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Low carbon transformation of oil enterprises: study on dynamic evolution under carbon emission regulation

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Abstract. Nowadays, global warming caused by greenhouse gas emissions has become a major challenge for countries around the world in the 21st century, and the "dual carbon" goal has set the direction for China's green development, providing unprecedented opportunities for the development of low-carbon technologies in China. In order to ensure the high-quality development of oil enterprises under the goal of "dual carbon", the low-carbon transition path of oil enterprises adopting in Carbon Dioxide-Enhanced Oil Recovery (CO_2-EOR) is explored. A dynamic evolutionary game model of the government, oil companies and consumers under carbon emission regulation is established, and the effects of carbon tax, CO_2-EOR technology emission reduction efficiency, market mismatch and other variables on the strategic choices of the game subjects are explored, and the evolutionary paths of the three are simulated using Matlab software. The results suggest that oil enterprises are less willing to invest in CO_2-EOR technology in scenarios where carbon tax costs are high, environmental benefits are lower, and market losses are higher, resulting in slower equilibrium evolution towards a realistic steady state. Based on these findings, we propose three countermeasures for the low-carbon transition of oil enterprises under the "dual carbon" target: (1) Optimizing the overall taxation design. (2) Promoting low-carbon technology innovation. (3) Upgrading the oil market. The results provide valuable insight into promoting the large-scale application of CO_2-EOR technology in oil enterprises in the future.

Keywords. Oil enterprises, government, consumers, carbon dioxide-enhanced oil recovery (CO_2-EOR), evolutionary game.

1. Introduction

Climate change poses a critical challenge for the 21st century, significantly impacting the economic and social development and ecological environment of every country. It is a major global issue that requires immediate action. Addressing climate change has become a global consensus and a significant trend [1]. In 2016, the Paris Climate Agreement received international signatories, and a general consensus emerged among countries to reduce greenhouse gas emissions and limit global warming to below 2°C by the end of this century compared to pre-industrial times [2]. To fulfill its responsibility in global climate governance, President Xi Jinping made a solemn pledge at the 75th session of the UN General Assembly in September 2020. He committed that China will strive to peak its CO_2 emissions by 2030 and pursue carbon neutrality by 2060 [3]. The "dual carbon" goal has set the green development direction for China, offering an unprecedented opportunity for the development of low-carbon technologies in the country. As the core component of the national energy system, the oil enterprises play a vital role in ensuring national energy security, stabilizing the national economy, and promoting low-carbon development. The enterprises have a crucial mission to accomplish by safeguarding national energy security and undertaking the essential task of advancing low-carbon development [4]. However, China's fossil fuel-based energy structure is difficult to transform in a short period. In the long-term, complete elimination of fossil energy consumption is not feasible. Within the industry, China's oil production remains stable, and there is a continuous rapid increase in natural gas production, leading to a sharp rise in energy consumption and carbon emissions. The task of achieving carbon peak and neutrality for oil enterprises in the region is incredibly challenging.

The development of low carbon technology is crucial for the transformation of energy structure and achieving green development [5]. Only through low carbon technology can we rapidly decrease carbon emissions after 2030 and reach the "dual carbon" strategic goal of carbon neutrality by 2060. Among various low carbon technologies, Carbon Capture Utilization and Storage (CCUS) is believed to be the future technology that can compensate for the deficiency of energy efficiency and renewable energy technologies, achieving near-zero CO_2 emissions resulting from the use of fossil fuels [6]. Among these technologies, Carbon Dioxide-Enhanced Oil Recovery (CO_2-EOR) is one of the most promising low carbon technologies. This method involves injecting captured CO_2 into developed reservoirs with a complete geological structure, good confinement, and detailed base information, simultaneously improving crude oil recovery and CO_2 storage through displacement, which has the dual benefits of significantly enhancing recovery and mitigating carbon emissions [7]. Based on demonstration projects conducted in Jilin and Daqing oil fields, CO_2-EOR technology has been proven to enhance oil field recovery rates by 10 to 25 percentage points. Moreover, it can significantly increase crude oil production, with the production of 1 ton of crude oil generated for every 2 to 3 tons of CO_2 injected. The technology presents significant advantages in oil increase and burial [8]. Based on preliminary evaluations, China's oil development for enhanced recovery has a CO_2 storage capacity of above 2 billion tons, which can increase crude oil recovery by more than 700 million tons [9].

