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Evolutionary Game and Simulation Analysis of Low-Carbon Technology Innovation With Multi-Agent Participation

XU-MEI YUAN AND CUI-CUI ZHENG 

School of Economics and Management, Yanshan University, Qinhuangdao 066004, China

Corresponding author: Xu-Mei Yuan (yxm@ysu.edu.cn)

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ABSTRACT Low-carbon technology innovation (LCTI) is an effective way to solve the problem of global climate change and reduce carbon emissions. Therefore, using evolutionary game theory, this research constructs a three-party evolutionary game model of LCTI involving the government, enterprises, and consumers. Moreover, this research investigates the strategic choices of the three parties in the process of LCTI, discusses the stability of the equilibrium point. In particular, it analyzes the influence of different factors on the strategic choices of the three parties through numerical simulation. The results indicate that, 1) the government, enterprises, and consumers are affected to different degrees by each other's initial willingness; 2) the intensity of government regulation, innovation subsidies, and carbon tax rates have different effects on enterprises and consumers; 3) consumers are more sensitive to innovation subsidies. These results could provide references for enterprises to promote the development of LCTI.


INDEX TERMS Tripartite evolutionary game, low-carbon technology innovation, simulation analysis.

I. INTRODUCTION

Climate change caused by excessive greenhouse gas emissions has attracted significant attention all over the world. In 2015, almost 200 countries promised the Paris agreement at the Paris climate conference, which defined the objectives of global climate governance. As the world's largest carbon emitter, China has made positive commitments to deal with climate issues. In 2020, at the general debate of the UN General Assembly and the Climate Ambition Summit, Chinese President Xi Jinping announced that China aims to have carbon dioxide emissions peak before 2030 and achieve carbon neutrality before 2060 [1]. In 2021, the government of China has written the "double carbon" goal into the government work report for the first time. China's 14th Five-Year Plan also points out to accelerate the promotion of green and low-carbon development. Carbon peak and neutrality goals have been upgraded to national strategies. Achieving the "double carbon" goal is inseparable from science and technology innovation [2]. Many studies have proved that low-carbon technology innovation (LCTI) is an effective way

to solve the problem of climate change and decrease carbon emissions [3]–[5].

LCTI aims to reduce energy consumption, environmental pollution, and carbon emission and achieve energy resources saving, ecological environment protection, and energy conservation through technology innovation [6], [7]. At this stage, the government has adopted innovation subsidies [8]–[11], carbon tax [12]–[15], and carbon emission trading systems [16]–[18] to guide enterprises to choose LCTI. However, the development of LCTI has not reached its expectations. Mainly because of the following reasons. When enterprises carry out LCTI, they are often restricted by factors such as high innovation cost and difficult promotion of innovation services [19], [20]. In addition, consumers are not enthusiastic about purchasing LCTI products due to the influence of consumption preferences [21], [22], product prices [23], social policy environment [24], and consumption habits [25]. Consequently, the government needs to assume the responsibility of administrative supervision and policy support, take more active economic means to provide financial assistance for enterprises and consumers, promote enterprises to carry out LCTI, and guide consumers to purchase LCTI products.

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At present, scholars' research on LCTI concentrates mainly on the application of LCTI achievements, the influencing factors, and the dynamic mechanism of LCTI. Among them, the research on the application of LCTI achievements mainly focuses on the fields of electric power [26], [27], construction [28], [29], new energy [22], agriculture [30], etc. Concerning the study on the influencing factors of LCTI, some scholars used empirical and qualitative analysis methods to study the influence of government policies, macro environment, and market on LCTI. For instance, Pettersson *et al.* [31] found that climate policy could promote the adoption of renewable energy in Sweden's electricity sector. Wu *et al.* [32] analyzed the factors affecting the development of prefabricated construction in China by using the factor analysis method. They concluded that the government is the leader in the development of prefabricated construction, technology, policy incentive, standardization, cost, and entrepreneurial cognition have a positive impact on the promotion of prefabricated construction. Bianka *et al.* [33] used the DNE21 + model, and the Investment Preference Index model to assess the impact of climate policy on the European power sectors. They concluded that the carbon price policy is conducive to stimulating European power technology innovation. Bi *et al.* [34] used factor analysis to analyze the effect of technology promotion, market pull, and government regulation on LCTI. They concluded that government regulation could positively facilitate the performance of LCTI. Xu *et al.* [35] used the structural equation model to analyze the influencing factors of technology innovation behavior of equipment manufacturing enterprises. They found that the willingness of technology innovation of equipment manufacturing enterprises plays a positive role in promoting their technology innovation behavior. Recently, the evolutionary game theory has been gradually applied to the research theme of green and low-carbon technology innovation. Most researches involved evolutionary games with different combinations between the government and enterprises and introduced different simulation models to analyze the effect of various factors on the evolutionary strategy behavior of each subject. First, the game between governments. For instance, Wang *et al.* [36] constructed a two-party evolutionary game model between the central government and local government. They analyzed the impact of different factors on the strategic choices of both sides. Second, the game between the government and enterprises. For example, Xu *et al.* [37] and Lyu *et al.* [38] established the evolutionary game model among the government and enterprises in the complex network environment to study the impact of government incentives and penalties on enterprise strategy selection from the perspective of LCTI diffusion. The results showed that enterprises' expectation of government reward and punishment affects the diffusion rate of LCTI. Xu *et al.* [39] also established a network evolution game model between the government and cloud manufacturing enterprises. They concluded that government rewards and punishments contribute to green collaborative innovation

among cloud manufacturing enterprises. Yang *et al.* [40] established a tripartite evolutionary game model involving the government, domestic enterprises, and foreign enterprises. They discussed the strategic choices of domestic enterprises and foreign enterprises under different regulatory measures. Third, the game between enterprises. Zhang *et al.* [41] and Wang and Zheng [42] constructed the evolutionary game model of green technology diffusion among manufacturing enterprises. They concluded that the implementation of different low-carbon policies has different effects on the speed of green technology diffusion among enterprises. Shi *et al.* [43] and Zhai *et al.* [44] established an evolutionary game model between two enterprises. They obtained that appropriate policy intervention is conducive to technical innovation by using the numerical simulation analysis method. In addition, some scholars began to pay attention to the role of public consumers in green and low-carbon technology innovation and introduced consumers as participants in the evolutionary game model. For example, Cao *et al.* [45] constructed a tripartite evolutionary game model of the government, enterprises, and public consumers. They analyzed the role of public consumers in promoting the diffusion of green technology innovation. Based on their research, Wang's research team [47-49] analyzed the strategic choices of the government, enterprises, and consumers by using the evolutionary game and system dynamics methods. They found that consumers' demand for green products and green consumption consciousness have an essential effect on promoting enterprise green technology innovation.

