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Stability analysis of carbon emission trading mechanism in China based on a tripartite evolutionary game

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This study investigates the evolution and stability of China's carbon emission trading system, addressing disparities between China's carbon market development and international practices. By constructing a three-party evolutionary game model involving the government, enterprises, and consumers, this paper identifies key factors influencing system stability and offers policy recommendations. The main contributions include: (1) Developing a dynamic model that incorporates consumer behavior, including the herd effect, to reveal the interplay between demand-side dynamics and market evolution. (2) Demonstrating that government regulatory costs, consumer preferences, and enterprise investment costs significantly impact market stability and green transitions. (3) Highlighting that carbon prices alone have limited influence on enterprise participation, underscoring the importance of comprehensive incentives. This work provides actionable insights to optimize policy design, enhance market efficiency, and promote low-carbon transformation in China.

Keywords China's carbon emission trading mechanism, Three-party evolutionary game, Stability analysis

Climate change has far-reaching impacts on ecosystems, economies, and public health. The IPCC's AR6 Synthesis Report[1] reveals that atmospheric carbon dioxide has reached its highest concentration in nearly two million years. Since the 1990s, the global carbon market has transitioned through three developmental stages (Fig. 1), evolving from experimental trials to mature systems, marking a shift in climate governance from reactive to proactive strategies. As a market-based mechanism, the Emissions Trading Scheme (ETS) incentivizes carbon reduction by pricing and trading emission rights, promoting cost-effective emissions reductions[2]. While national ETS systems differ in design and implementation, their common objective is to achieve emissions reduction through market mechanisms[3].

China, though a late entrant to the carbon market, has rapidly progressed from regional pilot programs to a unified national system. This system is designed to unlock emission reduction potential, refine market mechanisms, and enhance low-carbon transition efficiency. With increasing participation, the maturation of the MRV (monitoring, reporting, verification) system, and diversification of carbon financial products, China is positioned to become the world's largest carbon market. The transition from "dual control of energy" to "dual control of carbon emissions" has garnered significant attention from the government, enterprises, and society (Fig. 2), emphasizing the need to understand the evolutionary mechanisms of carbon trading and devise effective emissions reduction strategies.

Despite extensive research on carbon trading mechanisms, significant gaps remain. Most studies have focused on two-party interactions (e.g., government-enterprise or enterprise-consumer) and single influencing factors, often overlooking the dynamic and interdependent relationships among key stakeholders. Additionally, the roles of consumer behavior and feedback mechanisms, such as the herd effect, in shaping carbon market evolution have been underexplored. This study addresses these gaps by constructing a three-party evolutionary game model that integrates government, enterprises, and consumers, providing a comprehensive framework to analyze system stability and identify factors driving green transitions. The literature review in the next section details the gaps in previous research.

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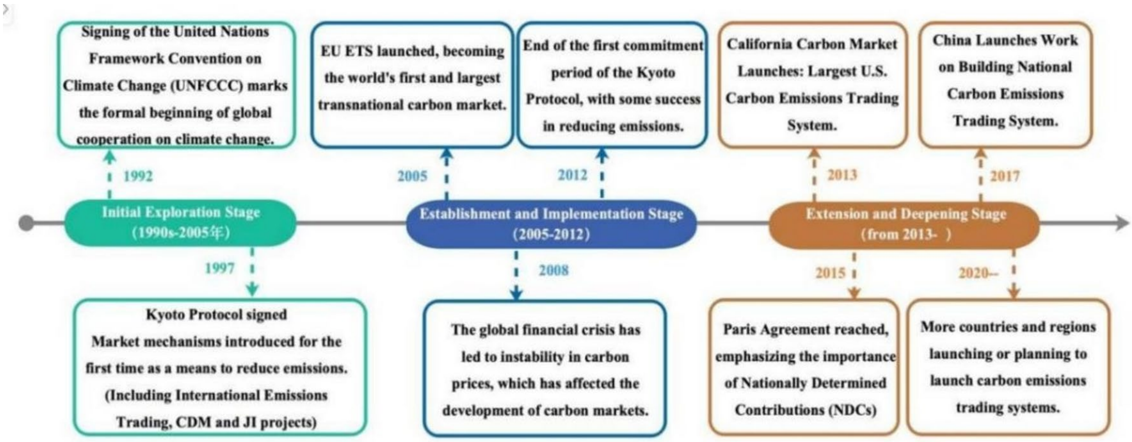

Fig. 1. Development History of The Global Carbon Market.

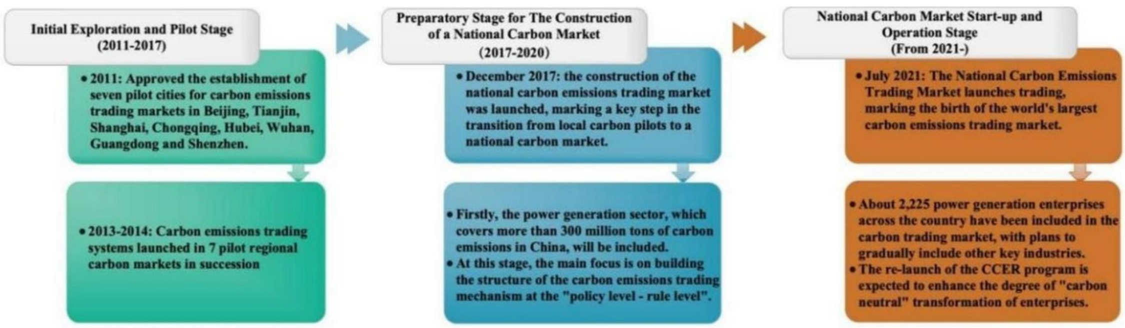

Fig. 2. Development History of China's Carbon Market.

The remainder of this paper is structured as follows: Section "Literature review" reviews the relevant literature. Section "Methodology" provides a logical analysis of the behavior of the key actors in the evolutionary game of carbon trading mechanisms. Section "Model construction, stability and numerical analysis" develops the model, examining the trilateral interactions among governments, enterprises, and consumers in a low-carbon context. Section "Conclusions and Policy proposals" concludes with policy recommendations and discusses the study's limitations.

Literature review

The carbon trading mechanism, as a crucial market-based tool to address climate change, internalizes the cost of carbon emissions through price mechanisms, thereby guiding enterprises, governments, and the public toward low-carbon transitions. However, the effectiveness of carbon trading mechanisms is influenced by various behavioral factors, including policy design, corporate actions, and public participation. Evolutionary game theory provides an effective framework for analyzing these complex dynamics. This study systematically reviews the existing literature on evolutionary game theory in the context of carbon trading mechanisms, identifies its limitations, and highlights the innovations and contributions of this research. (Table 1).