CO_2-EOR technology is a promising approach towards CO_2 resource utilization and promoting the green and low-carbon development of the petrochemical industry. It presents a realistic pathway for the green development of oil enterprises [10]. Low carbon technologies are expected to see an accelerated development phase, which will broaden opportunities for the green and low-carbon transformation of oil enterprises in policy, technology, and market levels. As such, investing in CO_2-EOR can provide effective technical support for oil enterprises. Retrofitting CO_2-EOR in the upstream of oil operations can serve as a crucial technical solution for enhancing the competitiveness of oil enterprises [11]. The government should prioritize the application of CO_2-EOR in oil enterprises to mitigate carbon emissions from fossil energy production and achieve near-zero carbon emissions from oil production processes. Investing in CO_2-EOR technology offers a promising opportunity for oil enterprises to meet their low-carbon goals [12]. Large-scale implementation of CO_2-EOR projects is the most viable approach for oil enterprises to reach carbon peaking goals by 2030 and achieve carbon neutrality by 2060. However, CO_2-EOR is still in the developmental and experimental stage, with uncertainties regarding technology, economics, and other aspects that must be considered for widespread implementation [13]. Additionally, there are challenges, such as the lack of incentive policies and difficulties in achieving industry-chain synergies. As a critical aspect of carbon emission regulations, the interaction and role of energy-consuming and high-emission energy enterprises with various stakeholders has long been a subject of scholarly attention. Today, scholars continue to focus on the study of these mechanisms and their wider implications [14]. Numerous scholars have constructed evolutionary game models of energy enterprises and governments or consumers to study the economic behavior of the participating agents from a dynamic perspective. Based on the existing research results, the influence of factors such as government regulation [15] and carbon tax policies [16], consumers' low-carbon preferences [17] and environmental efficiency [18] on the behavioral decisions of energy enterprises can be found. Considering that CO_2-EOR decision making is an important part of implementing carbon emission reduction targets, many scholars have conducted in-depth studies on the environmental risks [19-20] and economic benefits [21-22] of CO_2-EOR for oil enterprises, and constructed CO_2-EOR reservoir simulation [23], neural network optimization [24] and comparison of projects [11].

While existing studies have highlighted the importance of the multi-body synergistic relationship among the government, enterprises, and consumers in the low-carbon transition behavior of oil enterprises, they have neglected the evolutionary game aspect. Specifically, there is still a lack of decision models and evolutionary game analysis frameworks that consider oil enterprises' investment in CO_2-EOR technology. To address this gap, this study introduces a carbon emission regulation mechanism based on existing literature, constructs an evolutionary game model of oil enterprises, government, and consumers, and conducts simulation analyses to observe the dynamic path of the three parties involved in the game. The analysis explores the effect of variables such as carbon tax, CO_2-EOR technology emission reduction efficiency, and market mismatch on the strategy selection of the game subjects. The results provide valuable insight into promoting the large-scale application of CO_2-EOR technology in oil enterprises in the future.

2. Methodology

2.1. Issue description

In the oil market, the government, oil enterprises, and consumers are the three major players whose cooperation is essential for promoting and effectively implementing CO_2-EOR. However, they also experience conflicts among different interests. The government seeks to adopt regulatory policies that maximize social benefits, while oil companies aim to adopt CO_2-EOR to maximize their personal benefits, and consumers may hesitate to engage in market feedback to maximize their interests. Thus, achieving a win-win situation through synergy among these participants in the oil market is a key issue to be addressed.

2.2. Premise assumption and variable settings

It is widely recognized that each player's decisions in the oil market are influenced by both internal and external factors, making it difficult to achieve the assumption of complete rationality and full knowledge in reality. Then we propose assumption 1.

Assumption 1. The government, oil enterprises, and the consumers are all limited rational economic people.

The government has two options to incentivize oil enterprises to adopt CO_2-EOR, by implementing "regulation" policy or "no regulation" policy, respectively. When the government implements "regulation" policy, oil enterprises will be charged a carbon tax. When the government implements "no regulation" policy, oil enterprises will not have to pay for the cost of CO_2 emissions. Enterprises will meet their emission reduction standards with the "adoption" of CO_2-EOR, and when they do not adopt CO_2-EOR, they will emit more CO_2, thus causing more environmental pollution. For the consumers, they choose either positive or negative feedback on the behavior of the oil enterprises, guiding the oil enterprises to make the transition and receiving the corresponding indirect benefits. Then we propose assumption 2-4.

Assumption 2. The strategy choices of the three parties of the game are government (regulation, no regulation), enterprises (adoption, no adoption), and consumers (positive feedback, negative feedback). Suppose the probability that the government chooses the "regulation" strategy is x; the probability that the enterprise chooses the "adoption" strategy is y; the probability that the consumer chooses the "positive feedback" strategy is z, $(x, y, z \in [0,1])$.