To sum up, researchers have conducted more deep-going studies on LCTI, most of them concentrate mainly on the evolutionary game of different combinations between the government and enterprises, using different qualitative analysis methods and simulation models to explore the influence of various environmental regulation measures on LCTI, ignoring the demand and influence of consumers on LCTI. Thus, this research builds a tripartite evolutionary game model involving the government, enterprises, and consumers, analyzes the strategic choices of the government, enterprises, and consumers in the process of LCTI, discusses the stability of the equilibrium point, explores the influence of different parameters on the strategic choices of the three parties through numerical simulation. This article aims to provide targeted suggestions for promoting LCTI, offer decision-making support, and practical references for national managers of relevant departments to make policies and contribute to the development of the low-carbon economy.

The content of this research is as follows. Section2 describes the research problems, puts forward the basic assumptions, gives the parameters symbols and meanings, constructs a three-party evolutionary game model led by the government, enterprises, and consumers. Section3 analyzes the strategy selections of the three parties and determines the stable equilibrium state of the model. Section4 establishes the numerical simulation model and gives the analysis of the corresponding results. Finally, Section5 concludes and

proposes policy recommendations from three perspectives of the government, enterprises, and consumers.

II. TRIPARTITE EVOLUTIONARY GAME

MODEL CONSTRUCTION

A. PROBLEM DESCRIPTION

Evolutionary game theory is formed on the basis of biological evolution theory. It uses the percentage of individuals who choose different pure strategies in the group to replace the mixed strategies in game theory. It is widely used to analyze the decision-making choices of subjects [47-49]. LCTI is a systematic project, it involves the interests of the government, enterprises, universities, academic research institutions, and consumers, and its mechanism is complex. According to the existing research results and the purpose of this research, this paper concentrates upon the government, enterprises, and consumers. In this research, the government is the organizer and leader of LCTI. The government can encourage enterprises to carry out LCTI and promote consumers to purchase LCTI products through policy publicity, carbon tax punishment, innovation subsidies, and other means. Enterprises are the main body of LCTI. Enterprises can provide LCTI products and services for society. Consumers are buyers and users of LCTI products. Purchasing LCTI products produced by enterprises will stimulate enterprises to carry out LCTI from the consumption market.

B. BASIC ASSUMPTIONS

For the three-party evolutionary game model of LCTI, the following basic assumptions are proposed.

(1) According to the purpose of this research, there are three participants in LCTI: the government, enterprises, and consumers. They are all limited rational and have found the optimal strategic solution through multiple games. The strategies of government are (regulate, not regulate), where “regulate” refers to human, physical, and financial resources invested by the government to supervise and manage enterprises’ LCTI and provide innovation subsidies for enterprises and consumers. The strategies of enterprises are (low-carbon technology innovation, not low-carbon technology innovation), where “low-carbon technology innovation” refers to enterprises developing LCTI. The strategies of consumers are (purchase, not purchase), where “purchase” refers to consumers purchasing LCTI products.

(2) Set x ($0 \leq x \leq 1$) be the possibility of the government selecting the strategy of “regulate”; while $1-x$ represents the possibility of the government selecting the strategy of “not regulate.” Similarly, y ($0 \leq y \leq 1$) represents the possibility of enterprises selecting the strategy of “low-carbon technology innovation”; then, the possibility of enterprises selecting the strategy of “not low-carbon technology innovation” is $1-y$. Finally, z ($0 \leq z \leq 1$) represents the possibility of consumers selecting “purchase”; the possibility of consumers selecting “not purchase” is $1-z$.

(3) When the government selects the strategy of “regulate,” it needs to invest a certain amount of human, physical,

and financial resources in promoting and supervising LCTI. The cost generated during this period is C_1 . R_1 represents the revenue obtained by the government when enterprises do not carry out LCTI. If enterprises carry out LCTI, the increased benefits of the government select “regulate” or “not regulate” are R_{11} and R_{12} , such as the government’s reputation, environmental improvement, and other social utilities.

(4) When enterprises choose “low-carbon technology innovation,” the cost is C_2 . If they choose “not low-carbon technology innovation,” the benefit is R_2 . R_{21} and R_{22} , respectively, represents the increased benefits of LCTI by enterprises, when the government chooses “regulate” and “not regulate.” If enterprises choose “not low-carbon technology innovation,” they need to pay a carbon tax to the government as T .

(5) When consumers purchase LCTI products, the increased cost is C_3 , the increased benefit is R_{31} . If consumers do not purchase LCTI products, the income obtained is R_3 . When enterprises choose “low-carbon technology innovation,” consumers can get some environmental benefits E .

(6) α represents the cost subsidy coefficient of enterprise low-carbon technology innovation; β represents the subsidy coefficient for consumers to purchase LCTI products; γ represents the carbon tax rate; θ represents the government regulation intensity coefficient.

Based on the above mentioned assumptions, parameter symbols and meanings used through this research are listed below in Table 1.

C. MODEL CONSTRUCTION

According to the strategies available to the government, enterprises, and consumers, there are eight game strategy combinations among the three parties as follows: (G_x, E_y, C_z) , (G_x, E_y, C_{1-z}) , (G_x, E_{1-y}, C_z) , (G_x, E_{1-y}, C_{1-z}) , (G_{1-x}, E_y, C_z) , (G_{1-x}, E_y, C_{1-z}) , (G_{1-x}, E_{1-y}, C_z) , $(G_{1-x}, E_{1-y}, C_{1-z})$. Therefore, we can obtain the game matrix and the payoff matrix of the three parties, as shown in Tables 2 and 3.

III. TRIPARTITE EVOLUTIONARY GAME

MODEL ANALYSIS

A. ANALYSIS OF THE GOVERNMENT'S

STRATEGIC STABILITY

As can be seen from Table 3, the regulate, not regulate, and average expected revenue functions of the government are G_x, G_{1-x} , and \bar{G}_x , respectively. Then:

$$G_x = (R_{11} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 + \gamma T - \theta C_1 \tag{1}$$

$$G_{1-x} = R_{12}y + R_2 \tag{2}$$

$$\bar{G}_x = xG_x + (1-x)G_{1-x} \tag{3}$$

Thus, the dynamic replication equation of the government can be obtained from equations (1-3):

$$\begin{aligned} F_G(x) &= dx/dt = x(G_x - \bar{G}_x) \\ &= x(1-x)[(R_{11} - R_{12} - \alpha C_2 - \gamma T)y \\ &\quad - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1] \end{aligned} \tag{4}$$

TABLE 1. Parameter symbols and meanings.

