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Can command-and-control policy drive low-carbon transition in energy-intensive enterprises? -a study based on evolutionary game theory

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There are two views on whether command-and-control policy can promote carbon emission reduction: the "compliance cost" theory and the "innovation compensation" theory. In this paper, we construct an evolutionary game model among energy-intensive enterprises, verification agencies, and local governments from the game theory perspective to explore the impact of command-and-control policy on the low-carbon transition of energy-intensive enterprises. The interaction mechanism of the three actors and the main factors affecting the low-carbon transition of the enterprises are further analyzed with the help of the MATLAB simulation method. The study results show that command-and-control policies can promote the low-carbon transition of enterprises and have a suppressive effect on bribery behavior. In the actual game process, enterprises will compare the cost of low-carbon transition with that of no low-carbon transition. The cost of low-carbon transition is higher when the government's incentives and penalties are small, so there is a "compliance cost" effect, and the government cannot promote low-carbon transition by increasing the intensity of regulation. On the contrary, when the government's incentives and penalties are strong enough, enterprises will make a low-carbon transition spontaneously in the face of continuously increasing environmental regulation intensity, which supports the theory of "innovation compensation." In addition, increasing the profitability of product sales and increasing the cost of bribes are also effective ways to promote low-carbon transition. Finally, relevant policy recommendations were proposed based on the main conclusions. This work opens up a new perspective for environmental regulation theory and provides a theoretical reference and practical basis for developing low-carbon transition.

KEYWORDS

command-and-control policy, low-carbon transformation, carbon verification, environmental regulation, tripartite evolutionary game

1 Introduction

In recent years, the frequency of air quality problems, such as rising greenhouse gas emissions, has shown the urgency of implementing effective energy efficiency and emission reduction measures (Tong et al., 2018). In the process of achieving carbon peak and carbon neutrality goals, China is facing arduous carbon emission reduction tasks. Measures must be taken to limit the consumption of petrochemical energy, reduce economic dependence on the energy industry, and encourage more energy enterprises to undergo clean transformation to reduce carbon emissions throughout the industry (Jiang et al., 2023). In various industries of the national economy, the carbon emissions of energy-intensive industries are enormous, becoming a key goal of national carbon emission reduction work (Liu et al., 2022). Energy-intensive enterprises (hereinafter referred to as "enterprises"), as one of the social agents with the largest CO^2 emissions, their active implementation of carbon reduction strategies is inevitably required for China to successfully reach its carbon peak and carbon-neutral targets (Li and Wang, 2023).

However, due to the public nature of environmental goods, the negative externalities of environmental problems, and the scarcity of energy, it is difficult to achieve environmental friendliness by market regulation alone, so environmental regulation is needed to compensate for market failures. Without the full function of market-based instruments such as the carbon trading market, the means to promote carbon emission reduction in China is still dominated by government-led command-and-control policies (Blackman et al., 2018; Jiang et al., 2022). Since the 21st century, many researchers have been investigating the relationship between environmental regulation and carbon emissions reduction. Although there are various opinions on the nature of this effect, researchers agree that environmental regulation reduces carbon emissions (Mandal, 2010; Bi et al., 2014; Dirckinck-Holmfeld, 2015; Murray and Rivers, 2015; Hancevic, 2016; Galeotti et al., 2020). In the 1990s, Porter challenged the traditional economics view that "environmental protection and economic growth are mutually suppressive" and pioneered the "Porter hypothesis," which states that appropriate environmental regulation not only does not increase costs but also stimulates innovation, generates net benefits, and improves the competitive advantage of firms, thereby improving environmental quality (Porter, 1996). Currently, "compliance cost" and "innovation compensation" theories have been further developed.

The "compliance cost" theory suggests that environmental regulation will make it more difficult for enterprises to manage and increase environmental inputs such as sewage charges, resulting in less profitable investment in production, lower capital gains, and thus less investment in technological innovation, which is detrimental to environmental protection. The choice of environmental regulatory instruments significantly affects the process of low-carbon transition. Command-and-control (CAC) policies are fast-acting because of their coercive nature, but they are prone to market distortions and even adverse emission reduction effects (Tombe and Winter 2015; Chen et al., 2018), while market-based instruments (MBIs) can promote the green transition of enterprises through incentive guidance, but their effects may fade quickly after the policy is withdrawn. Unlike market-incentive instruments, command-and-control policies are less conducive to stimulating enterprises to conduct green technology R&D and innovation and promote low-carbon transition. Excessive environmental regulation or command-and-control policies may slow technological innovation or cause a rebound in energy demand. This could be more conducive to improving energy efficiency and reducing environmental pollution. In addition, command-and-control policies hurt technological innovation and indirectly hurt energy efficiency (Hu et al., 2020; Miao et al., 2021). At the same time, for some enterprises, the increase in investment in emission reduction and pollution control tends to neglect the expenditure on factors of production. It has a greater demand for energy than before, which will keep the increase in its earnings stable by increasing carbon emissions (Hu et al., 2021).

The "innovation compensation" theory is based on the Porter hypothesis, which believes that appropriate environmental regulations can promote technological progress and improve production efficiency, thus compensating for or exceeding the "compliance costs." This will generate innovation spillovers and reduce environmental pollution. Relevant studies have shown that environmental regulation promotes innovation in firm development (Wang et al., 2020; Zhang et al., 2020; Du et al., 2021). Rather than passively paying fines, firms face CAC policies and take the initiative to adjust their decisions, improve their technological innovation, and reduce the additional costs associated with CAC policies through the long-term benefits brought by technological innovation (Porter and Linde, 1995; Chen et al., 2020). As the government and society pay more attention to the environment, the increased intensity of environmental regulations may cause firms to face continuously high costs of following environmental regulations. Faced with the continuously increasing intensity of environmental regulations, rational firms will adopt technological innovation to increase the scale of technological innovation investment on the one hand and improve the efficiency of technological innovation, on the other hand, to cope with the challenges brought by environmental regulations for the long-term development of firms (Lanoie et al., 2011; Rubashkina et al., 2015). At the same time, while using CAC policies, the government often supports enterprise innovation financially or industrially to alleviate the problems of difficult and risky financing for enterprise technological innovation, to solve the worries of enterprise innovation reform, and to actively guide enterprise innovation (Cheng et al., 2017; Pan et al., 2019; Yin et al., 2019). CAC policies will directly influence enterprise innovation and indirectly promote enterprise low-carbon transformation through factors such as attracting foreign direct investment (Song et al., 2019).