Assumption 3. The government will pay a cost C_t when regulating and charge a carbon tax to the enterprises. If the enterprises choose the "adoption" strategy, the enterprises will be charged a carbon tax λT $(0<\lambda<1)$ and vice versa, T. At this point, the enterprises will bear the carbon tax aT and transfer the carbon tax (1-a) T to the consumer $(0<a<1)$.

Assumption 4. The total cost of the "adoption" strategy is denoted as C_m, and the CO_2-EOR technology will bring the enterprise an emission reduction benefit E. When the enterprise chooses the "no adoption" strategy and consumers choose the "positive feedback" strategy, the environmental cost is represented as C. The three agents allocate the environmental loss C based on the coefficients α, β, and θ, respectively.

As enterprises and consumers are interdependent and their interests are linked, a mismatch between supply and demand may occur in the market during the low-carbon transition process, leading to opportunistic behavior of "free-riding". Then we propose assumption 5.

Assumption 5. If enterprises choose the "adoption" of CO_2-EOR strategy and consumers choose the "negative feedback" strategy, consumers only need to pay a lower price to obtain the benefits brought by CO_2-EOR, and vice versa. K represents the mutual gain or loss in the presence of free-rider behavior.

2.3. Model construction

The purpose of establishing the "dual carbon" target is to accelerate the process of carbon emission reduction [25]. Carbon tax mechanism is a kind of institutional design with binding carbon emission, which is important for accelerating the process of carbon emission reduction. Therefore, introducing the carbon tax mechanism into the evolutionary game analysis framework of CO_2-EOR adoption by oil enterprises is of great practical significance to describe the above problem. Based on the above assumptions and variable settings, an evolutionary game analysis framework of CO_2-EOR adoption by oil enterprises under carbon emission regulation is constructed. The benefit matrix of government, business and consumers can be constructed as shown in Table 1.

Table 1. Benefits matrix for government, business and consumers

Benefits matrix		Enrterprise			
		Adoption		No Adoption	
		Consumer		Consumer	
		positive feedback	negative feedback	positive feedback	negative feedback
Government	Regulation	E-μλT-Cm	E-K-μλT-Cm	K-μT-αC	-μT
		-(1-μ)λT	K-(1-μ)λT	-K-(1-μ)T-βC	-(1-μ)T
		λT-Ct	λT-Ct	T-Ct-θC	T-Ct
	No Regulation	E-Cm	E-K-Cm	K-αC	0
		0	K	-K-βC	0
		0	0	-θC	0

3. Results

3.1. Expected utility function

When government implements "regulation", the expected utility function is X_1.

$$X_1 = yz(\lambda T - C_t) + y(1 - z)(\lambda T - C_t) + (1 - y)z + (1 - y)(1 - z)(T - C_t) \quad (1)$$

When government implements "no regulation", the expected utility function is X_2.

$$X_2 = (1 - y)z(-\theta C) \quad (2)$$

The average expected utility for the government is X.

$$X = xX_1 + (1 - x)X_2 \quad (3)$$

The replication dynamic equation for government strategy choice is F(x).

$$F(x) = \frac{dx}{dt} = x(X_2 - X) = x(1 - x)[(\lambda - 1)f(t)y - C_t + T] \quad (4)$$

Similarly, the replication dynamic equations for enterprise strategy choice is F(y) and the replication dynamic equations for consumer strategy choice is F(z).

$$F(y) = \frac{dy}{dt} = y(Y_2 - Y) = y(y - 1)[a(\lambda - 1)Tx - \alpha Cz - E + K + C_m] \quad (5)$$

$$F(z) = \frac{dz}{dt} = z(Z_2 - Z) = z(1 - z)[(a - 1)(\lambda - 1)Tx + \beta Cy + K] \quad (6)$$

3.2. Phase evolution diagram

In Eqs. (4), if $y_0=\frac{-f(t)+C_t}{(\lambda-1)T}$, there may exist two scenarios.

When $y=y_0$, $F(x)\equiv 0$, and all levels are stable in this case.

When $y\neq y_0$, $F(x)=0$, and there exist two stable points at x = 0 and x = 1.

The derivative of F(x) is $\frac{dF(x)}{dx}$, there may exist two scenarios.

$$\frac{dF(x)}{dx}=-2\left(-\frac{1}{2}+x\right)\left((1+(\lambda-1)y)T-C_t\right) \tag{7}$$

When $y>y_0$, $\frac{dF(x)}{dx}(x=0)>0$, $\frac{dF(x)}{dx}(x=1)<0$, x=1 is the evolutionary stability point.

When $y<y_0$, $\frac{dF(x)}{dx}(x=0)<0$, $\frac{dF(x)}{dx}(x=1)>0$, x=0 is the evolutionary stability point.