Parameters	Meanings
x	Possibility of government regulate LCTI
y	Possibility of enterprises carry out LCTI
z	Possibility of consumers purchase LCTI products
C_1	When the government regulates, supervision cost caused by human, physical, and financial resources
θ	The government regulation intensity coefficient
R_1	The government benefits when enterprises choose “not low-carbon technology innovation”
R_{11}	When enterprises choose “low-carbon technology innovation”and enterprises carry out LCTI, the government will increase the benefits, such as the social utility of the government’s reputation, environmental improvement, etc.
R_{12}	When enterprises choose “not low-carbon technology innovation” and enterprises carry out LCTI, the government will increase the benefits, such as the social utility of the government’s reputation, environmental improvement, etc.
α	Enterprises innovation cost subsidy coefficient, that is, the ratio of innovation subsidies given by the government to input costs for LCTI enterprises
β	Subsidy coefficient for consumers to purchase low-carbon innovative products, that is, the ratio of innovation subsidies given by the government to increased costs for consumers purchasing LCTI products
C_2	The cost when enterprises carry out LCTI
R_2	The benefits when enterprises choose “not low-carbon technology innovation”
R_{21}	When the government choose “regulate,” the benefits increased by enterprises through LCTI
R_{22}	When the government choose “not regulate,” the benefits increased by enterprises through LCTI
T	The carbon tax levied by the government on enterprises that do not carry out LCTI
γ	Carbon tax rate
θ	The government regulation intensity coefficient
C_3	The increased costs when consumers purchase LCTI products
R_3	The benefits obtained when consumers do not purchase LCTI products
R_{31}	The increased benefits when consumers purchase LCTI products
E	Some environmental benefits for consumers when enterprises engage in LCTI

TABLE 2. The game matrix of the three parties.

Government	Enterprises	Consumers	
		Purchase	Not purchase
Regulate	Low-carbon technology innovation	(G_x, E_y, C_z)	(G_x, E_y, C_{1-z})
	Not low-carbon technology innovation	(G_x, E_{1-y}, C_z)	(G_x, E_{1-y}, C_{1-z})
Not regulate	Low-carbon technology innovation	(G_{1-x}, E_y, C_z)	(G_{1-x}, E_y, C_{1-z})
	Not low-carbon technology innovation	(G_{1-x}, E_{1-y}, C_z)	$(G_{1-x}, E_{1-y}, C_{1-z})$

TABLE 3. The payoff matrix of the three parties.

Strategy combination	Government	Enterprises	Consumers
(G_x, E_y, C_z)	$R_1 + R_{11} - \alpha C_2 - \beta C_3 - \theta C_1$	$R_2 + R_{21} - C_2 + \alpha C_2$	$R_3 + E + R_{31} - C_3 + \beta C_3$
(G_x, E_y, C_{1-z})	$R_1 + R_{11} - \alpha C_2 - \gamma C_1$	$R_2 - C_2 + \alpha C_2$	$R_3 + E$
(G_x, E_{1-y}, C_z)	$R_1 + \gamma T - \beta C_3 - \theta C_1$	$R_2 - \gamma T$	$R_3 + R_{31} - C_3 + \beta C_3$
(G_x, E_{1-y}, C_{1-z})	$R_1 + \gamma T - \theta C_1$	$R_2 - \gamma T$	R_3
(G_{1-x}, E_y, C_z)	$R_1 + R_{12}$	$R_2 + R_{21} - C_2$	$R_3 + E + R_{31} - C_3$
(G_{1-x}, E_y, C_{1-z})	$R_1 + R_{12}$	$R_2 - C_2$	$R_3 + E$
(G_{1-x}, E_{1-y}, C_z)	R_1	R_2	$R_3 + R_{31} - C_3$
$(G_{1-x}, E_{1-y}, C_{1-z})$	R_1	R_2	R_3

The derivative of $F_G(x)$ shows that:

$$F'_G(x) = (1 - 2x)[(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1] \quad (5)$$

An analysis of the government’s evolutionary stable strategies such that $F_G(x) = 0$ then:

① When $(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1 = 0$, then $F_G(x) \equiv 0$. That means all

x are in an evolutionary stable strategy. That is, whether the government chooses the strategy of “regulate” or “not regulate.” The government’s strategic choice will not change with time, as shown in Figure 1a.

② When $(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1 > 0$, then $F'_G(x)|_{x=0} > 0$, and $F'_G(x)|_{x=1} < 0$. $x = 1$ is an evolutionary stable strategy; the government tends to choose “regulate,” as shown in Figure 1b.

③ When $(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1 < 0$, then $F'_G(x)|_{x=0} < 0$ and $F'_G(x)|_{x=1} > 0$. $x = 0$ is an evolutionary stable strategy; the government tends to choose “not regulate,” as shown in Figure 1c.

B. ANALYSIS OF ENTERPRISES’ STRATEGIC STABILITY

The low-carbon technology innovation, not low-carbon technology innovation, and average expected revenue functions of enterprises are E_y , E_{1-y} , and \bar{E}_y , respectively. Then:

$$E_y = \alpha C_2 x + R_{21} z + R_2 - C_2 \tag{6}$$

$$E_{1-y} = R_2 - \gamma T x \tag{7}$$

$$\bar{E}_y = y E_y + (1 - y) E_{1-y} \tag{8}$$

Thus, the dynamic replication equation of enterprises can be obtained from equations (6-8):

$$F_E(y) = dy/dt = y(E_y - \bar{E}_y) = y(1 - y)[(\alpha C_2 + \gamma T)x + R_{21} z - C_2] \tag{9}$$

The derivative of $F_E(y)$ shows that:

$$F'_E(y) = (1 - 2y)[(\alpha C_2 + \gamma T)x + R_{21} z - C_2] \tag{10}$$

An analysis of enterprises’ evolutionary stable strategies such that $F_E(y) = 0$ then:

① When $(\alpha C_2 + \gamma T)x + R_{21} z - C_2 = 0$, then $F_E(y) \equiv 0$. Thus, all y are in an evolutionary stable strategy. That is, whether enterprises choose the strategy of “low-carbon technology innovation” or “not low-carbon technology innovation,” enterprises’ strategic choice will not change with time, as shown in Figure 2a.

② When $(\alpha C_2 + \gamma T)x + R_{21} z - C_2 > 0$, then $F'_E(y)|_{y=0} > 0$, and $F'_E(y)|_{y=1} < 0$. Thus, $y = 1$ is an evolutionary stable strategy; enterprises tend to choose “low-carbon technology innovation,” as shown in Figure 2b.

③ When $(\alpha C_2 + \gamma T)x + R_{21} z - C_2 < 0$, then $F'_E(y)|_{y=0} < 0$, and $F'_E(y)|_{y=1} > 0$. Thus, $y = 0$ is an evolutionary stable strategy; enterprises tend to choose “not low-carbon technology innovation,” as shown in Figure 2c.