To sum up, traditional studies often focus on two-party games and single influencing factors. These studies lack sufficient dynamic analysis of the strategic interactions among governments, enterprises, and consumers, particularly in terms of coordination and negotiation among different stakeholders. Moreover, the analytical framework often overlooks the dynamic policy environment and long-term market effects, such as the potential impacts of policy changes and technological breakthroughs on market stability. Accordingly, this paper focuses on a three-party model and offers the following key contributions:

- Within the context of China's carbon market, this study systematically incorporates a broader range of factors influencing the design and development of the carbon trading mechanism, with a focus on diverse stakeholders. A feedback loop emerges in which consumers' preferences influence enterprises' strategies, and these strategies, in turn, shape consumer perceptions and behaviors. For instance, growing demand for low-carbon products motivates enterprises to reduce emissions, which further boosts consumer confidence in sustainable goods. Although individual consumers are not direct participants in China's national carbon market, they play a critical role as demand drivers, indirectly shaping market dynamics and policy decisions. By integrating consumer behavior into the game framework, this study highlights its essential role in linking market de-

Research Topic	Research Content and Conclusion
The Application of Evolutionary Game Models in Carbon Market Research	
Economic Effects of Government Regulation	Jiao et al.[4] models the evolution of strategies between local governments and enterprises, revealing how reward and punishment mechanisms can enhance carbon reduction efficiency Zhang et al.[5] develops an evolutionary game model to explore the dynamic decision-making of enterprises under carbon market regulations and the role of government enforcement in ensuring compliance Some researches highlight the dynamics of government-enterprise cooperation and competition in carbon markets, analyzing the role of penalties and subsidies through evolutionary game theory and SD models[6,7] Gao et al.[8]'s research models evolutionary games between stakeholders to design carbon sequestration compensation mechanisms for national parks within a carbon trading context Dong et al.[9] explores how to elucidate the governance efficiency of carbon trading markets in achieving emission reduction goals using the DID model
Influence of Green Consumption	Guo et al.[10] explores the interactions between government policies and household carbon reduction behaviors in consumer-focused carbon trading markets using evolutionary game theory
Synergy Between Green Production and Green Consumption	Wang and Cheng[11] applies evolutionary game theory to examine how carbon trading influences operational decisions within supply chains, particularly in terms of emission reduction investments
Carbon Trading Market Mechanism Design	
Carbon Quota Allocation and Market Liquidity	Ma and Wang[12]'s article uses the DCC-MVGARCH model, revealed a strong correlation between China's carbon trading and energy markets, but a negative correlation with the capital market, highlighting inefficiencies in China's carbon quota allocation Liu P D, et al.[13] focuses on how carbon quota trading affects competition and collaboration among enterprises, using evolutionary game theory to analyze stable strategies Liu Y, et al.[14] uses the super efficiency SBM model and a multi-phase DID model toanalyze how carbon trading policies influence the green total factor productivity of high-carbon industries. And concludes that improvement of the carbon quota allocation system, improve the information disclosure system of the carbon trading market is necessary Li B, et al. [15] discusses how evolutionary game models can optimize coordination mechanisms to enhance the carbon reduction effects of quota trading
Price Volatility and Market Stability	Li Y M, et al.[14] uses evolutionary game models to investigate how dynamic carbon pricing affects the investment strategies of governments and enterprises in renewable energy projects Ding and Cao[16] uses the GTAP-E model, analyzed the EU's carbon tariffs and found that China's domestic carbon market can mitigate "carbon leakage" more effectively than accepting "carbon tariffs." Yin and Li[17] uses the input–output model and Monte Carlo simulation o evaluate the strategic responses of Chinese enterprises to the EU's carbon border adjustment mechanism and puts forward a series of policy recommendations to resolve the adverse impact of CBAM
Factors Affecting Carbon Trading Market Stability	Li L X, et al.[18] examined the evolutionary game of carbon pricing in the context of renewable energy investment and low-carbon technology innovation Liu Y, et al.[19] investigates how carbon trading mechanisms stimulate urban-level green technology advancements using an evolutionary game approach Xu and Liu[20] employs a difference-in-differences model, incorporating the spatial effects of energy consumption, to examine the impacts of energy consumption structure optimization, total energy control, and carbon trading pilot policies on regional low-carbon economic transitions

Table 1. Summary of existing literature on evolutionary game theory in carbon trading mechanisms.

mand, enterprise strategies, and government interventions, offering a holistic perspective on carbon trading mechanisms.

- By integrating the concept that consumer behavior can exert feedback effects on both government and enterprises, this study constructs a dynamic, three-party repeated game model involving government, enterprises, and consumers. The model parameters are set and calibrated using empirical data, with the conclusions verified through simulation analysis.
- This research incorporates the herd effect in consumer decision-making, applying Social Learning (SL) theory to explore the evolutionary dynamics of low-carbon behavioral preferences. The herd effect, a significant driver of consumer decisions[21], highlights how individuals are influenced by the preferences and actions of their social group, shaping collective behavior and accelerating the adoption of low-carbon consumption trends. Ignoring the herd effect risks underestimating the rapid adoption potential of low-carbon products driven by social influence. It also neglects a critical feedback mechanism where consumer behavior influences enterprise strategies and government policies, creating a dynamic interplay that shapes market demand. By integrating the herd effect, this study offers a more comprehensive perspective on the mechanisms underlying carbon trading systems, addressing a previously underexplored area in carbon market research.

Methodology
Evolutionary game-theoretic analysis framework

Evolutionary game theory is a general framework for analyzing how rational participants continuously adjust their behavioral strategies through repeated interactions to achieve optimal responses and stable states[22]. In the context of carbon emission trading mechanisms, participants modify their strategies based on the actions of others, as well as shifts in market policies and environmental conditions. The core of evolutionary game theory in this setting is to explore how the strategic choices of market participants evolve over time as a result of these interactions.

Following the framework of evolutionary game theory, this study is structured as follows: (1) Key stakeholders in the carbon trading market, along with their strategic space and influencing factors, are identified (Fig. 3). Detailed model settings are described in Section "Main conclusions". (2) In Section "Model construction, stability and numerical analysis", the payoff matrix for each stakeholder is formulated, followed by the derivation of expected payoffs and replicator dynamic equations, which determine the evolution of strategic interactions. (3) The evolutionary stable strategies (ESS) are solved, and the evolutionary paths and stability of the system are analyzed. Equilibrium points are discussed separately, and the effects of various influencing factors on system evolution are assessed in Section "Conclusions and Policy proposals". (4) In Section 6 the optimization paths of the carbon emission trading mechanism are explored, focusing on key factors affecting strategic stability.