Similarly, the evolutionary stability conditions for enterprises and consumers can be obtained according to Eqs. (5) and (6), respectively. Figure 1 shows the evolutionary phase diagrams of the strategy choices of the game participants, and Figure 1(a) to Figure 1(c) correspond to the phase diagram changes of the respective strategy choices of the government, the enterprises and the consumer, respectively.

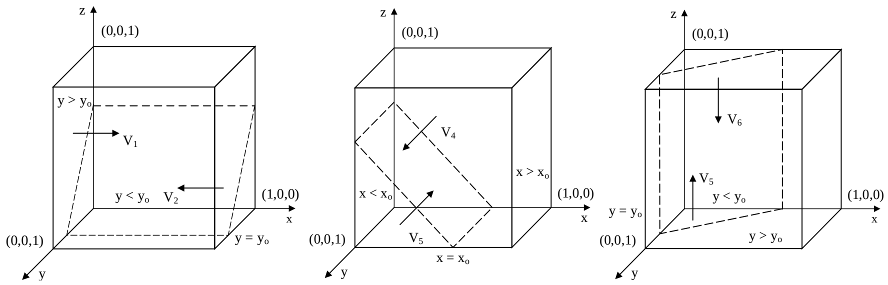

Figure 1. Phase diagram of the evolution of strategy choice of the game participants

As shown in Figure 1(a), the strategy state in the space V_1 indicates that the government will choose the “regulation” strategy, and x=1 is the evolutionary stability point; the strategy state in the space V_2 indicates that the government will choose the “no regulation” strategy, and x=0 is the evolutionary stability point. and V_2 are related to y_0. If the carbon tax T collected by the government from enterprises increases, y_0 becomes smaller, resulting in V_1 becoming larger and V_2 becoming smaller. That is, an increase in the carbon tax will promote the government's choice of a “regulation” strategy. If C_t, the cost to the government for the carbon tax system, and λ, the proportion of the carbon tax generated when enterprises adopt CO_2-EOR, increase, V_1 becomes smaller and V_2 becomes larger, and the government is more likely to choose a “no regulation” strategy.

As shown in Figure 1(b), the strategy state in space V_3 indicates that enterprises will choose the “no adoption” strategy, and y=0 is the evolutionary stability point; the strategy state in space V_4 indicates that enterprises will choose the “adoption” strategy, and y=1 is the evolutionary stability point. and V_4 are related to x_0. If α, C, K, μ and T increase, then x_0 becomes smaller, resulting in V_4 becoming larger and V_3 becoming smaller. That is, when the environmental cost of enterprises rises and the carbon tax of enterprises points out that the loss K arising from the mismatch between supply and demand in the market rises, enterprises are more willing to choose the “adoption” strategy, indicating that the government design carbon tax mechanism has a facilitating effect on enterprises' choice of “adoption” of CO_2-EOR. This suggests that the government's design of the carbon tax mechanism has a facilitating effect on enterprises' choice of CO_2-EOR. Similarly, if C_m increases, V_3 becomes larger and V_4 becomes smaller, indicating that enterprises are more willing to choose the "no adoption" strategy when the cost of choosing the “adoption” strategy is too high.

As shown in Figure 1(c), the strategy state in the space V_5 indicates that consumers will choose the “positive feedback” strategy, and z=1 is the evolutionary stability point. the strategy state in the space V_6 indicates that consumers will choose the “negative feedback” strategy, and z=0 is the evolutionary stability point. The change in the size of V_5 and V_6 is related to y_0. If λ, μ and T increase, y_0 becomes smaller, resulting in a smaller V_5 and larger V_6. That is, when the carbon tax increases, consumers are more likely to evolve to a “negative feedback” strategy. If K, β, and C increase, y_0 becomes larger, leading to a larger V_5 and smaller V_6. That is, when the loss K from the mismatch between supply and demand in the market and the environmental cost to the enterprises increases, the consumer evolves a stable strategy of “positive feedback”.

3.3. Evolutionary stability condition

If $a=(\lambda-1)T$, $b=-C_t+T$, $c=a(\lambda-1)T$, $d=-\alpha C$, $e=-E+K+C_m$, $f=(a-1)(\lambda-1)T$, $g=\beta C$, $h=K$, then F(x), F(y) and F(z) are simplified.