C. ANALYSIS OF CONSUMERS’ STRATEGY STABILITY

The purchase, not purchase, and average expected revenue functions of consumers are C_z , C_{1-z} , and \bar{C}_z , respectively. Then:

$$C_z = \beta C_3 x + E_y + R_3 + R_{31} - C_3 \tag{11}$$

$$C_{1-z} = E_y + R_3 \tag{12}$$

$$\bar{C}_z = z C_z + (1 - z) C_{1-z} \tag{13}$$

Thus, the dynamic replication equation of consumers can be obtained from equations (11-13):

$$F_C(z) = dz/dt = z(E_z - \bar{E}_z) = z(1 - z)[\beta C_3 x + R_{31} - C_3] \tag{14}$$

The derivative of $F_C(z)$ shows that:

$$F'_C(z) = (1 - 2z)[\beta C_3 x + R_{31} - C_3] \tag{15}$$

An analysis of consumers’ evolutionary stable strategies such that $F_C(z) = 0$ then:

① When $\beta C_3 x + R_{31} - C_3 = 0$, then $F_C(z) \equiv 0$. Thus, all z are in an evolutionary stable strategy. That is, whether consumers choose the strategy of “purchase” or “not purchase,” the consumers’ strategic choice will not change with time, as shown in Figure 3a.

② When $\beta C_3 x + R_{31} - C_3 > 0$, $F'_C(z)|_{z=1} < 0$, then $F'_C(z)|_{z=0} > 0$, and. Thus, $z = 1$ is an evolutionary stable strategy; consumers tend to choose “purchase,” as shown in Figure 3b.

③ When $\beta C_3 x + R_{31} - C_3 < 0$, then $F'_C(z)|_{z=0} < 0$, and $F'_C(z)|_{z=1} > 0$. Thus, $z = 0$ is an evolutionary stable strategy; consumers tend to choose “not purchase,” as shown in Figure 3c.

D. STABILITY ANALYSIS OF EQUILIBRIUM POINTS

In order to find the equilibrium point of the evolutionary game among the three parties, we set $F_G(x) = 0$, $F_E(y) = 0$, $F_C(z) = 0$. Consequently, we obtain the three-party replication dynamical system, which can be expressed as:

$$\begin{cases} F_G(x) = x(1 - x)[(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1] = 0 \\ F_E(y) = y(1 - y)[(\alpha C_2 + \gamma T)x + R_{21} z - C_2] = 0 \\ F_C(z) = z(1 - z)[\beta C_3 x + R_{31} - C_3] = 0 \end{cases} \tag{16}$$

According to equation (16), eight local equilibrium points are derived: (0, 0, 0), (1, 0, 0), (0, 1, 0), (0, 0, 1), (1, 0, 1), (1, 1, 0), (0, 1, 1), (1, 1, 1).

Based on the method proposed by Friedman, the evolutionary stable strategy of the system can be obtained from the local stability analysis of the Jacobian matrix [49]. Therefore, we obtain the Jacobian matrix (A) from the above equation (16), as follows:

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}$$

where

$$A_{11} = (1 - 2x)[(R_{11} - R_{12} - \alpha C_2 - \gamma T)y - \beta C_3 z + R_1 - R_2 + \gamma T - \theta C_1] \tag{17}$$

$$A_{12} = x(1 - x)(R_{11} - R_{12} - \alpha C_2 - \gamma T) \tag{18}$$

$$A_{13} = -x(1 - x)\beta C_3 \tag{19}$$

$$A_{21} = y(1 - y)(\alpha C_2 + \gamma T) \tag{20}$$

$$A_{22} = (1 - 2y)[(\alpha C_2 + \gamma T)x + R_{21} z - C_2] \tag{21}$$

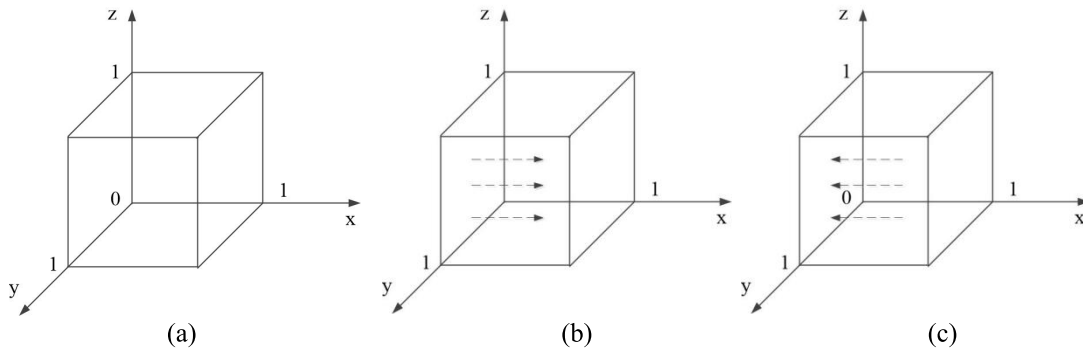


FIGURE 1. The evolution process of the government's strategy choice.

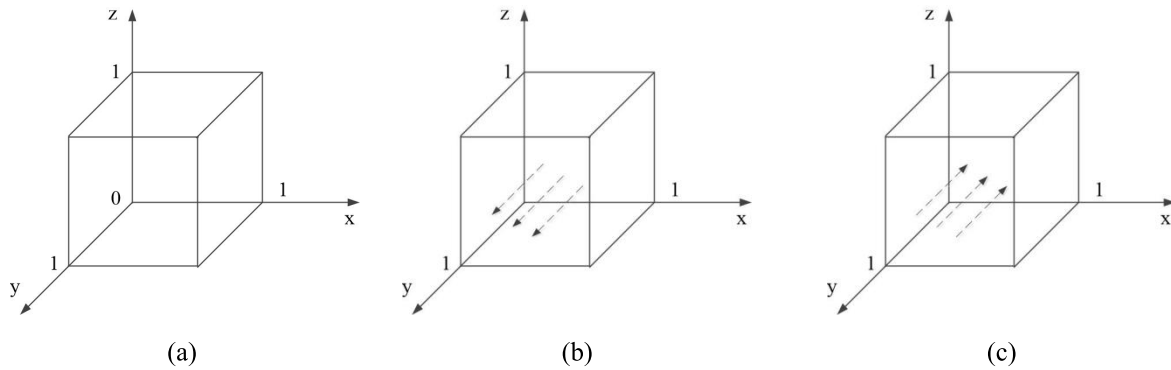


FIGURE 2. The evolution process of enterprises' strategy choice.