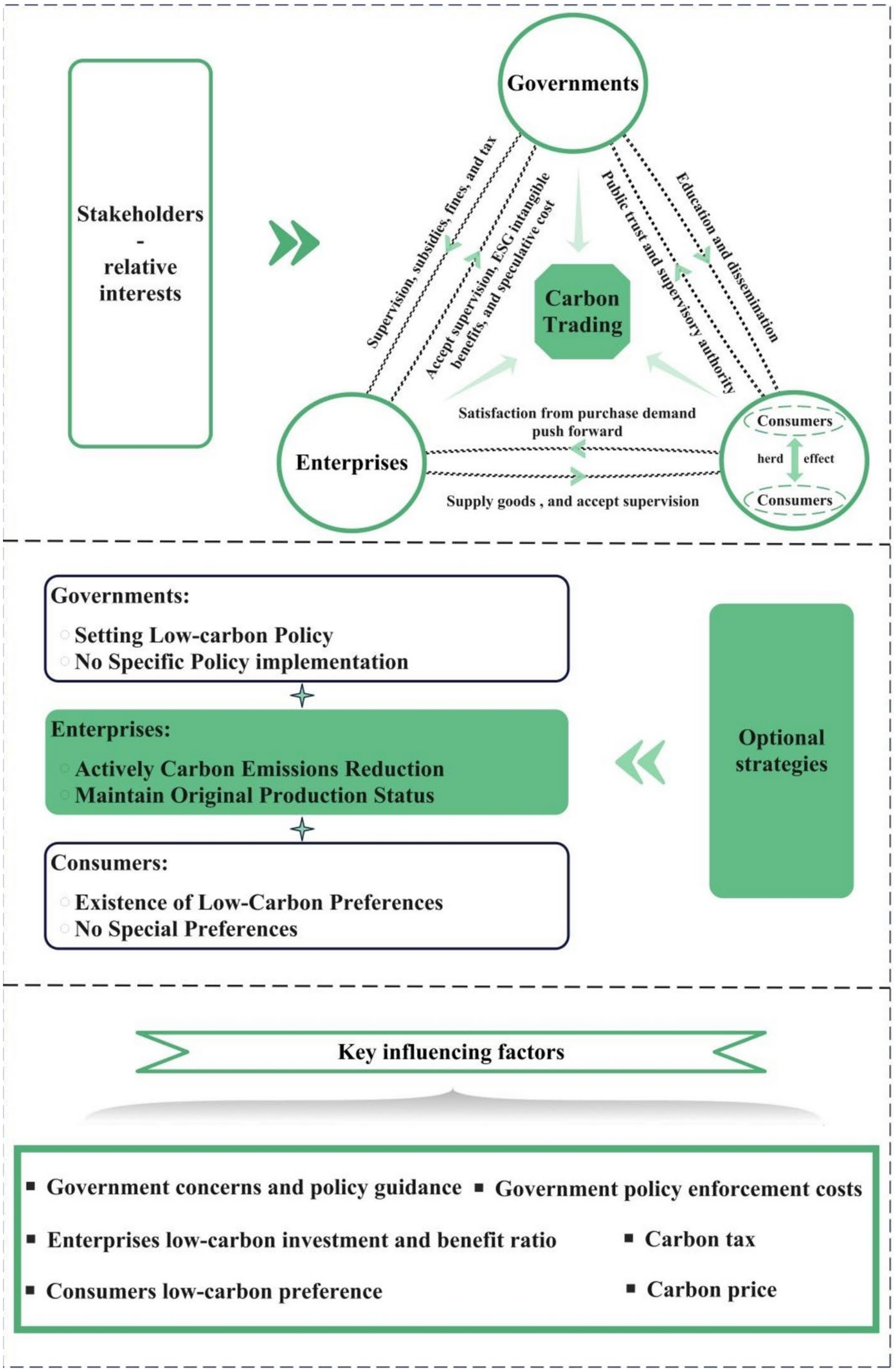

Fig. 3. Evolutionary Game-theoretic Analysis Framework for Carbon Trading.

All theoretical analyses are further demonstrated through numerical simulations. The numerical results, presented in figures, are generated using Matlab R2022a.

Model assumptions and variables

Assumption 1 (*Rational Participants*): In this study, the government (policy makers and market regulators), high-emission enterprises (hereafter "enterprises"), and consumers are the primary stakeholders in the game. It is assumed that all parties are boundedly rational and do not have complete information symmetry. Each group seeks to maximize its own interests, and they are modeled as collective entities rather than individuals.

Assumption 2 (*Strategy Selection*): Under an imperfect carbon trading mechanism, the government can either implement a low-carbon policy or refrain, with probabilities of x and 1-x, respectively. Enterprises choose to reduce emissions with a probability of y, or not with 1-y. Consumers may prefer low-carbon products with a probability of z, or have no preference with 1-z, where $x,y,z \in [0, 1]$.

Assumption 3 (*Government Behavior*): In a carbon trading system with imperfect design, the government intervenes to maintain market stability by either enforcing a strict low-carbon policy at a cost of C_g or weak regulation at a lower cost C_w ($C_g > C_w$). Strict regulation may yield higher or lower returns (θR_g) compared to the baseline market returns (R_g) without specific policies, where (θ) reflects the impact of government policies on the market. By leveraging social influence and promoting low-carbon policies, the government enhances social acceptance and gains credibility (M) when consumers benefit from improved welfare. In addition, carbon taxes (T) can offset regulatory costs while encouraging emission reductions, and governments may offer support (S)) through subsidies, tax incentives, or technical assistance to compliant enterprises, while penalizing non-compliant firms (K) for over-emission.

Assumption 4 (*Enterprise Behavior*): Enterprises, influenced by consumer herd psychology, may pass on the costs of emission reduction through higher prices for low-carbon products, gaining revenue (R_c) compared to the status quo (R_w). An enterprise reducing emissions through low-carbon technologies emits (Q_1), while those that do not emit (Q_2). Carbon trading involves initial costs (C_d) and potential savings (C_r). Firms may earn revenue from selling surplus allowances or pay for shortfalls (Q_3) based on the carbon price (P_c), and those that actively reduce emissions also benefit from intangible ESG gains (U). Investments in abatement technology incur a cost (I_r).

Assumption 5 (*Consumer Behavior*): There are two reasons for incorporating consumer herd behavior into the analytical framework. First, behavioral psychology demonstrates that individuals are influenced by the preferences and actions of others within their social group. Second, studies show that consumers' green preferences are significantly correlated with corporate and government policies, indicating that herd behavior can amplify these effects. Consumers following the herd (α) in low-carbon choices derive psychological benefits (g), which reinforce their preference for aligning with group norms and accelerate the adoption of green consumption practices. Increased environmental awareness enhances satisfaction from low-carbon consumption (L_1), while unchanged perceptions result in lower satisfaction (L_2), directly influencing market demand for sustainable goods. Although individual consumers are not yet direct participants in China's national carbon market, their behavior indirectly affects market dynamics through demand shifts and their influence on corporate and government strategies. As such, their specific benefits from the trading process are not considered in this analysis.

The relevant parameters and definitions for model formulation are collected in Table 2.

Model construction, stability and numerical analysis

Based on the interactions among the three stakeholders (Fig. 3) and Assumptions 1–5, the corresponding trilateral payoff matrix is presented in Table 3. It is important to note that Table 4 reflects only the individual gains from consumer strategies, without accounting for the herd effect. The impact of the herd effect on consumer behavior will be incorporated into the replication dynamic equation F(z).

Model construction and stability analysis

Following Table 4, the expected payoffs of government choosing participation in carbon market regulation or market-driven (indicated as V_{x1} and V_{x2}, respectively) are obtained as:

$$\begin{aligned} V_{x1} &= y\left[z\cdot(\theta\cdot R_g - C_g + M + T\cdot P_c\cdot Q_2 - S) + (1-z)\cdot(\theta\cdot R_g - C_g + T\cdot P_c\cdot Q_2 - S)\right] + (1-y)\left[z\cdot(\theta\cdot R_g - C_g + M + T\cdot P_c\cdot Q_1 + K) + (1-z)\cdot(\theta\cdot R_g - C_g + T\cdot P_c\cdot Q_1 + K)\right] \\ V_{x2} &= y\left[z(R_g - C_w) + (1-z)(R_g - C_w)\right] + (1-y)\left[z(R_g - C_w) + (1-z)(R_g - C_w)\right] \\ \bar{V}_x &= x\cdot V_{x1} + (1-x)\cdot V_{x2} \end{aligned} \tag{1}$$

The replicated dynamic equation for government is:

$$F(x) = \frac{dx}{dt} = x\left(V_{x1} - \bar{V}_x\right) = -x\,(x-1)\left[C_w - C_g + K - R_g + T\cdot P_c\cdot Q_1 + \theta\cdot R_g - y\,(S + K + T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2) + M\cdot z\right] \tag{2}$$

The aggregate expected payoffs and replicated dynamic equation for enterprises can be similarly derived.

$$F(y) = \frac{dy}{dt} = y\left(V_{y1} - \bar{V}_y\right) = -y\,(y-1)\left[C_r - I_r + 2P_c\cdot Q_3 + x\,(S + K + U + T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2) + z\,(R_c - R_w + U - U\cdot x)\right] \tag{3}$$

Considering the herd effect on consumers, the quantitative equation of herd effect is introduced and the modified expected return is shown in equation as follows:

Parameters	Definitions
Associated with Governments	
R_g	Revenue available to the government by no low-carbon policy
θ	The impact factor for low-carbon policies on the revenue
C_g	Costs of setting a low-carbon policy
C_w	Costs of implementing no specific policy with weak supervision
M	Gains for the government's intangible benefits
T	Carbon tax rate
S	Governments' support for emission reduction enterprises
K	Governments' penalties for non-compliant firms
Associated with Enterprises	
Q_1	carbon emission under prior production
Q_2	carbon emission under low-carbon production
R_c	Income from the sale of low-carbon products or services
R_w	Income from the sale of original products or services
C_d	Operating costs with no low-carbon actions
C_r	Operational cost savings after investing in low-carbon technologies
I_r	Investment costs of abatement technologies for enterprises
U	Corporate ESG intangible benefits
P_c	Carbon price
Q_3	Surplus/Shortfall allowances or CCERs
Associated with Consumers	
L_1	The satisfaction gained through low-carbon preferences rises
L_2	The satisfaction gained by conducting regular purchasing behaviors
α	Intensity of herd effect
g	Psychological benefits gained by following group norms