$$F(x) = \frac{dx}{dt} = x(X_2 - X) = x(1 - x)(ay + b) \tag{8}$$

$$F(y) = \frac{dy}{dt} = y(Y_2 - Y) = y(y - 1)(cx + dz + e) \tag{9}$$

$$F(z) = \frac{dz}{dt} = z(Z_2 - Z) = z(1 - z)(fx + gy + h) \tag{10}$$

In multiple group evolutionary games, the sufficient condition for an evolutionary stable strategy (ESS) is that the ESS is a strict Nash equilibrium. If the evolutionary game equilibrium is asymptotically stable, then the ESS must be the set of pure strategic Nash equilibria that are fixed points of the evolutionary dynamics [26]. Let F(x)=0, F(y)=0 and F(z)=0. From these, eight pure strategy local equilibrium points of the system can be obtained: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$. According to Friedman theory, the evolutionary stability strategy of the system is judged by the stability of the Jacobi matrix [27]. Thus, by taking partial derivatives of the government, enterprises and consumer replication dynamic equations for x, y and z, respectively, the Jacobi matrix is J.

$$J = \begin{pmatrix} (1-2x)(ay+b) & ax(1-x) & 0 \\ cy(1-y) & (1-2y)(cx+dz+e) & d(1-y) \\ fz(1-z) & gz(1-z) & (1-2z)(fx+gy+h) \end{pmatrix} \tag{11}$$

In the Jacobi matrix, the asymptotic stability of the equilibrium is judged by the fact that all eigenvalues have negative real parts. If all eigenvalues have negative real parts, the equilibrium is stable; if at least one eigenvalue has a positive real part, the equilibrium is unstable. Table 2 summarizes the eigenvalues of the eight pure strategy equilibrium points and the conditions for satisfying the ESS.

Table 2. Eigenvalues of equilibrium points and asymptotic stability conditions

Balancing point	λ1	λ2	λ3	Stable conditions
E1(0,0,0)	b	e	h	b<0,e<0,h<0
E2(1,0,0)	-b	e+c	h+f	-b<0,e+c<0,h+f<0
E3(0,1,0)	b+a	-e	h+g	b+a<0,-e<0,h+g<0
E4(0,0,1)	b	e+d	-h	b<0,e+d<0,-h<0
E5(1,1,0)	-b-a	-e-c	h+f+g	-b-a<0,-e-c<0,h+f+g<0
E6(1,0,1)	-b	e+c+d	-h-f	-b<0,e+c+d<0,-h-f<0
E7(0,1,1)	b+a	-e-d	-h-g	b+a<0,-e-d<0,-h-g<0
E8(1,1,1)	-b-a	-e-c-d	-h-f-g	-b-a<0,-e-c-d<0,-h-f-g<0

Table 2 reveals that the evolutionary game system may converge to eight pure strategy evolutionary stable equilibria. Among them, $E_7(0, 1, 1)$ represents the ideal equilibrium for the evolutionary game system, but the realistic equilibrium is $E_8(1, 1, 1)$. The latter reflects the adoption of carbon tax policies by the government, the implementation of CO_2-EOR technology by enterprises, and negative feedback from consumers. This is because the government aims to encourage more oil enterprises to adopt CO_2-EOR strategies, guide consumers towards green consumption behavior, and thus enhance the efficacy of government regulation. The following numerical simulation will illustrate the dynamic evolutionary trajectory of the game system towards $E_8(1, 1, 1)$.

4. Discussion

MATLAB system simulation tools are used for the simulation of the dynamic evolution of the strategies of the game participants. This section first assigns values to the model parameters based on publicly available information and literature, and then simulates the effect of various parameters on the convergence of the system to a realistic evolutionary stable equilibrium $E_8(1, 1, 1)$.

4.1. Parameter assignment

To verify the validity of the evolutionary stability analysis, the model is assigned with values satisfying the stability condition of $E_8(1, 1, 1)$ in conjunction with the realistic situation. T, C_t, C_m, E and λ are the main parameters assigned to the system. The carbon tax should be formulated according to China's specific national conditions, not only to achieve the emission reduction target, but also to minimize the negative impact on the macroeconomy. According to the China Environment Yearbook 2022, the "amount of emission fees deposited" is used to assign the value T to the carbon tax, and the "amount of environmental protection investment for the environmental protection projects completed" is used to assign the value C_m to the cost of adopting CO_2-EOR, and the "budget of environmental supervision department" is assigned to the value C_t to the cost of regulating carbon tax policy. It is calculated that $T:C_t:C_m$ is 1: 0.2: 12, so that T=1,

C_t=0.2, C_m=12. In addition, according to the emission reduction effect of CO_2-EOR project, the emission reduction benefit E of enterprises is assigned to 0.5, and the proportion of carbon tax charged λ is assigned to 0.8.

4.2. Different subject analysis

1. Government behavior analysis

To analyze the impact of the change in government behavior on the evolutionary game process, T is assigned to 1, 1.5 and 1.8, and the simulation results of replicating the system of dynamic equations evolving 50 times over time are shown in Figure 2.