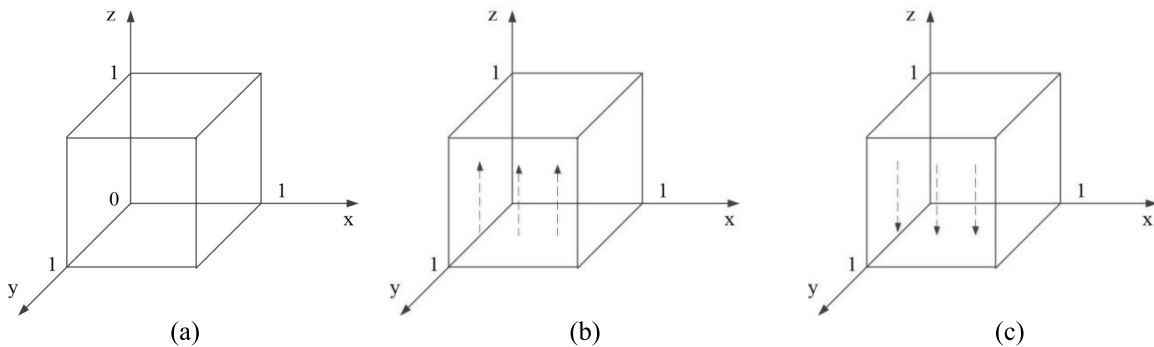


FIGURE 3. The evolution process of consumers' strategy choice.

$$A_{23} = y(1 - y)R_{21} \tag{22}$$

$$A_{31} = z(1 - z)\beta C_3 \tag{23}$$

$$A_{32} = 0 \tag{24}$$

$$A_{33} = (1 - 2z)[\beta C_3 x + R_{31} - C_3] \tag{25}$$

Based on Lyapunov's indirect method, if the equilibrium point is an evolutionary stable strategy, the eigenvalue of the point in the corresponding Jacobian matrix is less than 0, that is, $\lambda < 0$ [50]. Therefore, the eigenvalues of each equilibrium point can be obtained by substituting each of the eight equilibrium points into the Jacobin matrix, as shown in Table 4.

By observing Table 4, it is clear that the second eigenvalue λ_2 of the three eigenvalues of the equilibrium point (0,1,0) is positive, concluding that this equilibrium point is not

asymptotically stable. To facilitate the analysis of the symbols of eigenvalues corresponding to different equilibrium points and have generality, the stability strategy of the evolutionary game is discussed in two cases:

Case 1: when $-R_{11} + R_{12} + \alpha C_2 + \beta C_3 - R_1 + R_2 + \theta C_1 < 0$, $C_2 - \alpha C_2 - \gamma T - R_{21} < 0$, and $C_3 - \beta C_3 - R_{31} < 0$, that is, the benefits of the government selecting to regulate is greater than that of selecting not to regulate, the income of enterprises carrying out LCTI is greater than that of not carrying out LCTI, and the income of consumers purchasing non-LCTI products is less than that of purchasing LCTI products. Meanwhile, it can be seen from Table 4 that the eigenvalues of the Jacobian matrix corresponding to (1,1,1) are negative, so (1,1,1) is the evolutionary stability strategy. As can be seen from Table 4, $R_{31} - C_3 + \beta C_3 > 0$ and

TABLE 4. Eigenvalue of Jacobin matrix.

Strategy combination	Government	Enterprises	Consumers
	λ_1	λ_2	λ_3
(0,0,0)	$R_1 - R_2 + \gamma T - \theta C_1$	$-C_2$	$R_{31} - C_3$
(1,0,0)	$R_1 - R_2 + \gamma T - \theta C_1$	$\gamma T - C_2 + \alpha C_2$	$R_{31} - C_3 + \beta C_3$
(0,1,0)	$R_{11} - R_{12} - \alpha C_2 + R_1 - R_2 - \theta C_1$	C_2	$R_{31} - C_3$
(0,0,1)	$-\beta C_3 + R_1 - R_2 + \gamma T - \theta C_1$	$R_{21} - C_2$	$C_3 - R_{31}$
(1,0,1)	$\beta C_3 - R_1 + R_2 - \gamma T + \theta C_1$	$\gamma T + R_{21} - C_2 + \alpha C_2$	$C_3 - \beta C_3 - R_{31}$
(1,1,0)	$-R_{11} + R_{12} - R_1 + R_2 + \alpha C_2 + \theta C_1$	$C_2 - \alpha C_2 - \gamma T$	$R_{31} - C_3 + \beta C_3$
(0,1,1)	$R_{11} - R_{12} + R_1 - R_2 - \alpha C_2 - \beta C_3 - \theta C_1$	$C_2 - R_{21}$	$C_3 - R_{31}$
(1,1,1)	$-R_{11} + R_{12} - R_1 + R_2 + \alpha C_2 + \beta C_3 + \theta C_1$	$C_2 - \alpha C_2 - \gamma T - R_{21}$	$C_3 - \beta C_3 - R_{31}$

$R_{11} - C_{12} - \alpha C_2 - \beta C_3 + R_1 - R_2 - \theta C_1 > 0$, (1,1,0) and (0,1,1) are two unstable points. In this case, the system is stable at the point (1,1,1), and its corresponding evolutionary stable strategy is (regulation, low-carbon technology innovation, purchase).

Case 2: When $R_1 - R_2 + \gamma T - \theta C_1 < 0$, $\gamma T - C_2 + \alpha C_2 < 0$, and $R_{31} - C_3 + \beta C_3 < 0$, the regulatory cost of the government is greater than the regulatory income, and the income of consumers from purchasing LCTI products is less than the cost. At this time, it can be seen from Table 4 that the eigenvalues of the Jacobian matrix correspond to the equilibrium points (0,0,0) and (1,0,0) are negative, that is, (0,0,0) and (1,0,0) are two evolutionary stability strategies; and since $C_3 - R_{31} > 0$, (0,0,1) is an unstable point. In this case, the system is stable at point (0,0,0) and (1,0,0). Their corresponding evolutionary stability strategies are (not regulate, not low-carbon technology innovation, not purchase) and (regulate, not low-carbon technology innovation, not purchase).

IV. NUMERICAL SIMULATION

From the whole process of LCTI, case 1 is a more appropriate choice, that is, the government chooses the “regulate” strategy, enterprises choose the “low-carbon technology innovation” strategy, and consumers choose the “purchase” strategy. The reasons involve three main aspects. First, at present, LCTI is inseparable from the active promotion and supervision of the government. Government participation can promote the LCTI of enterprises. Second, as the core of LCTI, enterprises choosing to carry out LCTI can improve their social reputation, win the trust of consumers, and lay a foundation for their future development. Third, consumers are users of LCTI products. If consumers purchase LCTI products, they can encourage enterprises to carry out LCTI from the demand side.

To further verify the stability of the three-party evolution of the government, enterprises, and consumers and analyze the impact of relevant parameters on LCTI, this research uses Matlab software to simulate case 1. Referring to the assignment method in literature [30], the initial value of relevant variables of each participant is set as follows: $C_1 = 0.8$, $C_2 = 4$, $C_3 = 0.5$, $T = 2$, $\alpha = 0.6$, $\beta = 0.4$, $\gamma = 0.3$,

$\theta = 0.3$, $R_1 = 6$, $R_2 = 6$, $R_{11} = 7$, $R_{12} = 2$, $R_{21} = 6$, $R_{31} = 0.8$.