The existing research on low-carbon transformation mainly focuses on exploring development models (Wu et al., 2020), constructing indicator systems (Lou et al., 2019), and evaluating the process of low-carbon transformation (Li et al., 2018; Shari et al., 2020). In terms of studying the influencing factors of low-carbon transformation, scholars have explored the different impacts of energy intensity (Zhang C. et al., 2019), industry scale (Du et al., 2018), economic development (Shen et al., 2018), technological innovation (Yin and Li, 2018; Wang et al., 2021), energy structure (Cui et al., 2020; Quan et al., 2020), and investment (Li and Li, 2020; Zhang et al., 2021). However, there is very little literature on the impact of command-and-control policies on low-carbon transformation of enterprises, this article compensates for the shortcomings of existing literature in this regard.

In terms of evolutionary game models, in recent years, the perfect rationality and complete information conditions based on traditional game players have been challenging, and the evolutionary game's bounded rationality hypothesis is more realistic. More and more scholars have used evolutionary game theory to explore the low-carbon emission reduction of enterprises. For example, Zhang S. et al. (2019) and Chen et al. (2022) built an evolutionary game model between the government and manufacturers. Their results show that the cost of carbon emission reduction of enterprises, the government's punishment for excess emissions, and the Carbon emission trading price will simultaneously affect the government's choice of carbon policy and the implementation of enterprise production and emission reduction. Tong et al. (2019) and Kang et al. (2019) constructed a two-party evolutionary game between retailers and manufacturers in the same supply chain. The results show that Carbon emission trading prices, carbon quotas, and consumers' low-carbon preferences are the key factors affecting the decision-making behavior of the subject. Previous literature mainly studied from the perspective of how the evolutionary game between the government and related enterprises affects the low-carbon transformation of enterprises, without considering the positive role played by verification agencies as carbon emission supervisors in the low-carbon transformation of enterprises.

In summary, there is no consensus on whether the effect of CAC policies on carbon emissions is a "compliance cost" effect or an "innovation compensation" effect. In this regard, most of the previous literature is based on data obtained from the practical experience of environmental regulation in various countries using data modeling. However, data modeling is often limited by the sample, which may lead to different results. For example, there are differences in the selection of samples between developed and developing countries, periods, regional sizes, and industries. In addition, it is also a question of what kind of environmental regulation is appropriate in the Porter hypothesis, what level of government incentives and penalties, and the profitability of firms. This work provides supportive insights into the interaction process between stakeholders, including enterprises, verification agencies, and local governments. In particular, it is based on evolutionary game theory, which can exclude the influence of regional differences and differences in sample characteristics, and the results are more general. By constructing a three-way evolutionary game model consisting of local governments, enterprises, and verification agencies, we explore the impact of various parameter changes on players' strategic choices and enterprises' low-carbon transition and analysis the "innovation compensation" and "compliance cost" effects that exist in the low-carbon transformation process of enterprises. In addition, some management strategies and practical insights into the low-carbon transition process for energy-intensive enterprises are presented. This work opens up a new perspective for environmental regulation theory and provides a theoretical reference and practical basis for the development of the low-carbon transition of enterprises.

This paper is structured as follows. Section 2 presents the model assumptions and model construction. Section 3 performs the system stability analysis. Section 4 conducts numerical simulation analysis. Finally, in Section 5, conclusions are drawn, and policy recommendations are given.

2 Underlying assumptions and model construction

2.1 Basic assumptions

Under the carbon trading mechanism, Enterprises must adhere to the specified carbon quota standards and regulate their carbon emissions strictly, or they may face substantial fines from the government (Li W. et al., 2023). In this process, enterprises often replace traditional energy sources and optimize their production processes to promote a low-carbon transition (Pan and Dong, 2023; Yu et al., 2023). The ability of the verification agency to accurately verify a company's carbon emissions and report them truthfully to relevant authorities determines the success of low-carbon transformation efforts (Li Y. et al., 2023). Enterprises and verification agencies might conspire to pursue their benefits, resulting in obstacles to low-carbon transformation initiatives (Chen et al., 2023). Additionally, government oversight may be lacking, which can directly contribute to a decrease in intrinsic motivation for transitioning to low-carbon practices (Zhang et al., 2023). Given the presence of interaction mechanisms among governments, verification agencies, and enterprises, a game theory emerges as an optimal approach for examining the behavior and strategies of these three stakeholders in the low-carbon transition process.

We can construct a logical relationship diagram between energy-intensive enterprises, verification agency, and local government, as shown in Figure 1.

To construct a game model, analyze the stability of various strategies and equilibrium points, as well as the impact relationships of various factors, the following assumptions are made.

Hypothesis 1. Enterprises, verification agencies and local governments are all finite rational participants. During decision-making, participants need access to all information and thus cannot develop strategies to maximize their interests. However, they can learn, imitate, and adjust their strategies to achieve optimal results. As a result, their strategy choices evolve and become stable.

Hypothesis 2. The probability of enterprises choosing low-carbon transition is x, "x = 0" means no participation in the low-carbon transition, and "x = 1"means participation in the low-carbon transition; the probability of verification agencies choosing verification is y, when y = 0 and y = 1, which means no verification and verification respectively; the probability that the local government chooses to regulate is z. When z = 0, the government adopts lax regulation; when z = 1, the government adopts strict regulation, where $x, y, z \in [0,1]$.