Table 2. Parameters and definitions for model formulation. Data Sources: The parameter values and initial conditions are set based on empirical data, theoretical foundations, and practical circumstances to ensure scientific rigor and applicability. The data sources include: (1) Policy documents and official reports on the national carbon market, issued by environmental protection departments, energy management bureaus, and other relevant government agencies. (2) Academic literature and cutting-edge research on carbon trading, game theory, and environmental economics. (3) Guidelines and standards from organizations such as the International Carbon Disclosure Project (CDP) and the International Trade Center (ITC), as well as China's carbon emission accounting guidelines for 24 key industries and regional carbon management standards for key sectors. (4) Historical data (including carbon prices, trading volumes, and emissions from listed power industry enterprises) from Wind and LSEG, used to empirically verify the impact of emission reduction technology investments on the carbon trading mechanism.

		Consumers	
Governments	**Enterprises**	**Existence of low-carbon preferences (z)**	**Have no special preference actions (1-z)**
Set a low-carbon policy (x)	Actively reduce carbon emission (y)	$\theta \cdot R_g - C_g + M + T \cdot P_c \cdot Q_2 - S$	$\theta \cdot R_g - C_g + T \cdot P_c \cdot Q_2 - S$
		$R_c - C_d + C_r - I_r - T \cdot P_c \cdot Q_2 + S + U + P_c \cdot Q_3$	$R_w - C_d + C_r - I_r - T \cdot P_c \cdot Q_2 + S + U + P_c \cdot Q_3$
		$L_1 - R_c$	$L_2 - R_w$
	Maintain original actions (1-y)	$\theta \cdot R_g - C_g + M + T \cdot P_c \cdot Q_1 + K$	$\theta \cdot R_g - C_g + T \cdot P_c \cdot Q_1 + K$
		$R_w - C_d - P_c \cdot Q_3 - T \cdot P_c \cdot Q_1 - K$	$R_w - C_d - P_c \cdot Q_3 - T \cdot P_c \cdot Q_1 - K$
		$L_2 - R_w$	$L_2 - R_w$
No implement a specific policy (1-x)	Actively reduce carbon emission (y)	$R_g - C_w$	$R_g - C_w$
		$R_c - C_d + C_r - I_r + U + P_c \cdot Q_3$	$R_w - C_d + C_r - I_r + P_c \cdot Q_3$
		$L_1 - R_c$	$L_2 - R_w$
	Maintain original actions (1-y)	$R_g - C_w$	$R_g - C_w$
		$R_w - C_d - P_c \cdot Q_3$	$R_w - C_d - P_c \cdot Q_3$
		$L_2 - R_w$	$L_2 - R_w$

Table 3. Payoff matrix of the model.

Equilibrium points	Eigenvalues	Conditions of ESSs
$E_1(0,0,0)$	$\lambda_1=-\alpha\cdot g$ $\lambda_2=C_r-I_r+2P_c\cdot Q_3$ $\lambda_3=C_w-C_g+K-R_g+T\cdot P_c\cdot Q_{1+}\theta\cdot R_g$	$C_r-I_r+2P_c\cdot Q_3<0$ $C_w-C_g+K-R_g+T\cdot P_c\cdot Q_{1+}\theta\cdot R_g<0$
$E_2(1,0,0)$	$\lambda_1=-\alpha\cdot g$ $\lambda_2=C_g-C_w-K+R_g-T\cdot P_c\cdot Q_1-\theta\cdot R_g$ $\lambda_3=C_r-I_r+K+S+U+2P_c\cdot Q_3+T\cdot P_c\cdot Q_1-T\cdot P_c\cdot Q_2$	$C_g-C_w-K+R_g-T\cdot P_c\cdot Q_1-\theta\cdot R_g<0$ $C_r-I_r+K+S+U+2P_c\cdot Q_3+T\cdot P_c\cdot Q_1-T\cdot P_c\cdot Q_2<0$
$E_3(0,1,0)$	$\lambda_1=-C_r+I_r-2P_c\cdot Q_3$ $\lambda_2=L_1-L_2-R_c+R_w-\alpha\cdot g$ $\lambda_3=C_w-C_g-R_g-S+T\cdot P_c\cdot Q_2+\theta\cdot R_g$	$-C_r+I_r-2P_c\cdot Q_3<0$ $L_1-L_2-R_c+R_w-\alpha\cdot g<0$ $C_w-C_g-R_g-S+T\cdot P_c\cdot Q_2+\theta\cdot R_g<0$
$E_4(1,1,0)$	$\lambda_1=-C_w+C_g+R_g+S-T\cdot P_c\cdot Q_2-\theta\cdot R_g$ $\lambda_2=-C_r+I_r-K-S-U-2P_c\cdot Q_3-T\cdot P_c\cdot Q_1+T\cdot P_c\cdot Q_2$ $\lambda_3=(1-\alpha)(L_1-L_2-R_c+R_w)-\alpha\cdot g$	$-C_w+C_g+R_g+S-T\cdot P_c\cdot Q_2-\theta\cdot R_g<0$ $-C_r+I_r-K-S-U-2P_c\cdot Q_3-T\cdot P_c\cdot Q_1+T\cdot P_c\cdot Q_2<0$ $(1-\alpha)(L_1-L_2-R_c+R_w)-\alpha\cdot g<0$
$E_5(1,0,1)$	$\lambda_1=-\alpha\cdot g$ $\lambda_2=C_g-C_w-K-M+R_g-T\cdot P_c\cdot Q_1-\theta\cdot R_g$ $\lambda_3=C_r-I_r+K+R_c-R_w+S+U+2P_c\cdot Q_3+T\cdot P_c\cdot Q_1-T\cdot P_c\cdot Q_2$	$C_g-C_w-K-M+R_g-T\cdot P_c\cdot Q_1-\theta\cdot R_g<0$ $C_r-I_r+K+R_c-R_w+S+U+2P_c\cdot Q_3+T\cdot P_c\cdot Q_1-T\cdot P_c\cdot Q_2<0$
$E_6(0,1,1)$	$\lambda_1=L_2-L_1+R_c-R_w-\alpha\cdot g$ $\lambda_2=I_r-C_r-R_c+R_w-U-2P_c\cdot Q_3$ $\lambda_3=C_w-C_g+M-R_g-S+T\cdot P_c\cdot Q_2+\theta\cdot R_g$	$L_2-L_1+R_c-R_w-\alpha\cdot g<0$ $I_r-C_r-R_c+R_w-U-2P_c\cdot Q_3<0$ $C_w-C_g+M-R_g-S+T\cdot P_c\cdot Q_2+\theta\cdot R_g<0$
$E_7(0,0,1)$	$\lambda_1=-\alpha\cdot g$ $\lambda_2=C_r-I_r+R_c-R_w+U+2P_c\cdot Q_3$ $\lambda_3=C_w-C_g+K+M-R_g+T\cdot P_c\cdot Q_1+\theta\cdot R_g$	$C_r-I_r+R_c-R_w+U+2P_c\cdot Q_3<0$ $C_w-C_g+K+M-R_g+T\cdot P_c\cdot Q_1+\theta\cdot R_g<0$
$E_8(1,1,1)$	$\lambda_1=-C_w+C_g-M+R_g+S-T\cdot P_c\cdot Q_2-\theta\cdot R_g$ $\lambda_2=(1-\alpha)(L_2-L_1+R_c-R_w)-\alpha\cdot g$ $\lambda_3=I_r-C_r-K-R_c+R_w-S-U-2P_c\cdot Q_3-T\cdot P_c\cdot Q_1+T\cdot P_c\cdot Q_2$	$-C_w+C_g-M+R_g+S-T\cdot P_c\cdot Q_2-\theta\cdot R_g<0$ $(1-\alpha)(L_2-L_1+R_c-R_w)-\alpha\cdot g<0$ $I_r-C_r-K-R_c+R_w-S-U-2P_c\cdot Q_3-T\cdot P_c\cdot Q_1+T\cdot P_c\cdot Q_2<0$
$E_9(x^*,y^*,z^*)$	Saddle point	