A. INITIAL WILLINGNESS ON THE SYSTEM EVOLUTION

This section analyzes the impact of the initial willingness of the government, enterprises, and consumers on the system evolution under the condition that other parameters remain unchanged. It is assumed that the initial willingness of the government, enterprises and consumers is the same, which is $x = y = z$, where x , y , and z assume the values of 0.4, 0.5, and 0.6, respectively. As can be seen from Figure 4, with the increase of the initial willingness of the government, enterprises, and consumers, the speed of each participant converging to 1 is accelerating. Therefore, under the premise of satisfying the interests of all parties, it can be seen from Figure 4a and Figure 4b that the differences in the initial willingness of the government, enterprises, and consumers will have a particular effect on the evolution speed of the system strategy, but will not change the final strategic choices of the three parties, that is, the government selects the strategy of “regulate,” enterprises select the strategy of “low-carbon technology innovation,” and consumers select the strategy of “purchase,” and the system converges to the asymptotically stable point (1,1,1).

Figure 5a shows the effect of the change of the government’s initial willingness x on the strategic choices of enterprises and consumers under the condition that other parameters remain unchanged. We can find that the initial willingness x of the government rises from 0.4 to 0.6, and both enterprises and consumers will eventually converge to 1. Meanwhile, with the increase of x , the convergence speed of y and z gradually accelerates, and y converges to 1 quicker, and finally, the three subjects converge to (1,1,1). It can be seen that when the initial willingness of enterprises and consumers remains unchanged, with the increase of the initial willingness x of the government, the convergence rate of enterprises and consumers to 1 will accelerate, and enterprises respond more quickly to the change of the initial willingness of the government.

Figure 5b shows the influence of the change of enterprises’ initial willingness y on the strategic choices of the

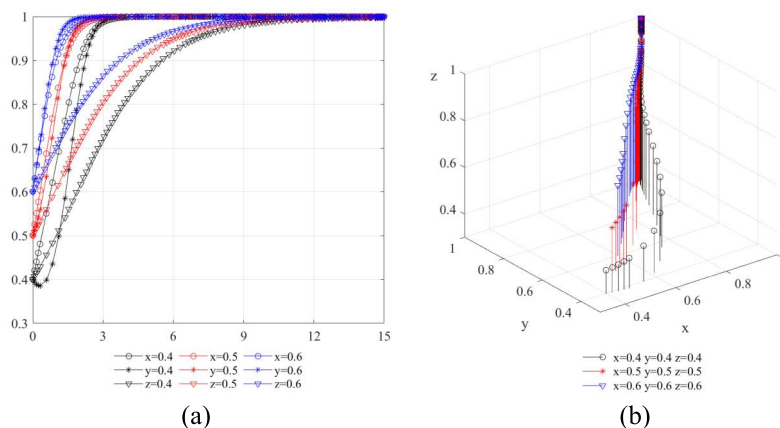


FIGURE 4. The impact of the initial willingness x , y , and z on the system evolution.

government and consumers under the condition that other parameters remain unchanged. We can find that the initial willingness y of enterprises rises from 0.4 to 0.6, and both the government and consumers will eventually converge to 1. Meanwhile, with the increase of y , the convergence speed of x and z will gradually accelerate, and the convergence speed of z will be quicker. Ultimately, the three subjects converge to (1,1,1). The results prove that when the initial willingness of the government and consumers remains unchanged, with the increase of the initial willingness y of the enterprises, the convergence rate of the government and consumers to 1 will accelerate, and consumers respond more quickly to the change of the initial willingness of enterprises.

Figure 5c shows the influence of the change of consumers' initial willingness z on the strategic choices of the government and enterprises when other parameters remain unchanged. We can find that the initial willingness z of consumers rises from 0.4 to 0.6, and both the government and enterprises will eventually converge to 1. Concurrently, with the increase of z , the convergence speed of x and y will gradually accelerate, and the convergence speed of y to 1 is quicker. Finally, the three subjects converge to (1,1,1). The results prove that when the initial willingness of the government and enterprises remains unchanged, as the initial willingness z of consumers increases, the convergence rate of the government and enterprises to 1 will accelerate, and enterprises respond more quickly to the change of consumers' initial willingness.

B. GOVERNMENT REGULATION INTENSITY COEFFICIENT ON THE SYSTEM EVOLUTION

This section analyzes the influence of the government regulation intensity coefficient θ on the system evolution under the condition that other parameters remain unchanged. In Figure 6, the government regulation intensity coefficient increases from 0.1 to 0.9; at this time, the possibility of the strategy for the government choosing "regulate" and the strategy for consumers choosing "purchase" gradually decreases. In contrast, the possibility of the strategy for

enterprises choosing "low-carbon technology innovation" gradually increases. We can see that the government regulation has a certain influence on promoting enterprises LCTI. The greater the intensity of the government regulation, the greater the possibility of the strategy for the government selecting "low-carbon technology innovation." However, with the increase of the intensity of government supervision, the cost of human, physical resources, and financial resources during the supervision period will also increase, which reduces the possibility of the government choosing "regulate." The government's supervision will encourage consumers to choose the strategy of "purchase." At the same time, government regulatory measures can also encourage consumers to purchase LCTI products. Still, with the increase of the government regulation intensity coefficient, the evolution speed of consumers slows down, mainly because the greater the intensity of government regulation, the more enterprises produce LCTI products at one time, consumers may have a choice barrier when purchasing, which will eventually lead to a decrease in the possibility of consumers' strategy. Therefore, increasing the government regulation intensity coefficient has a certain influence on both enterprises and consumers, and the influence on enterprises is more significant.

C. ENTERPRISES INNOVATION COST SUBSIDY COEFFICIENT ON THE SYSTEM EVOLUTION

This section analyzes the influence of enterprise innovation cost subsidy coefficient α on the system evolution under the condition that other parameters remain unchanged. As shown in Figure 7, if the innovation cost subsidy coefficient for enterprises increases from 0.1 to 0.9, the possibility of the government selecting "regulate" and consumers selecting "purchase" is gradually decreasing. In contrast, the possibility of enterprises selecting "low-carbon technology innovation" is gradually increasing. This is mainly because the government gives innovation cost subsidies to enterprises, which is conducive to reducing the cost of LCTI, improving

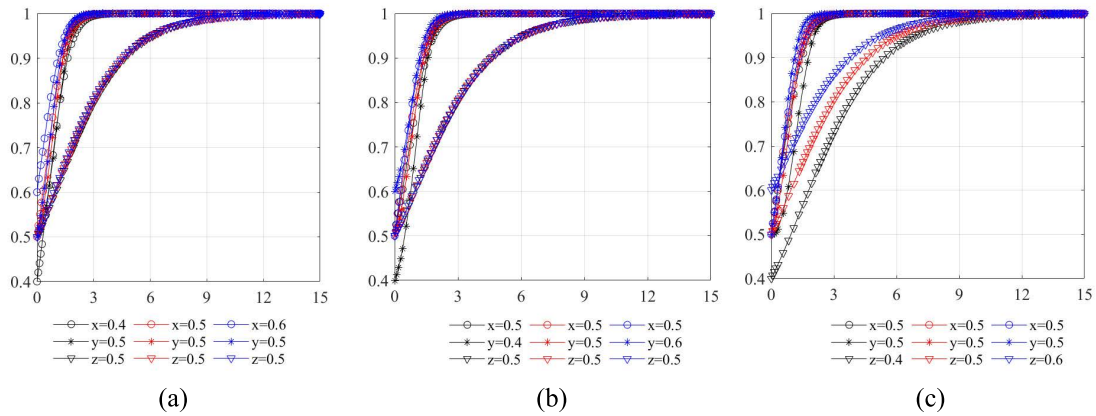


FIGURE 5. Impact of the individual change of the initial willingness x , y and z on the system evolution:(a) $x = 0.4, 0.5$, and 0.6 ; (b) $y = 0.4, 0.5$, and 0.6 ; (c) $z = 0.4, 0.5$, and 0.6 .