Hypothesis 3. Energy-intensive enterprises are a type of enterprise that relies heavily on energy and consumes a lot in the production process, which products mainly include non-ferrous metals, fossil fuels, glass, etc (Lo et al., 2015; Posch et al., 2015). The profit from product sales of the enterprises is RP, the production cost of enterprises engaged in the low carbon transition is C_L, and the production costs for enterprises not participating in the low carbon transition is C_H, $C_L > C_H$. When an enterprise participates in the low-carbon transition, it can meet the carbon emission standard set by the government and pass the verification agency's verification; when an enterprise does not participate in the low-carbon transition, its carbon emission often exceeds the standard, then the enterprise bribes the verification agency to pass the verification. The bribery amount of the enterprise is B_T, $B_T<(C_L-C_H)$, and the enterprise also has falsifying behaviors such as falsifying production records and false propaganda (Liang et al., 2023), and the cost is C_P.

Hypothesis 4. The benefit of the verification agency providing services to local government is V_T. When enterprises do not

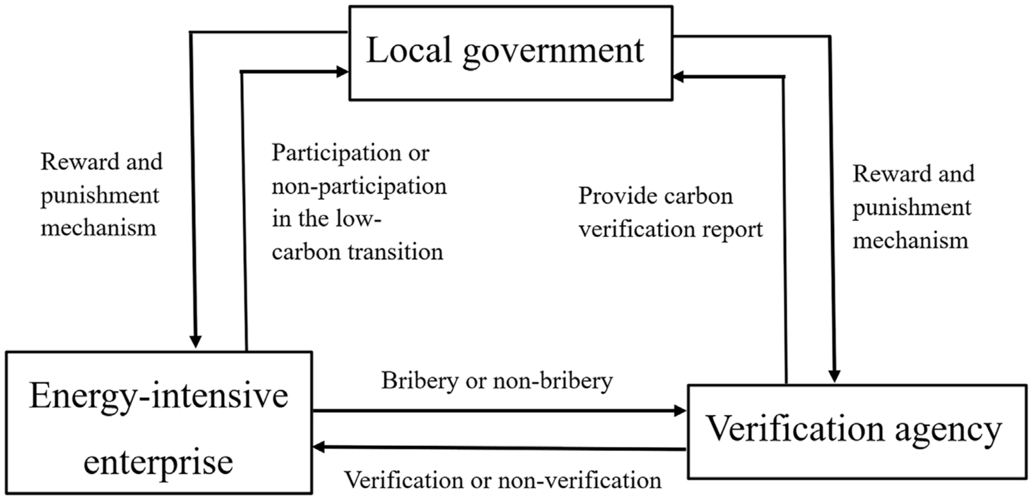

FIGURE 1
Illustration of the game relationships among game players.

TABLE 1 Parameters symbol descriptions.

Parameters	Descriptions
R_P	The profit from product sales of the enterprises
C_L	Production costs of enterprises engaged in the low-carbon transition
C_H	Production costs for enterprises not participating in the low-carbon transition
B_T	The bribery amount of the enterprise
C_P	The cost of falsifying behaviors for enterprises
V_T	Profits from services provided by verification agencies
C_T	The speculative cost of bribes accepted by verification agencies
C_G	The cost of strict government regulation
F_P	Penalties for enterprises exceeding carbon emission limits
F_T	The penalty amount of the verification agencies
M_P	The subsidy for enterprises from the local government
M_T	Rewards for verification agencies that fulfill their supervisory responsibilities
A_G	The social benefits of enterprises engaged in the low-carbon transition
D_G	The cost of cleaning up the environment for the local government
T_G	Administrative penalties imposed by the central government on local governments for inadequate supervision

participate in the low carbon transition, the enterprises' carbon emission exceedance is discovered if the verification agency rejects the bribe from enterprises. If the verification agency accepts the bribe, it colludes with enterprises. If the verification agency accepts the bribe, its speculative cost is C_T, which mainly includes falsifying verification records, issuing false reports, and enhancing information security.

Hypothesis 5. When local governments strictly regulate, violations by enterprises and verification agencies will be discovered. Enterprises not participating in low-carbon transformation and exceeding carbon emissions will be fined F_P. If the verification agency accepts bribes, it will be fined F_T. If the enterprise engages in low-carbon transformation, it will receive a subsidy of M_P from the local government, and the local government will reward M_T to the verification agency that fulfills its supervisory responsibilities. When the local government is lax, the enterprises' and monitoring agencies' information is unavailable, and the government regulators will not give rewards and punishments. Let the cost of strict regulation by local governments be C_G.

TABLE 2 Payoff matrix among each game player.

Game players		Enterprises			
		Participation *x*		Non-participation 1-*x*	
		Verification agencies		Verification agencies	
		Refusal of bribes *y*	Acceptance of bribes 1-*y*	Refusal of bribes *y*	Acceptance of bribes 1-*y*
Local government	Strict regulation *z*	R_P-C_L + M_P, V_T, -C_G + A_G	R_P-C_L + M_P, V_T-C_T-F_T, -C_G-M_P + F_T + A_G	-C_H-C_P-F_P, V_T + M_T, -C_G + F_P-M_T	R_P-C_H-C_P-B_T-F_P, V_T-C_T + B_T-F_T, -C_G + F_P + F_T-D_G
	Lax regulation 1-*z*	R_P-C_L, V_T, A_G	R_P-C_L, V_T-C_T, A_G	-C_H-C_P, V_T, 0	R_P-C_H-C_P-B_T, V_T-C_T + B_T, -D_G-T_G

Hypothesis 6. The participation of enterprises in low-carbon transition benefits public health, economic development and social stability and brings social benefits to local governments A_G. When enterprises do not participate in the low-carbon transition and collude with verification agencies, they pollute and damage the environment, increase environmental cleanup costs, affect public health and economic development, and cost the local government D_G to maintain social stability and regulate the carbon trading market. The central government has an essential responsibility for the exercise of the authority of local governments, which needs to monitor the entrusted affairs executed by localities to prevent the execution of affairs from deviating from the central government's intended "double carbon" goals(Hong, 2017; Sun et al., 2021). When the local government adopts a loose regulatory strategy, resulting in a lack of regulation and excessive carbon emissions by enterprises, the central government will hold the local government accountable with an administrative penalty amount of T_G, $T_G > C_G$.

2.2 Payoff matrix and dynamic replication equation

Parameters and definitions related to the tripartite evolutionary game model for the low-carbon transition of enterprises are outlined in Table 1.