Table 4. Conditions for evolutionary stable strategies (ESSs) at various equilibrium points.

$$\begin{cases} V_{z1} = x\left[y\cdot(L_1-R_c)+(1-y)\cdot(L_2-R_w)\right]+(1-x)\left[y\cdot(L_1-R_c)+(1-y)\cdot(L_2-R_w)\right] \\ V_{z2} = x\left[y\cdot(L_2-R_w)+(1-y)\cdot(L_2-R_w)\right]+(1-x)\left[y\cdot(L_2-R_w)+(1-y)\cdot(L_2-R_w)\right] \\ \bar{V}_z = z\cdot V_{z1}+(1-z)\cdot V_{z2} \end{cases}$$

$$\begin{cases} V_{z1}' = (1-\alpha)\cdot V_{z1}+\alpha\cdot g\cdot z \\ V_{z2}' = (1-\alpha)\cdot V_{z2}+\alpha\cdot g\cdot(1-z) \\ \bar{V}_z' = z\cdot V_{z1}'+(1-z)\cdot V_{z2}' \end{cases} \tag{4}$$

$$F(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=z(V_{z1}'-\bar{V}_z')\left[\alpha\cdot g(1-2z)+y(\alpha\cdot x-1)(L_1-L_2-R_c+R_w)\right]$$

A mixed strategy equilibrium in an asymmetric game model will not be an evolutionarily stable equilibrium[23]. Following $F(x)=F(y)=F(z)=0$, a conclusion concerning the equilibrium points for this dynamic system can be immediately obtained as follows.

Proposition 1. From F(x)=0, F(y)=0, F(z)=0, there are nine equilibrium points in this model: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(1,1,0)$, $E_5(1,0,1)$, $E_6(0,1,1)$, $E_7(0,0,1)$, $E_8(1,1,1)$. $E_9(x^*,y^*,z^*)$ is the saddle point.

Subsequently, the Jacobian matrix can be obtained by solving the partial derivatives of Eq. F(x), F(y), F(z). According to the Lyapunov discriminant[24], when all eigenvalues $\lambda<0$ of the Jacobian matrix, then the corresponding equilibrium is an evolutionarily stable point of the system, and if at least one $\lambda>0$, then the ESS are summarized in Table 4.

$$J=\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}=\begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}$$

where,

$$J_{11} = (1-2x)\left[C_w - C_g + K - R_g + T\cdot P_c\cdot Q_1 + \theta\cdot R_g - y\left(S+K+T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2\right) + M\cdot z\right]$$
$$J_{12} = x(x-1)\left(S+K+T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2\right)$$
$$J_{13} = -x(x-1)M$$
$$J_{21} = -y(y-1)\left[\left(K+S+U+T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2\right) - U\cdot z\right]$$
$$J_{22} = (1-2y)\left[C_r - I_r + 2P_c\cdot Q_3 + x\left(K+S+U+T\cdot P_c\cdot Q_1 - T\cdot P_c\cdot Q_2\right) + z\left(R_c - R_w + U - U\cdot x\right)\right]$$
$$J_{23} = -y(y-1)\left(R_c - R_w + U - U\cdot x\right)$$
$$J_{31} = \alpha\cdot yz(z-1)\left(L_1 - L_2 - R_c + R_w\right)$$
$$J_{32} = z(z-1)(\alpha\cdot x - 1)\left(L_1 - L_2 - R_c + R_w\right)$$
$$J_{33} = (2z-1)\left[\alpha\cdot g(1-2z) + y(\alpha\cdot x - 1)\left(L_1 - L_2 - R_c + R_w\right)\right] - 2\alpha\cdot g\cdot z(z-1)$$

Numerical analysis

This section presents numerical simulations of the triangular evolutionary game model discussed earlier. Initially, the study establishes baseline parameter values, which are then adjusted to analyze the evolutionary paths toward different equilibria. Additionally, a sensitivity analysis is conducted.

Currently, in China's national carbon market, the government retains control over all carbon allowances, which are distributed free of charge. At the same time, participation in the national carbon trading market is limited to over 2,000 key emission-control enterprises in the power generation sector, whose carbon reduction obligations are mandatory. Moreover, Chinese export enterprises have become more active in the carbon market due to recent constraints from carbon border taxes and stringent carbon reduction requirements in export destinations. In addition, with the introduction of China's "dual carbon" goals and the implementation and promotion of green strategies in recent years, consumer awareness of green and low-carbon practices has significantly increased. This is evident from the rising production and purchase rates of electric vehicles, demonstrating the driving force of consumer preferences on corporate green production. Given the current status and future expectations of China's carbon trading mechanism, equilibrium E_8 is selected as the benchmark case.

The initial parameter values are categorized into three groups:

(1) Government decisions, scaled and adjusted based on existing literature and reports, for example, R_g, C_g, C_w are numerically determined based on the proportion of regulatory costs to carbon market revenues during the initial phase of China's pilot carbon markets. According to practical observations, during the early development stages of the carbon markets in Guangdong and Hubei, regulatory costs typically accounted for 10% to 12% of transaction volumes. Considering that the national carbon market is still in its early development phase, the experiences from China's pilot carbon markets serve as the basis for these setting[25]. The numerical settings for government subsidies and penalties are based on the proportions used by Qu and Hou[26] and Wang et al.[27] in their article regarding the implementation of active regulation by the government。

(2) Enterprise actions, derived from typical real-world scenarios such as carbon prices and the costs of daily operations during emission reductions. Referring to the real-world case of Toyota's collaboration with steel suppliers to develop low-carbon production processes, the ratio of costs (C_d-C_r+I_r) to revenue (R_w) after investing in green technologies should be approximately 0.8[28,29] .

(3) Existing studies typically set the value of a between 0.6 and 0.9. Therefore, this paper initially sets it to 0.8[30–32]. The parameter values (Array 1) for the benchmark case (E_8) are summarized in Table 5.

As outlined in the stability analysis in Section "Main conclusions", the stable evolutionary strategies of the government, enterprises, and consumers are influenced by various factors. To better visualize and assess the evolution of each stakeholder's strategic choices, simulating the evolution paths of equilibrium points is crucial. Given the unique nature of China's national carbon market, where emission-control enterprises meeting specific standards are mandated to participate in trading and adhere to local government regulations, the power industry remains the primary market participant. If enterprises opt not to reduce emissions or engage in trading, the carbon market cannot function effectively. Therefore, four equilibrium points where enterprises actively reduce emissions are selected for simulation. The four parameter sets (Table 5) are evolved over 50 iterations from different initial strategy combinations, with the results presented in Fig. 4.

The analysis of these evolution paths demonstrates that in all four equilibrium points (Table 6), enterprises opt to actively invest in emission reduction technologies and participate in carbon trading, suggesting that the carbon trading mechanism effectively promotes emission reduction awareness and drives green transformation in enterprises. The differences arise in the strategic behaviors of governments and consumers. Further sensitivity analysis of key parameters will provide theoretical support for developing targeted intervention mechanisms based on the benchmark case.