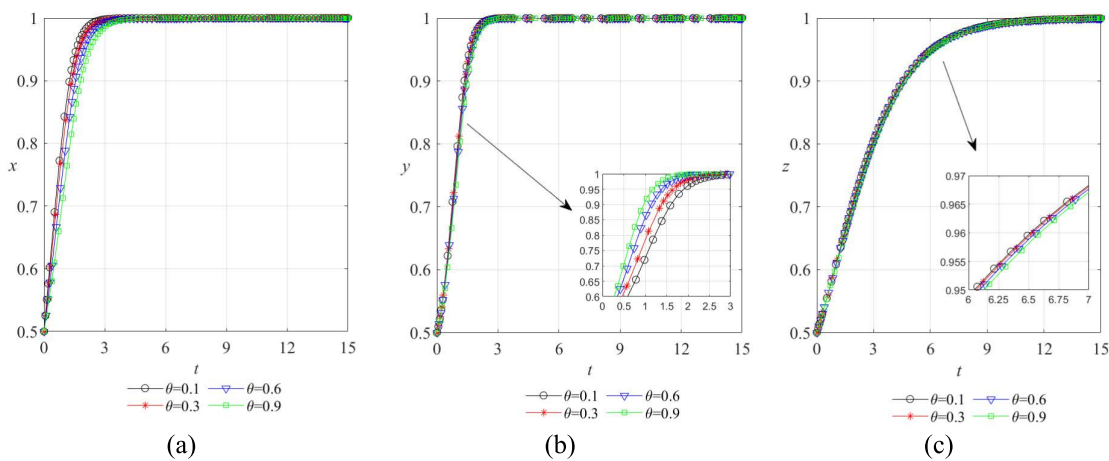


FIGURE 6. Impact of the government regulatory intensity coefficient on the system evolution.

the enthusiasm of enterprises for LCTI, increasing the proportion of enterprises choosing the strategy of “low-carbon technology innovation” gradually. By encouraging enterprises to choose LCTI, the government can obtain more social benefits, but it will invariably increase the government cost. Consequently, when the cost of government supervision is greater than social benefits, it will eventually lead to the government reducing the possibility of the strategy of “regulate.” Meanwhile, the innovation cost subsidy has an active effect on consumers’ purchase of LCTI products. However, if enterprises produce too many products of the same type, it will eventually lead to a barrier of choice for consumers and reduce the possibility of the strategy of “purchase.”

D. CONSUMERS PURCHASE SUBSIDY COEFFICIENT ON THE SYSTEM EVOLUTION

This section analyzes the effect of the change of consumers purchase subsidy coefficient β on the evolutionary results of the system under the condition that other parameters held constant. In Figure 8, the purchase subsidy coefficient for consumers increases from 0.1 to 0.9, in the meantime,

the possibility of the government’s strategy of selecting “regulate” will gradually decrease, the possibility of enterprises’ strategy of “low-carbon technology innovation” and consumers’ strategy of “purchase” will gradually increase. The results show that increasing the purchase subsidy coefficient can not only mobilize consumers’ initiatives to purchase LCTI products, but also promote enterprises to carry out LCTI from the demand side. However, under different consumer purchase subsidies, the possibility of enterprises selecting the “low-carbon technology innovation” strategy has little change, indicating that the incentive effect of consumer purchase subsidies on enterprises is not apparent. Similar to the government’s analysis of enterprises innovation cost subsidy, if consumers purchase subsidy coefficient too large, it will eventually reduce the possibility of the government’s strategy of choosing “regulate.”

E. CARBON TAX RATE ON THE SYSTEM EVOLUTION

This section analyzes the impact of the change of carbon tax rate γ on the evolutionary results of the system under the condition that other parameters remain unchanged. It can

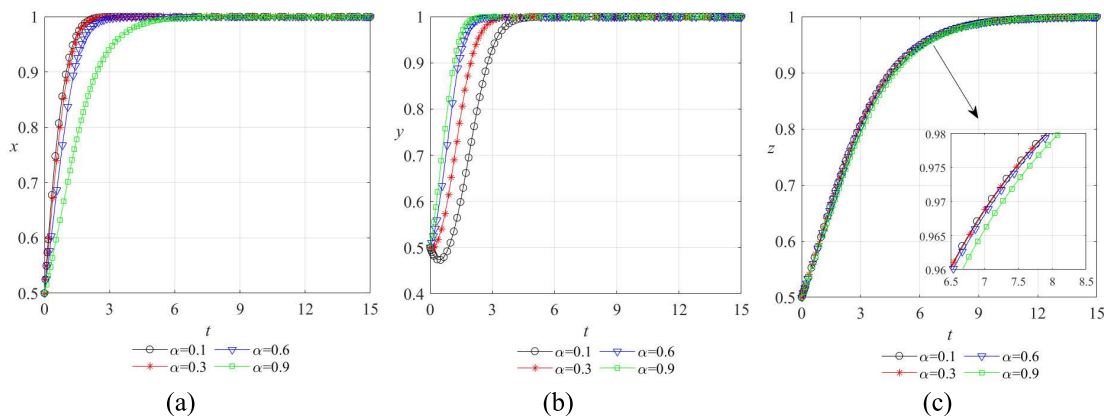


FIGURE 7. Impact of enterprises innovation subsidy coefficient on the system evolution.