Table 2 below displays the payoff matrix for the tripartite evolutionary game of enterprises' low carbon transition, using the parameters and definitions listed in Table 1.

According to the payment matrix of the tripartite low-carbon transition of enterprises in Table 2, the expected benefits of enterprises choosing participation or non-participation in the low-carbon transition and the average expected benefits are as follows:

$$\begin{cases} E_{11} = yz[R_P - C_L + M_P] + y(1-z)[R_P - C_L] \\ \quad +(1-y)z[R_P - C_L + M_P] + (1-y)(1-z)[R_P - C_L] \\ E_{12} = z[(1-y)(R_P - B_T) - C_H - C_P - F_P] \\ \quad +(1-z)[(1-y)(R_P - B_T) - C_H - C_P] \\ E_1 = xE_{11} + (1-x)E_{12} \end{cases} \tag{1}$$

The dynamic replication equation for enterprises choosing to participate in the low-carbon transition strategy is as follows:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(E_{11} - E_1) \\ &= x(x-1)[C_L - C_H - C_P - B_T - y(R_P - B_T) - z(F_P + M_P)] \end{aligned} \tag{2}$$

The expected benefits of the verification organization selecting a verification or non-verification approach and the average expected benefits are expressed as:

$$\begin{cases} E_{21} = x[z(V_T + M_T) + (1-z)V_T] + (1-x)[z(V_T + M_T) + (1-z)V_T] \\ E_{22} = x[z(V_T - C_T - F_T) + (1-z)(V_T - C_T)] + (1-x)[V_T - C_T + B_T - zF_T] \\ E_2 = yE_{21} + (1-y)E_{22} \end{cases} \tag{3}$$

The dynamic replication equation for the verification agencies' choice of verification strategy can be obtained as follows:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(E_{21} - E_2) \\ &= y(y-1)[(1-x)(B_T - M_T) - z(F_T + M_T) - C_T] \end{aligned} \tag{4}$$

The expected benefits of local governments choosing strict or lax regulation and the average expected benefits are as follows:

$$\begin{cases} E_{31} = -C_G + xA_G - xM_P - yM_T + (1-x)F_P + (1-y)F_T - (1-x)(1-y)D_G \\ E_{32} = xA_G - (1-x)[0 + (1-y)(D_G - T_G)] \\ E_3 = zE_{31} + (1-z)E_{32} \end{cases} \tag{5}$$

The dynamic replication equation for the local governments' choice of strict regulatory strategy is expressed as follows:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(E_{31} - E_3) \\ &= z(z-1)[C_G - F_P - F_T - T_G + x(M_P + F_P + T_G) \\ &\quad + y(M_T + F_T + T_G) - xyT_G] \end{aligned} \tag{6}$$

The dynamic replication equation provides a framework for studying strategy choice and changes in evolutionary games. It can help us better understand the changes in individual agents' behavior, which can help us design more effective strategies to solve the problem. In conclusion, Eqs 2, 4, and 6 constitute a set of dynamic replication equations for the low-carbon transition system of enterprises.

TABLE 3 The eigenvalues of the Jacobi matrix for each equilibrium point.

Balancing point	λ1	λ2	λ3
$\mathbf{E_1}$(0,0,0)	C_H-C_L + C_P + B_T	-B_T + C_T	F_P + T_G + F_T-C_G
$\mathbf{E_2}$(1,0,0)	C_L-C_H-C_P-B_T	C_T	F_T-C_G-M_P
$\mathbf{E_3}$(0,1,0)	C_H-C_L + C_P + R_P	B_T-C_T	F_P-M_T-C_G
$\mathbf{E_4}$(0,0,1)	C_H-C_L + C_P + B_T + F_P + M_P	M_T + F_T + C_T-B_T	C_G-F_P-F_T-T_G
$\mathbf{E_5}$(1,1,0)	C_L-C_H-C_P-R_P	-C_T	-C_G-M_P-M_T
$\mathbf{E_6}$(1,0,1)	C_L-C_H-C_P-B_T-F_P-M_P	F_T + M_T + C_T	C_G + M_P-F_T
$\mathbf{E_7}$(0,1,1)	C_H-C_L + C_P + R_P + F_P + M_P	B_T-M_T-F_T-C_T	C_G + M_T-F_P
$\mathbf{E_8}$(1,1,1)	C_L-C_H-C_P-R_P-F_P-M_P	-F_T-M_T-C_T	C_G + M_T + M_P

3 System stability analysis

The dynamics of enterprises, verification agencies and local government strategies evolve as the game progresses. According to the principle of stability in differential equations, when the replicated dynamic equations for the three parties in the game converge to zero, the system approaches a stable state.

From F(x) = 0,F(y) = 0,F(z) = 0, we can get eight system local equilibrium points: E1 (0,0,0), E2 (1,0,0), E3 (0,1,0), E4 (0,0,1), E5 (1,1,0), E6 (1,0,1), E7 (0,1,1), E8 (1,1,1). The partial derivatives of F(x), F(y), and F(z) concerning x, y, and z are solved separately to obtain the Jacobi matrix:

$$J = \begin{bmatrix} J_1 & J_2 & J_s \\ J_t & J_5 & J_6 \\ J_l & J_s & J_s \end{bmatrix} = \begin{bmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{bmatrix} = \begin{bmatrix} (2x-1)[C_L - C_H - C_P - B_T - y(R_P - B_T) - z(F_P + M_P)] \\ x(x-1)(B_T - R_P)x(x-1)(-F_P - M_P) \\ y(y-1)(-B_T + M_T)(2y-1)[(1-x)(B_T - M_T) - z(F_T + M_T) - C_T] \\ y(y-1)(-F_T - M_T) \\ z(z-1)(M_P + F_P + T_G - yT_G)z(z-1)(M_T + F_T + T_G - xT_G) \\ (2z-1)\begin{bmatrix} C_G - F_P - F_T - T_G + x(M_P + F_P + T_G) \\ +y(M_T + F_T + T_G) - xyT_G \end{bmatrix} \end{bmatrix} \tag{7}$$

According to the Lyapunov stability theorem for ordinary differential equations, an equilibrium point that meets the condition of having all negative eigenvalues in the Jacobian matrix is considered an evolutionarily stable strategy (ESS) for the dynamic replicator system. By inserting each of the eight equilibrium points into the Jacobian matrix, the associated eigenvalues for each point can be determined, as displayed in Table 3. The analysis of the evolutionary stability strategy of the equilibrium points is shown in Table 4.