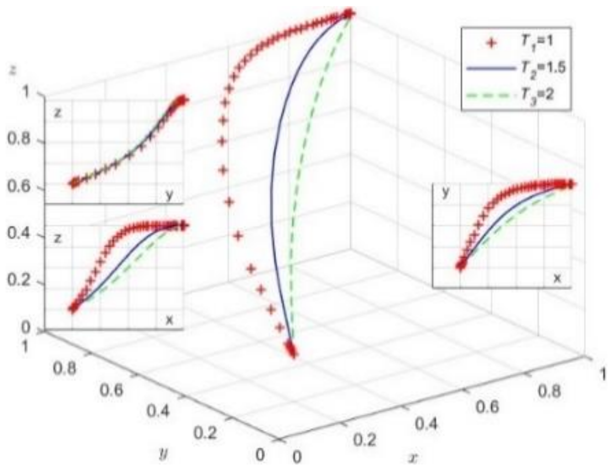

Figure 2. Impact of government actions

The figure shows that the enhancement of carbon tax accelerates the implementation of government regulatory strategies but slows down oil enterprises' adoption of CO_2-EOR technology and positive consumer feedback. This is basically in line with Wang [28] that under a carbon tax policy, manufacturers' profits will be significantly reduced, while this reduction effect is more severe for high-consumption manufacturers. This may be due to the fact that carbon tax revenue and environmental benefits can compensate for the government's regulatory costs and maximize government benefits, while oil enterprises face limitations in obtaining higher production increases and emission reduction benefits at this stage due to technical challenges associated with CO_2-EOR. Additionally, positive feedback from consumers on oil products is impacted by tax burden shifting. Therefore, the government should consider the transition costs of oil enterprises when implementing the carbon tax mechanism, actively promote technological innovation in the upstream of oil, reasonably set the carbon tax standard for oil production, strengthen control of oil prices, especially during periods of price instability, and appropriately increase oil supply to ensure price stability, effectively speeding up the transition of oil enterprises while protecting consumers' rights and interests.

2. Enterprise behavior analysis

In order to analyze the impact of the change in enterprises behavior on the evolutionary game process, E and λ are assigned 0.5, 1, 1.5 and 0.8, 0.4, 0.2, respectively, and the simulation results of replicating the system of dynamic equations evolving 50 times over time are shown in Figure 3.

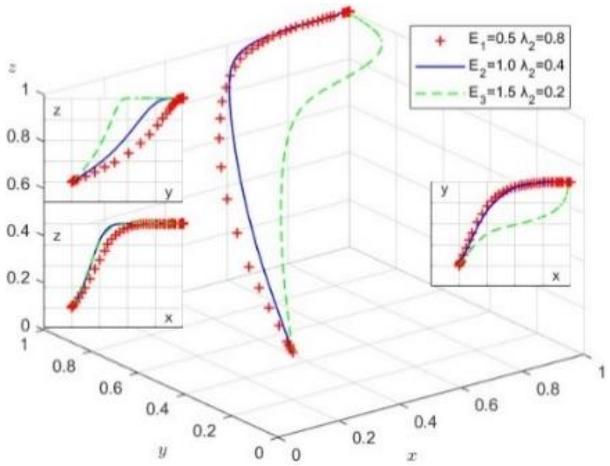

Figure 3. Impact of enterprise actions

The figure shows that CO_2-EOR technological innovation can accelerate the evolution of the adoption of CO_2-EOR technology by enterprises and positive feedback from consumers while slowing down the evolution of the implementation of the carbon tax mechanism by the government. Green technology innovation in energy enterprises can promote the transformation and upgrading of the energy system, achieving carbon peak and carbon neutrality goals [29]. CO_2-EOR technology innovation can significantly reduce CO_2 emissions of oil enterprises, thereby minimizing environmental damage caused by CO_2 emissions. This ultimately maximizes the overall economic and environmental benefits for oil enterprises and consumers. Additionally, the government may delay regulating carbon emissions due to concerns over regulation costs. Therefore, oil enterprises should prioritize promoting the research, development, and application of low-carbon technologies upstream, making every effort to improve the quality and efficiency of oil production, resulting in significant reductions in CO_2 and other pollutant emissions. Secondly, strengthening the connection and interaction between the upstream and downstream of oil can maintain consumer demand and positive feedback for oil products, achieving a smooth transition of oil enterprises through the synergistic relationship between oil enterprises and consumers.

3. Consumer behavior analysis

To analyze the impact of consumer behavior changes on the evolutionary game process, K is assigned to 0.2, 0.8 and 1.5, and the simulation results of replicating the system of dynamic equations evolving 50 times over time are shown in Figure 4.