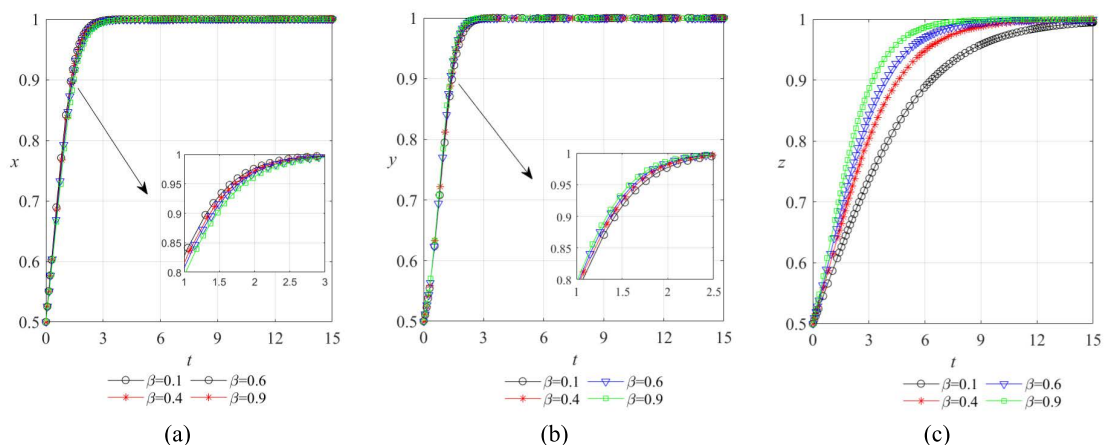


FIGURE 8. Impact of consumers purchase subsidy coefficient on the system evolution.

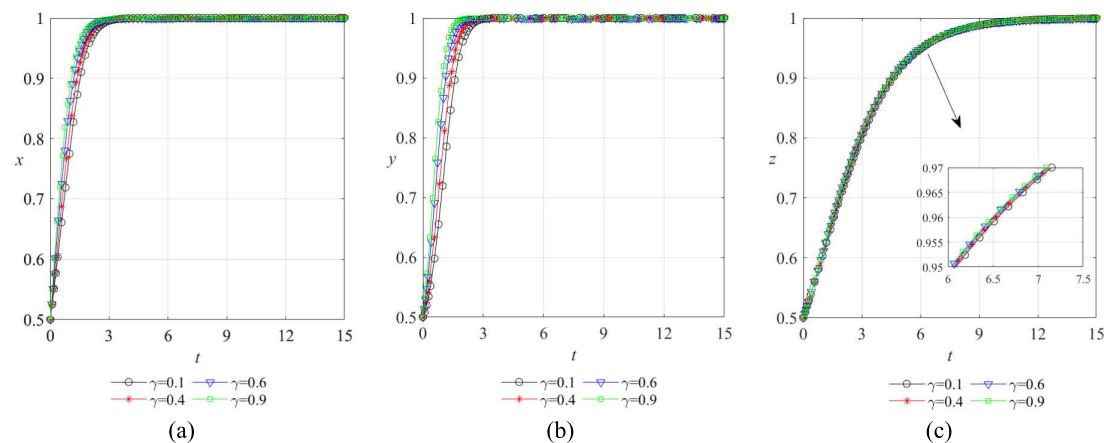


FIGURE 9. Impact of the carbon tax rate on the system evolution.

be seen from Figure 9 that the higher the carbon tax rate, the higher the possibility of strategies that the government chooses “regulate,” enterprises choose “low-carbon technology innovation,” and consumers choose “purchase.” When the carbon tax rate increases, the possibility of the government choosing the “regulate” strategy also increases,

making the government finally choose the “regulate” strategy. From the above analysis, we can see that the collection of the carbon tax has little influence on the strategic choice of the government. For enterprises, the government raises the carbon tax rate will increase the possibility of enterprises choosing “low-carbon technology innovation”

strategy, indicating that the carbon tax plays a prominent part in promoting LCTI. For consumers, increasing the carbon tax rate will raise the price of non-LCTI products, which will reduce consumers' enthusiasm to choose non-LCTI products. As a result, the carbon tax levied by the government has a positive incentive effect on consumers to purchase LCTI products. Consumers will eventually choose the "purchase" strategy. However, under different carbon tax rates, the strategic possibility of consumers changes little, indicating that the incentive influence of the carbon tax on consumers is not obvious.

V. CONCLUSION AND RECOMMENDATIONS

Under the condition of bounded rationality, this paper builds a three-party evolutionary game model of LCTI among the government, enterprises, and consumers. On this basis, combined with the numerical simulation method, this research analyzes the strategic choices and influencing factors of the three parties. The conclusions are as follows:

(1) In the process of LCTI, the strategic choice of each participant affects the stability of the system. The government, enterprises, and consumers eventually converge to the optimal equilibrium state of (1,1,1). That is, the final strategy of the tripartite game players is (regulate, low-carbon technology innovation, purchase).

(2) The government, enterprises, and consumers are affected by each other's initial willingness with different effects. The government, as a regulator, has a more critical influence on the initial willingness of enterprises and consumers, and consumers are more sensitive to the initial willingness of the government. Enterprises and consumers are asymmetrically influenced by each other, and enterprises respond faster to changes in consumers' initial willingness.

(3) Government regulation, innovation subsidies, and carbon tax measures are the main factors influencing enterprises' LCTI. Raising regulation, innovation subsidies, and carbon taxes within a specific range can help enterprises develop LCTI. Compared with enterprises, innovation subsidies have a more significant impact on consumers.

Combined with the above conclusions, this research proposes the following suggestions.

(1) The government should play a leading role. On the one hand, the government provides a good policy environment for enterprises, pays attention to the combination of various ways, increases the financial support for LCTI, and improves the motivation of enterprises to develop LCTI activities. Meanwhile, the government ought to pay attention to the supervision strength, reasonably plan the supervision cost, avoid wasting resources, reduce the enthusiasm of enterprises for LCTI, and hinder the development of LCTI. On the other hand, the government should also provide subsidies for consumers, reduce consumers' purchase costs, encourage consumers to purchase LCTI products, stimulate enterprises to carry out LCTI from the demand side

(2) Consumers should establish good environmental awareness and a low-carbon consumption concept. Moreover,

the government should strengthen the publicity of the importance of LCTI through public service advertising, news, and other means to enhance consumers' understanding of LCTI products.

(3) As the main body of LCTI, enterprises should root the concept of low-carbon development in daily operation, establish a good "low-carbon environmental protection image," actively promote the development of LCTI, reduce environmental pollution and carbon emissions through LCTI.

This research utilizes evolutionary game and numerical simulation methods to draw some practical conclusions. Still, there are also the following shortcomings: besides the initial willingness of participants, government regulation intensity, innovation subsidies, and carbon tax measures, LCTI is also influenced by some other factors. In the future, the influencing factors and more stakeholders of LCTI will be fully considered, and more fruitful research results may be obtained. Due to the limitation of conditions, there is a lack of using actual data for numerical simulation, which needs further strengthened in future research.

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XU-MEI YUAN was born in 1970. She received the Ph.D. degree from Tianjin University, Tianjin, China, in 1998. She is currently a Full Professor with the School of Economics and Management, Yanshan University. Her current research interests include innovation system management, logistics, and supply chain management.



CUI-CUI ZHENG was born in 1988. She is currently pursuing the Ph.D. degree in management science and engineering with Yanshan University. Her research interests include innovative systems management and innovation networks.