Sensitivity analysis for governments decision

(1) *Costs of Setting a Low-Carbon Policy* (C_g): To assess the sensitivity of governments to regulatory costs, C_g is set to 20, 40, 60, 80, and 100, respectively. Figure 5(a) shows that higher supervision costs reduce the incentive for governments to implement low-carbon policies, with strategy evolving from strict regulation to a free market. This shift occurs as governments may face deficits from the regulatory burden and opt for deregulation

Parameters	Array 1: $E_8(1,1,1)$	Array 2: $E_3(0,1,0)$	Array 3: $E_4(1,1,0)$	Array 4: $E_6(0,1,1)$
R_g	200	200	200	200
θ	1.2	1	1.2	1
C_g	60	120	60	120
C_w	35	35	35	35
M	15	15	15	15
T	0.05	0.05	0.05	0.05
S	10	10	10	10
K	30	30	30	30
Q_1	100	100	100	100
Q_2	70	70	70	70
R_c	70	140	140	70
R_w	100	100	100	100
C_d	70	70	70	70
C_r	10	10	10	10
I_r	25	25	25	25
U	8	20	8	20
P_c	5	5	5	5
Q_3	10.5	10.5	10.5	10.5
L_1	0.9	0.8	0.8	0.9
L_2	0.2	0.5	0.5	0.2
α	0.8	0.8	0.8	0.8
g	8	2	2	8

Table 5. Parameter values for reaching different equilibrium points.

to balance economic and social considerations. Governments can mitigate these costs by encouraging businesses and consumers to adopt green practices, expanding carbon-inclusive finance, and increasing revenue from carbon trading.

(2) *Impact Factor of Low-Carbon Policies on Revenue* (θ): By varying θ from 0.8 to 1.6, the evolutionary results (Fig. 5(b)) indicate that as the impact factor increases, governments are more likely to implement low-carbon policies. However, governments will only regulate carbon trading mechanisms if they derive additional benefits from the carbon market.

(3) *Government Support* (S): Setting S at 3, 10, 25, 40, and 50 reveals that governments tend to support enterprises' low-carbon transitions when subsidies are low (Fig. 5(c)). As subsidies increase, there is a threshold beyond which governments opt to reduce or eliminate them. Notably, when subsidies are between 40 and 50, governments initially adopt low-carbon policies but eventually revert to a free market approach.

(4) *Government Penalty* (K): Varying K from 10 to 50 (Fig. 5(d)) shows that penalties prompt governments to adopt low-carbon policies and take active supervision. However, penalties do not significantly influence the speed of the government's decision-making, and increasing penalties does not affect the rate of policy adoption.

Proposition 2. Governments will implement low-carbon policies if the cost of setting such policies is lower than not doing so, if the enhancement factor for low-carbon revenue is substantial, and if increased support accelerates the transition to a free carbon market. However, the imposition of penalties does not affect the speed of government decision-making.

Sensitivity analysis for enterprises action

(1) Investment costs of abatement technologies for enterprises (Ir) and Surplus/Shortfall allowances or CCERs (Q_3). To assess the sensitivity of enterprises to the costs of abatement technologies and allowances, *Ir* is adjusted from 25 to 65, while Q_3 moves inversely, from 10.5 to 2.5. Figure 6(a) shows that as the cost of low-carbon investments increases without a corresponding rise in surplus allowances or a reduction in shortfall allowances, enterprises are less incentivized to reduce emissions and participate in carbon trading. Thus, enterprises must consider the ratio of low-carbon investment to benefits when making decisions.

(2) Carbon price (P_c). Increasing the carbon price from 2 to 10 with a step of 2, the results shown in Fig. 6(b). The impact of carbon price changes on enterprises' behavior is limited, indicating that other key factors should be leveraged to influence corporate decisions.

Proposition 3. Enterprises are more likely to actively reduce emissions if the ratio of low-carbon investment to benefits is favorable. However, carbon price alone has a limited effect on their decision-making. An increase in carbon price will not necessarily enhance corporate willingness to reduce emissions unless accompanied by factors such as the availability of tradable carbon allowances.

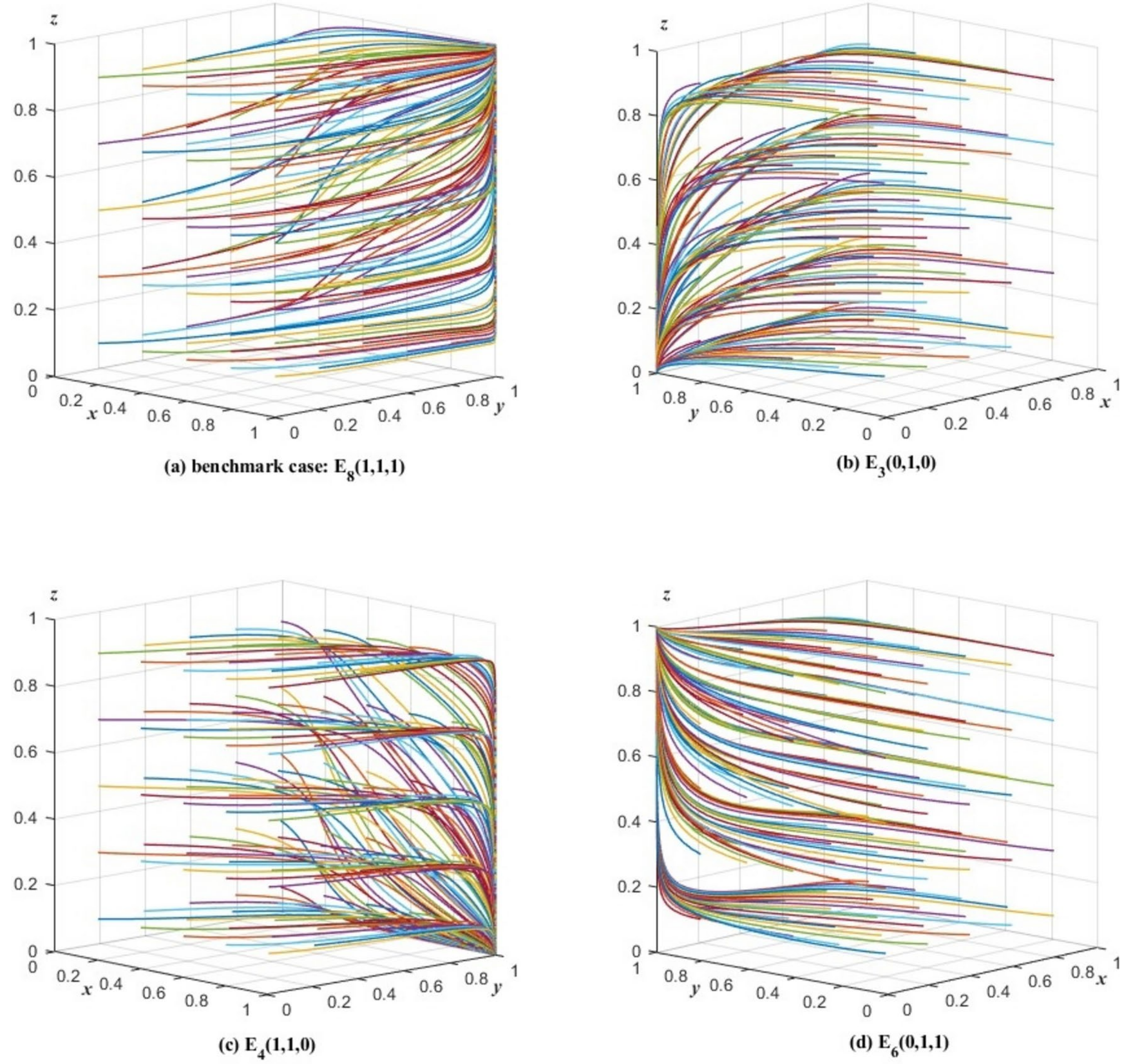

Fig. 4. Evolutionary Paths of Four Equilibrium Points.