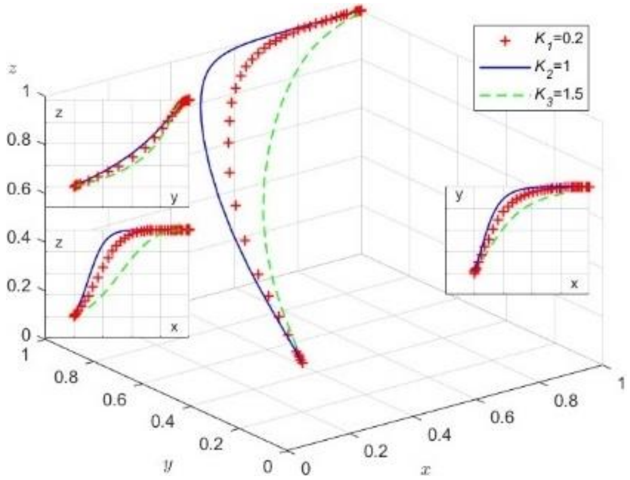

Figure 4. Impact of consumer actions

The figure shows that moderate market supply-demand mismatch loss accelerates the adoption of CO_2-EOR technology and positive consumer feedback by oil enterprises, whereas a higher market supply-demand mismatch loss increases the probability of government regulation. This market mismatch between supply and demand is different from the past, it is more similar to the supply and demand of ecosystem services, reflecting a harmonious relationship between humans and nature [30]. This is because heavier market supply-demand mismatch can lead oil enterprises to underestimate consumer demand for green products, discouraging their low-carbon transition. On the other hand, lighter market supply-demand mismatch can lead oil enterprises to overestimate consumer elasticity for traditional oil products, making it difficult to promote their low-carbon transition. Moreover, during the painful period of market transformation, the government should regulate the behavior of oil enterprises and consumers through carbon emission regulation to ensure the stable operation of the oil market. To achieve this, the government should improve the oil market mechanism and play a macro-regulatory role, while enterprises should accurately analyze the market supply and demand situation and meet the diversified energy needs of consumers, in turn, forming a green, low-carbon, efficient, and flexible oil market gradually.

4.3. Different situation analysis

Three different future evolutionary situations are simulated by assigning different values to the impact parameters based on the $E_8(1,1,1)$ condition (Table 3).

Table 3. Parameter settings for three situations.

Parameter	Situation 1	Situation 2	Situation 3	Parameter	Situation 1	Situation 2	Situation 3
T	1	1.5	1.8	C	1.2	1.2	1.2
C_t	0.2	0.2	0.2	K	0.8	1.5	0.2
C_m	2	2	2	λ	0.8	1.2	0.4

Situation 1 is base situation, assuming that the government adopts a lower carbon tax and enterprises receive lower environmental benefits and carbon tax breaks by adopting CO_2-EOR. In this case, the loss from market mismatch is moderate, and enterprises and consumers bear equal impact of the carbon tax.

Situation 2 is high tax situation, assuming that the government adopts a higher carbon tax and enterprises adopt CO_2-EOR to obtain moderate environmental benefits. Because of the limited emission reductions from CO_2-EOR technology, enterprises incur the highest carbon tax costs. At this point, losses from market mismatches are higher and enterprises pass on the impact of the higher carbon tax to consumers.

Situation 3 is innovation situation, where the government adopts a higher carbon tax, and the enterprises obtains the highest environmental benefits and spends the lowest carbon tax cost due to the innovation of CO_2-EOR technology. In this case, the loss from market mismatch is the lowest, and enterprises pass on the lowest carbon tax impact to consumers.

As can be seen from Figure 5, the evolution of oil enterprises' adoption of CO_2-EOR technology accelerates in the base scenario, but the evolution of government regulation and positive consumer feedback slows down. This may be because lower policy pressure and environmental pressure can make it easier for oil enterprises to go through the difficult transition period and maximize the benefits of oil enterprises in this scenario. In addition, it is difficult for the government to obtain sufficient carbon tax revenues to cover the regulatory costs in the base case, and it is difficult for consumers to obtain higher environmental benefits in the lower CO_2-EOR technology scenario.

In the high tax situation, the evolution of the government's adoption of regulatory strategies accelerates, but the adoption of CO_2-EOR technologies by oil enterprises and positive feedback from consumers slows down. This happens because the government is able to obtain sufficient carbon tax revenues to cover the regulatory costs in the higher carbon tax situation, but higher policy pressure and transition costs disincentivize oil enterprises from producing oil, leading to a slowdown in the transition of oil enterprises, which is consistent with Luo [31]. Additionally, positive consumer feedback on oil products is hindered by tax burden shifting.