From Table 4, only points E4 (0, 0, 1) and E5 (1, 1, 0) satisfy the condition that all eigenvalues are negative under certain conditions, so the rest of the equilibrium points are unstable. When C_H - C_L + C_P + B_T + F_P + M_P < 0 and M_T + F_T + C_T - B_T < 0, the replicated dynamic system has a stable point E4 (0, 0, 1). From C_L > C_H + B_T + B_T + C_P + F_P, we know that the explicit cost of bribing the verification agency is (C_H + B_T + C_P) and the implicit cost is (F_P + M_P) for the firm. F_P can be seen as the penalty that the enterprise will receive for making the bribe, and M_P can be seen as the reward that the enterprise will not receive for choosing to bribe. The cost of making the low carbon transition C_L is greater than the total cost of bribing the verification agencies, so enterprises will choose to bribe the verification agency to conceal the carbon emission overrun from the government. From B_T - M_T > C_T + F_T, we know that for the verification agency, the amount of bribe B_T is so large that even after subtracting the reward M_T for performing regulatory duties, it is still greater than the sum of the cost of counterfeiting C_T and the government fine F_T and the verification agency will often accept the bribe from the enterprise so as not to conduct carbon verification for the enterprise. It indicates that when the cost of low carbon transition is high, the local government's penalty and reward are small, and the benefit of bribing the verification agency is high, the evolutionary game stabilization strategy is (no participation, no verification, strict regulation). It means that when the amount of penalties and rewards set by the local government is not enough to restrain the behavior of enterprises and verification agencies effectively, the strategy of enterprises and verification agencies tilted in the direction of non-participation in low carbon transformation and non-verification, and the lack of effectiveness of local government regulation. In this case, enterprises perceive that the cost of low-carbon transition is higher than that of no low-carbon transition, and the strict regulation by local governments cannot promote the low-carbon transition of enterprises, and even increase the transition cost of enterprises, which also a reflection of the "Compliance cost " effect.

When F_P + M_P > C_L—C_H—C_P—B_T > 0 and M_T + F_T > B_T—C_T > 0, both government incentives (M_P and M_T) and penalties (F_P and F_T) for firms and verification agencies are high, and the system has only one stability point E5 (1, 1, 0). It shows that when the local government gives considerable incentives to enterprises and verification agencies, and the penalties are also substantial, the three-party game system will not be a lousy strategy combination of (non-participation, non-verification, and strict regulation), but will become the ideal state of (participation, verification, lax regulation). With the continuous increase of government penalties, rational enterprises will adopt technological innovation and carry out low-carbon transformation to reduce carbon emissions, which embodies the "innovation compensation" effect. Moreover, the changes in the sales revenue of enterprises, the cost of strict regulation by local governments, and the number of administrative

TABLE 4 Analysis of the evolutionary stabilization strategy (ESS) at equilibrium points.

Balancing point	Jacobi matrix eigen -value real part sign	Stability	Judgment conditions
$E_1(0,0,0)$	(±,±,+)	Unstable	—
$E_2(1,0,0)$	(+,+,±)	Unstable	—
$E_3(0,1,0)$	(+,±,±)	Unstable	—
$E_4(0,0,1)$	(-,-,-)	ESS	C_H-C_L + C_P + B_T + F_P + M_P < 0, M_T + F_T + C_T-B_T<0
$E_5(1,1,0)$	(-,-,-)	ESS	—
$E_6(1,0,1)$	(±,+,+)	Unstable	—
$E_7(0,1,1)$	(+,±,+)	Unstable	—
$E_8(1,1,1)$	(-,-,+)	Unstable	—

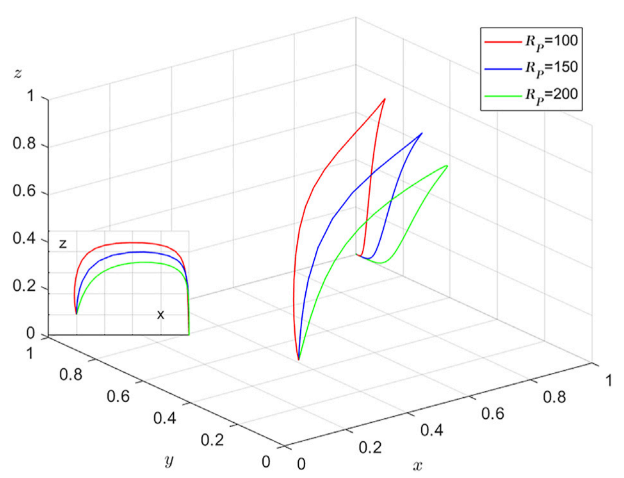

FIGURE 2
The impact of profit from product sales of the enterprises.

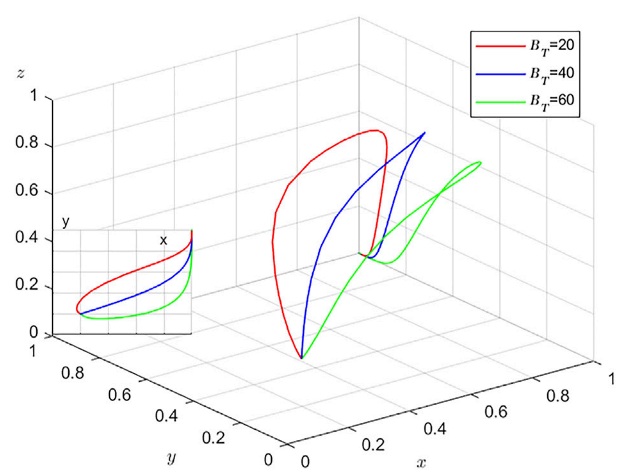

FIGURE 3
The impact of the bribery amount of the enterprise.

penalties for poor regulation by local governments still need to change the evolutionary stability. Therefore, the government should consider the interests of all parties when setting the reward and punishment mechanism to ensure that the cost of collusion between enterprises and verification agencies is higher to avoid the emergence of redundant equilibrium points so that the combination of strategies for the ideal state (participation, verification, lax regulation). In the ideal state, enterprises spontaneously make the low-carbon transition, verification agencies refuse to bribe for verification, and the government's regulatory pressure is effectively relieved. A reasonably designed reward and punishment mechanism by the government can guarantee the orderly implementation of the low-carbon transition of enterprises.

