probabilities of government, enterprises and research institutions on the collaborative innovation strategy evolution trajectory are investigated. The results show that the government plays an important role in promoting collaborative innovation. Regardless of the initial willingness of enterprises and scientific institutions to cooperate, the optimal strategy of government is always incentive support. The initial collaboration probabilities of enterprises and institutions have the significant impact on the strategic evolution of both sides, and enterprises play a more decisive role in the formation process of collaborative low-carbon technology innovation.

Acknowledgements

This study is supported by Social Science Foundation of Hebei Province (Grant number HB21YJ009).

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