In the innovation situation, the adoption of CO_2-EOR technology and positive consumer feedback accelerates for oil enterprises, but the implementation of carbon tax mechanisms by the government slows down. This is because oil enterprises break through the limits of CO_2-EOR technology and gain higher production and emission reduction benefits, which benefits both themselves and consumers. Though CO_2-EOR technology innovation reduces tax revenue of government regulation, the government incentivizes more oil enterprises to adopt CO_2-EOR and leads more consumers to adopt green consumption behavior, reflecting the effectiveness of government carbon emission regulation. Overall, carbon tax policies aim to produce multi-objective optimization, including more investment in technology, higher expected profits and consumer surplus, and fewer carbon emissions [32].

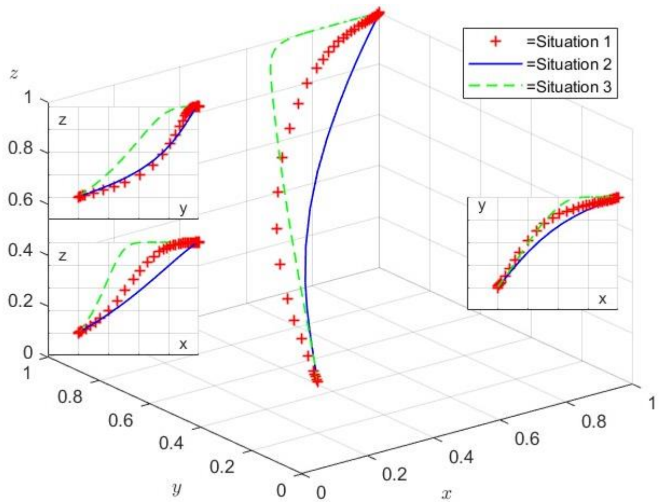

Figure 4. Simulation results for different situation

5. Conclusions

This paper employs the theory of evolutionary game to establish a dynamic evolutionary game model of government, oil enterprises, and consumers. Numerical simulation is conducted using Matlab software to analyze the evolutionary paths of these three agents under different scenarios. Based on current policies and hotspots, the study concludes the following conclusions:

(1) the evolutionary process of the government, oil enterprises, and consumers is closely related to the values of carbon tax T, CO_2-EOR environmental benefit E, emission reduction effort λ, and market supply and demand mismatch loss K. With the constant values of other variables, the three parties of the game show different states with different values of T, E, λ and K.

(2) an increase in carbon tax may enhance the implementation of carbon tax mechanisms by the government, but it can hinder the evolutionary speed of oil enterprises to adopt CO_2-EOR technology and elicit negative consumer feedback.

(3) with the innovation of CO_2-EOR technology, the likelihood of oil enterprises to adopt CO_2-EOR technology and elicit positive consumer feedback increases, but it slows down the government's progress towards implementing a carbon tax mechanism. (4) a moderate market supply-demand mismatch loss can accelerate the evolution of oil enterprises' adoption of CO_2-EOR technology and positive consumer feedback, whereas a higher market supply-demand mismatch

loss can increase the probability of the government's implementation of a carbon tax mechanism.

Based on the findings of this study, we propose the following recommendations in order to promote low-carbon transition in the oil enterprises:

(1) Optimize the design of the carbon tax mechanism. The government's carbon tax policy should consider the balance between low-carbon emission reduction and the interests of economic development and social stability. A reasonable tax relief and low-carbon emission reduction tax incentive mechanism should be designed to optimize the overall tax design and maintain a balanced overall tax burden. This will encourage low-carbon emission reduction while maintaining the vitality of oil enterprises and enhancing their ability to cope with low-carbon transition pressure.

(2) Promote low-carbon technology innovation. oil enterprises must increase energy and carbon reduction transformation of oil production processes and strive to promote the construction of green oil and fields. Through CO_2-EOR technology, oil production processes can be improved, making them more efficient, green, and low carbon. In the near to medium term, CO_2 drive oil technology can be leveraged to improve recovery rates, and in the long term, CO_2 storage in depleted oil reservoirs can be used to contribute to carbon reduction solutions for society while achieving emission reductions for themselves.

(3) Promote oil market upgrading. The key to promoting society's transition to a low-carbon society lies in the formation of a new green and low-carbon market order. The government should establish a sound oil market mechanism, actively promote the awareness of green and low-carbon consumption, and encourage oil enterprises to transform through the market for low-carbon. oil enterprises should meet the demand for oil from consumption upgrades, build their enterprises into high-level service platforms, and provide the market with oil products of qualified quality, reasonable prices, and environmental standards.

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