4 Numerical simulation analysis

To explore the optimization path of the low-carbon transition efforts of enterprises, we present numerical simulations of the evolutionary paths of enterprises, verification agencies, and local governments under setting different parameter variations. The values of the parameters in this paper are determined by analyzing the behavior of parties involved in the low-carbon transition process using relevant parameter settings from carbon emission reduction-related research (Meng et al., 2022; Qin and Wang, 2022; Wei et al., 2022).

Suppose that the profit from product sales of the enterprises R_P = 150, the production costs of enterprises participating and not participating in the low carbon transition C_L = 185 and C_H = 100, the bribery amount of the enterprise B_T = 40, the cost of falsifying behaviors for enterprises C_P = 10, the penalties for companies exceeding carbon emission limits F_P = 40, the subsidy for enterprises from the local government M_P = 20, the speculative cost of bribes accepted by verification agencies C_T = 10, the penalty amount of testing agency F_T = 20, the rewards for verification agencies that fulfill their supervisory responsibilities M_T = 15, the cost of strict government regulation C_G = 15, and the administrative penalties imposed by the central government on local governments for inadequate supervision T_G = 40. Let the array 1 be: R_P = 150, C_L-C_H = 85, C_P = 10, B_T = 40, F_P = 40, M_P = 20, C_T = 10, F_T = 20, M_T = 15, C_G = 15, T_G = 40. Based on array 1, analyze the influence of R_P, B_T, M_T, M_P, F_T, and T_G on the process and outcome of the evolutionary game.

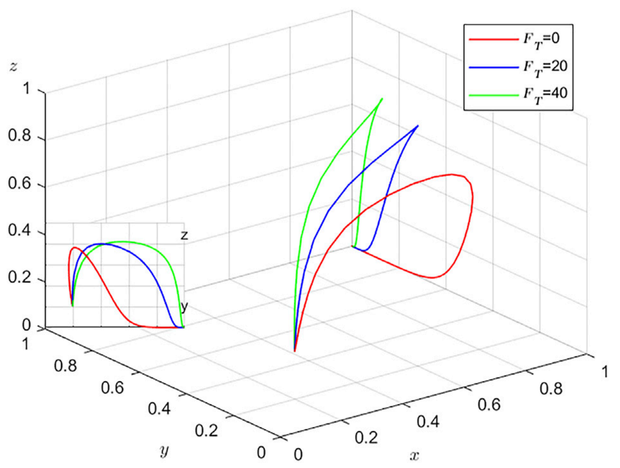

FIGURE 4
The impact of penalty amount of verification agencies.

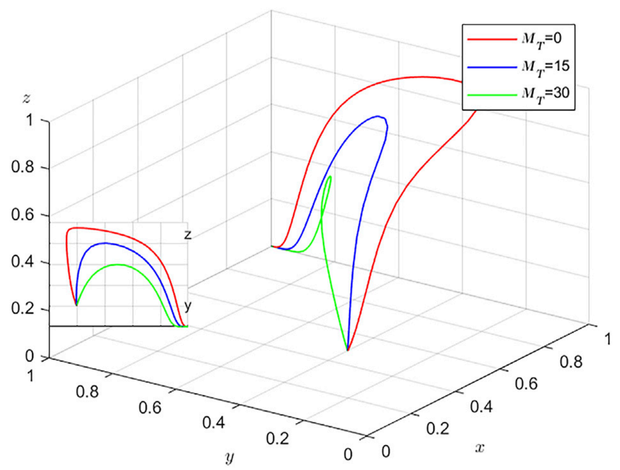

FIGURE 5
The impact of rewards for verification agencies that fulfill their supervisory responsibilities.

First, to assess the impact of R_P variation on the evolutionary game's progress and outcomes, R_P values of 100, 150, and 200 were assigned. Figure 2 displays the simulation outcomes after replicating the dynamic equation system for 50 iterations. Figure 3 displays the simulation results obtained by assigning B_T values of 20, 40, and 60 to analyze its influence on the evolutionary game process and outcome.

As seen from Figure 2, during the evolution of the system to the stabilization point, the increase in corporate profits can accelerate the evolution of corporate stabilization in participating in low-carbon transition strategies. As R_P increases, the probability of corporate participation in low-carbon transition rises. The probability of strict regulation by local governments decreases. Therefore, for enterprises with large carbon emissions from backward production technology, preferential policies can be used to increase their income to promote low-carbon transition. Figure 3 shows that in the evolutionary process, as B_T increases, the probability of enterprises participating in low-carbon transition increases, and the probability of verification agencies rejecting bribes for verification decreases. The government can increase the cost of bribery by increasing the power of media disclosure, expanding the influence of corporate reputation, fostering public awareness of environmental protection, and other market measures to enhance the willingness of companies to make a low-carbon transition.

Next, the simulation results are shown in Figure 4 for $F_T = 0, 20, 40$ and Figure 5 for $M_T = 0, 15, 30$. Figure 4 shows that before the probability evolution of enterprises' participation in low-carbon transition stabilizes at 1, the probability of strict regulation by local government increases when F_T increases. After the probability evolution of enterprises' participation in low-carbon transition stabilizes at 1, the probability of strict government regulation gradually decreases and stabilizes at 0. The increase of F_T increases the probability of verification agencies' refusal to bribe for verification. Figure 5 shows that, in the evolutionary process, an increase in M_T decreases the probability of strict regulation by local governments. Therefore, local governments should reasonably develop reward and punishment mechanisms to replace fixed payments for services in the form of bonus dividends so that verification agencies can share the responsibility with the government to ensure the stable advancement of enterprises' low-carbon transition efforts.