Equilibrium Point	Government Strategy	Enterprise Strategy	Consumer Preference	Formation Mechanism
$E_8(1,1,1)$	Implements low-carbon policy	Actively reduces emissions	Preference for low-carbon products	The government reduces enterprise emission reduction costs through subsidies and discourages non-compliant behavior with penalties. Enterprises benefit from low-carbon policies and are driven by consumer preferences to adopt green transformations. High consumer preference reinforces market dynamics
$E_3(0,1,0)$	No low-carbon policy	Actively reduces emissions	No preference for low-carbon products	The government refrains from implementing low-carbon policies due to high regulatory costs. Enterprises, driven by market pressure or carbon prices, choose to reduce emissions. Consumers show negligible demand for low-carbon products
$E_4(1,1,0)$	Implements low-carbon policy	Actively reduces emissions	No preference for low-carbon products	The government incentivizes enterprises through subsidies and penalties to engage in emission reduction, but insufficient consumer demand prevents full market alignment
$E_6(0,1,1)$	No low-carbon policy	Actively reduces emissions	Preference for low-carbon products	The government avoids intervention due to high regulatory costs. Consumer preferences and the herd effect drive enterprises to adopt green transformations. Enterprises profit from low-carbon technologies and market-driven mechanisms

Table 6. Formation mechanisms of low-carbon policies and their impact on market dynamics.

Sensitivity analysis for consumer behavior

(1) The impact factor for low-carbon policies on the revenue (θ). Increasing θ from 0.8 to 1.6 shows that consumer preferences remain largely unchanged as θ rises (Fig. 6(c)). In the context of China's carbon market, where consumers are not yet direct participants, they remain insensitive to carbon market benefits. The government

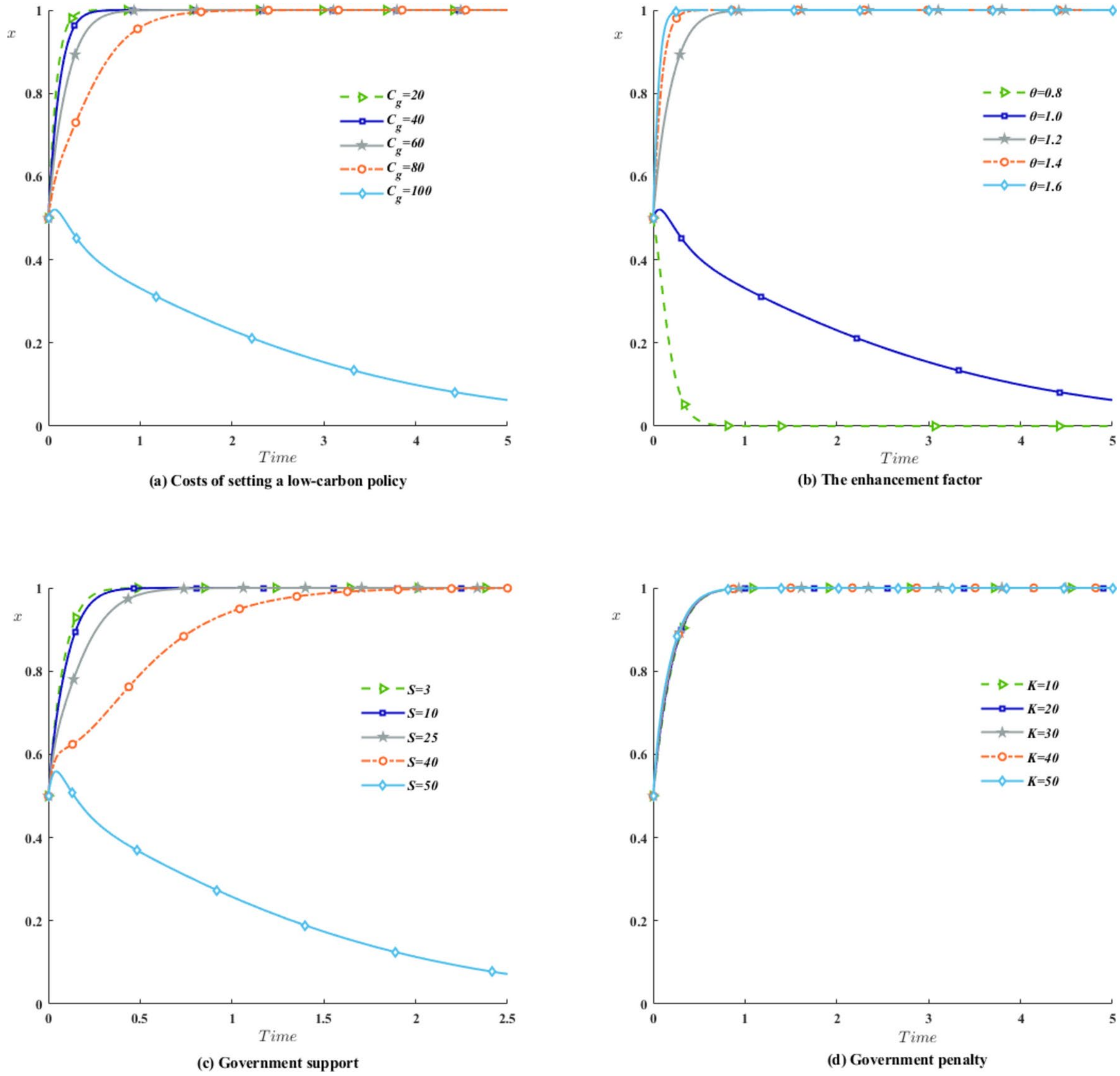

Fig. 5. Sensitivity Analysis for Government Decision.

should focus on translating carbon market gains into social welfare to increase consumer acceptance, thereby influencing their low-carbon choices.

(2) Intensity of herd effect (α). To examine the sensitivity of the herd effect, α is set at 0.8, 0.7, 0.6, 0.5, and 0.4 (Fig. 6(d)). The results indicate that consumers consistently choose low-carbon preferences if the herd effect exists. However, as the intensity of the herd effect increases, the transition from original preferences to low-carbon preferences slows.

Proposition 4. Consumers will adopt low-carbon preferences if they benefit from the carbon market or if a moderate herd effect exists. In practice, consumer choices in favor of low-carbon products will influence firms' green production decisions due to market dynamics. Additionally, if consumers can participate in carbon trading, their behavior will be further shaped by the herd effect.