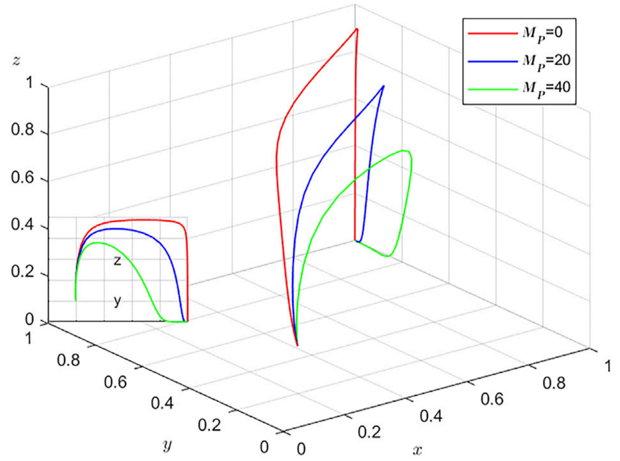

FIGURE 6
The impact of subsidy for enterprises from the local government.

Further, the simulation results of replicating the dynamic equation system with 50 times of time evolution by assigning $M_P = 0, 20, 40$, respectively, are shown in Figure 6; the simulation results of assigning $T_G = 0, 20, 40$, respectively, are shown in Figure 7. Figure 6 shows that in the evolutionary stabilization process, the probability of strict regulation by local governments decreases as M_P increases, and the probability of verification by verification agencies increases. Figure 7 shows that after the probability of enterprises' participation in the low-carbon transition stabilizes at 1, an increase in T_G leads to an increase in the probability of strict government regulation. Although the incentive

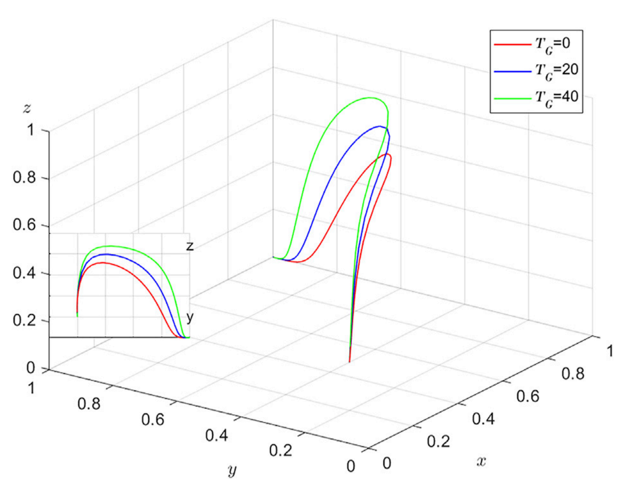

FIGURE 7
The impact of administrative penalties on local governments.

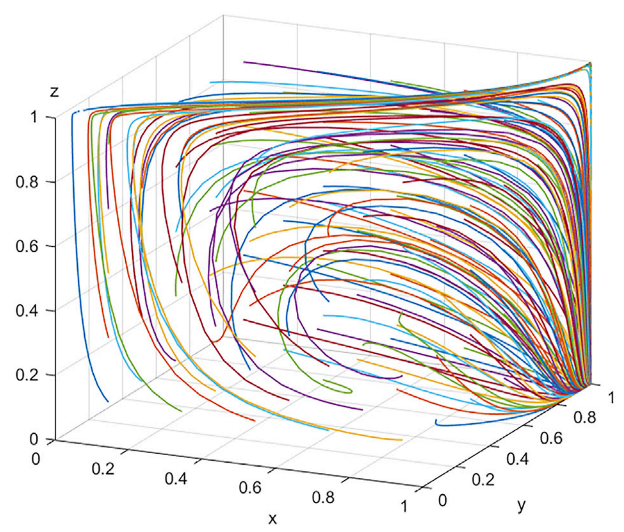

FIGURE 9
Array 2 evolves 50 times.

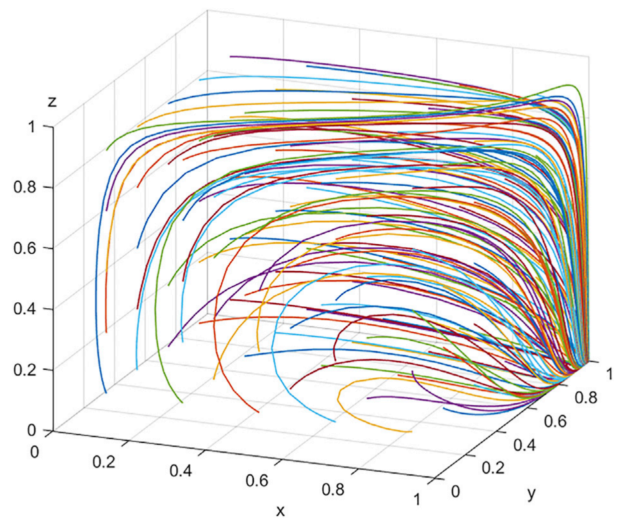

FIGURE 8
Array 1 evolves 50 times.

mechanism of local government for enterprises can promote their participation in the low-carbon transition, it could be more conducive to the performance of regulators themselves. Severe administrative penalties imposed by the central government can maintain a higher probability rate of strict regulation by local governments, which further increases the willingness of enterprises to make a low-carbon transition.

Assign array 2: $R_P = 150$, $C_L\text{-}C_H = 105$, $C_P = 10$, $B_T = 50$, $F_P = 25$, $M_P = 15$, $C_T = 10$, $F_T = 18$, $M_T = 12$, $C_G = 15$, $T_G = 40$, satisfying the conditions for the existence of stable point E4 (0, 0, 1). The two sets of values evolved 50 times over time from different initial strategy combinations, and the results are shown in Figures 8, 9.

As shown in Figure 8, the system has only one stabilization point (1, 1, 0) when only one combination of evolutionary stabilization strategies (participation, verification, and lax regulation) exists, consistent with the findings in the previous paper. Figure 9 shows that the system has two evolutionary stability points (0, 0, 1) and (1, 1, 0), i.e., the strategy combinations of firms, verification agencies, and local governments (non-participation, non-verification, strict regulation) and (participation, verification, lax regulation) are two evolutionary stability strategy combinations. Therefore, the local government should strengthen the information construction and examine the interests of enterprises and verification agencies in many aspects to ensure that enterprises choose to carry out low-carbon strategies need lower costs and avoid the situation that irregularities such as bribery hinder the low-carbon transition work of enterprises. As can be seen, the simulation analysis is consistent with the conclusions of the previous stability analysis. Its validity is a practical guide for the low-carbon transition work of energy-intensive enterprises.

In summary, R_P, B_T, M_T, M_P, F_T, and T_G are all factors that influence enterprises to make a low-carbon transition during the implementation of command-and-control type policies. Enterprises compare the total cost of participating and not participating in the low-carbon transition and make decisions that determine whether command-and-control environmental regulations are effective. Previous studies have used samples from different industries in different countries, such as China, the United Kingdom, and Denmark (Bi et al., 2014; Dirckinck-Holmfeld, 2015; Murray and Rivers, 2015), the cement industry *versus* the coal-fired power generation industry, and so on (Mandal, 2010; Hancevic, 2016). Therefore, these samples differ in corporate profitability, the extent of policy implementation, and the severity of regulatory penalties. In addition, it has been noted that CAC policies can produce significant environmental benefits in developing countries (Blackman et al., 2018). These may all lead to a debate on whether "compliance cost" or "innovation compensation."

5 Conclusion and policy recommendations

5.1 Conclusion

In implementing imperative environmental regulation tools, they are achieving low-carbon transformation of enterprises resulting from game interaction among three stakeholders. In the context of "double carbon" objectives, this paper analyzes the system's stability conditions and evolutionary paths under each strategy based on the tripartite evolutionary game among local governments, enterprises, and verification agencies under environmental regulation. It uses MATLAB numerical simulation to explore the optimization paths of local governments to promote the low-carbon transition of energy-intensive enterprises. Compared with the previous literature that used data modeling for research, this study is based on evolutionary game theory, which can eliminate the impact of regional differences and sample characteristics differences, and the results are more general. The main conclusions are summarized as follows.

(1) Command-and-control policies can promote the low-carbon transformation of energy-intensive enterprises while inhibiting bribery between enterprises and verification agencies. Strict regulation and law enforcement make bribery more difficult and risky, reducing enterprises' motivation to evade environmental regulations through bribery.
(2) In the actual process of the game, enterprises weigh the costs of low-carbon transition and those of not, and the costs of low-carbon transition are higher when the government rewards and punishments are small. On the contrary, when the government's incentives and penalties are strong enough, enterprises will make a low-carbon transition spontaneously in the face of continuously increasing environmental regulation intensity, which supports the theory of "innovation compensation."
(3) Improving product sales profitability can increase enterprises' motivation to engage in low-carbon transformation. If low-carbon products can obtain higher market demand and prices, enterprises will have greater motivation to invest in low-carbon technology and innovation.
(4) Increasing the cost of bribery can reduce the incentive effect of bribery. If bribery costs are high, companies are more inclined to improve product competitiveness and profitability through legal means rather than relying on bribery to evade environmental regulations.

5.2 Policy recommendations

Based on the above findings, policy recommendations are obtained as follows:

In terms of command-and-control policies: 1) Strengthen environmental regulation and law enforcement efforts to ensure adequate supervision of the low-carbon transformation of energy-intensive enterprises. Increase the resources and capabilities of verification agencies to reduce the occurrence of bribery; 2) Develop strict regulations and systems, clearly define the low-carbon transformation requirements that energy-intensive enterprises should comply with. Moreover, clarify punishment measures. These will increase the risk and cost of companies evading environmental regulations through bribery, thereby reducing their motivation; 3) Strengthen information sharing and cooperation among industries to more effectively monitor and prevent bribery. Establish a reporting mechanism and reward system to encourage employees and the public to expose behaviors involving bribery.

In terms of reward and punishment mechanisms: 1) Establish low-carbon transformation incentive measures, such as tax exemptions, subsidies, rewards, etc., to reduce the cost of low-carbon transformation for enterprises. The government can provide technical support and consulting services to assist enterprises in implementing low-carbon technology and innovation; 2) Increase the penalties for enterprises that do not meet the requirements of low-carbon transformation, such as fines and revocation of licenses, to increase the motivation for enterprises to follow low-carbon transformation.

In terms of corporate profitability: 1) Promote market demand and price recognition of low-carbon products, and improve consumers' awareness and preference for low-carbon products through publicity and education activities; 2) Establish a low-carbon product certification and standard system so that consumers can clearly distinguish and choose low-carbon products, thus encouraging enterprises to invest in low-carbon technology and innovation; 3) Encourage enterprises to carry out green finance and sustainable development investment, and provide loans and financial support to enterprises committed to low-carbon transformation.

In terms of regulating enterprise behavior: 1) Strengthen the formulation and implementation of anti bribery laws and regulations, and improve the legal risk and punishment of bribery; 2) Increase the protection of bribery reporting mechanism, protect the rights and interests of informants, and reward effective reporting; 3) Strengthen the internal compliance mechanism and moral education of the enterprise, cultivate employees' integrity awareness, and reduce the occurrence of bribery.

5.3 Research limitations of this paper

Under the strict supervision of the government, due to the problems of administrative ability and professional quality, the government cannot fully guarantee to find the problem of fraud in carbon emission reporting. In addition, although MATLAB numerical simulation can intuitively provide valuable information about system behavior and is more cost-effective, it is still the result of approximate calculation. The model used is usually based on assumptions and simplification, which may not capture the complexity and nonlinear behavior of the system entirely and accurately. Finally, based on evolutionary game theory, this paper only discusses the relationship between energy-intensive enterprises, verification agencies, and the government. The feedback mechanism between other stakeholders, such as the public and other subjects, needs further study.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CZ: Conceptualization, methodology, data collection, data curation, writing original draft and editing. YH: Validation, writing—review, funding acquisition. RZ: Methodology, data curation, editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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