Conclusions and Policy proposals

Main conclusions

This study focuses on understanding the dynamic interactions among government policies, enterprise strategies, and consumer preferences in China's carbon trading mechanism. By incorporating consumer behavior, particularly the herd effect, into the analytical framework, it highlights the critical role of demand-side dynamics in shaping market evolution and policy design. The main conclusions are as follows:

(1) Dynamic Interactions and Feedback Mechanism: The interactions among government policies, enterprise strategies, and consumer preferences form a dynamic feedback loop that significantly influences the evolution of the carbon trading system. For example, increasing consumer demand for low-carbon products

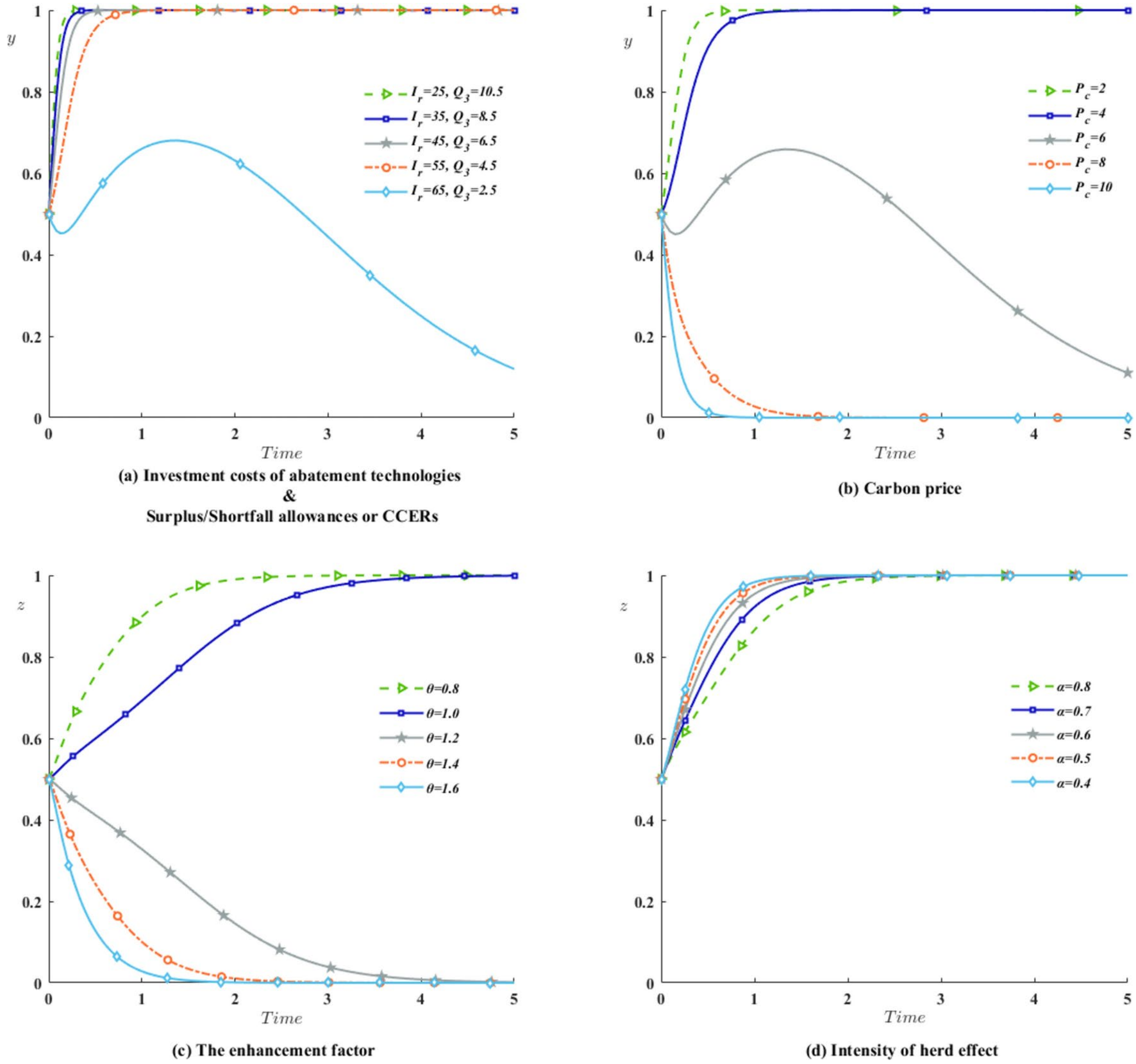

Fig. 6. Sensitivity Analysis for Enterprises and Consumers Actions.

incentivizes enterprises to adopt green transformations, which in turn strengthens government regulation and policy implementation.

(2) Role of Government Regulation and Costs: Active government regulation, supported by effective policies such as subsidies and penalties, is essential for maintaining market stability. However, high regulatory costs can deter government intervention, highlighting the need for innovative mechanisms like market stability reserves (MSR) to optimize regulatory efficiency.

(3) Limited Impact of Carbon Prices on Enterprises: While carbon prices influence enterprise behavior, their impact is less significant compared to factors like investment costs for emission reduction technologies and the availability of carbon allowances. Enterprises are more likely to participate in carbon trading if the ratio of low-carbon investment to benefits is favorable.

(4) Significance of Consumer Behavior: Consumers play a critical role as demand drivers in the carbon trading mechanism. Their low-carbon preferences and herd behavior amplify market dynamics, motivating enterprises to adopt green production practices. Although consumers are not yet direct participants in China's national carbon market, their behavior indirectly shapes policy decisions and market evolution.

(5) Herd Effect as a Key Driver: The herd effect significantly accelerates the adoption of low-carbon consumption, as individuals tend to align their behavior with group norms. Ignoring this effect could lead to underestimating the rapid adoption potential of low-carbon products and the broader implications for market stability.

Building on these findings, future research should focus on three key areas. First, it should explore how consumer participation in carbon trading, such as through individual carbon credits, can further enhance market efficiency. Second, it should investigate the long-term effects of integrating digital tools, such as blockchain and artificial intelligence, into the regulation and transparency of carbon markets. Third, it should examine cross-regional and international coordination mechanisms to improve the scalability and stability of carbon trading systems.

Policy proposals

Based on the conclusions above and the current state of China's national carbon market, the following optimization paths for carbon emission trading mechanisms are proposed from the perspectives of government, enterprises, and consumers:

(1) Government Policy and Guidance: Government engagement in carbon trading directly affects market development and efficiency. The government should establish clear policy objectives and development plans to encourage carbon reduction and low-carbon technology innovation. Policies should prioritize high-emission industries such as steel and cement. For example, Guangdong Province implemented a differentiated quota allocation strategy in the power sector, effectively reducing emissions while balancing economic growth. Similar tailored strategies should address industry-specific challenges and regional disparities.
(2) Regulatory Costs: The government should implement an efficient monitoring, reporting, and verification (MRV) system. Provinces and municipalities should adhere to standardized carbon accounting practices to ensure data accuracy and transparency. Integrating automation and AI technologies, as trialed in Hubei Province, has significantly reduced regulatory costs while improving data accuracy. Additionally, establishing a market stability reserve (MSR) can help balance market supply–demand fluctuations and reduce oversight burdens.
(3) Enterprise Low-Carbon Investment and Benefit Ratio: Enterprises, as the main actors in the carbon market, must consider the costs and benefits of emission reduction. To support participation, the government should provide R&D funding and tax breaks. For example, Zhejiang Province has piloted carbon finance initiatives, providing risk-sharing mechanisms to reduce enterprises' upfront costs for low-carbon investments. Policies should also promote carbon capture and storage (CCS) in industries like cement and chemicals, which face higher emission reduction costs.
(4) Carbon Price Stability and Predictability: The stability and predictability of carbon prices are critical for market confidence and long-term investment. While carbon price changes have a limited impact on evolutionary outcomes, the government can stabilize market expectations by implementing price corridors, minimum and maximum price limits, and other measures. Establishing a carbon futures market, as seen in Shanghai's carbon exchange, can mitigate price volatility and enhance market confidence. Integrating quota banking and borrowing systems, along with carbon funds, can further stabilize the market during periods of price shocks.
(5) Consumer Preference for Low-Carbon Products: Consumer demand for low-carbon products drives corporate emission reductions. The government should increase public awareness of climate change through education and provide transparent product carbon footprints via carbon labeling. For example, Guangdong's green consumption subsidy program incentivized low-carbon product adoption, leveraging consumer behavior to amplify market demand. Expanding such initiatives and enhancing social incentives, such as eco-product certifications, can further promote green consumption.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions
All authors contributed to the study conception and design. Conceptualization, methodology and formal analysis were performed by Nanyu Chen, Hongyu He, Yanzhi Zhao. The first draft of the manuscript was written by Nanyu Chen. Article revised by The funding acquisition from Yanzhi Zhao and Hongyu He. All authors have read and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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