Research in International Business and Finance 78 (2025) 102956

Contents lists available at ScienceDirect

Research in International Business and Finance

journal homepage: www.elsevier.com/locate/ribaf

The effects of regulatory mechanism on enterprise carbon reduction policies

Xi Zhang [a], Qingyuan Zhu [a], Petr Hajek [b], Brian Lucey [c], Mohammad Zoynul Abedin [d,*]

[a] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, PR China
[b] Science and Research Centre, Faculty of Economics and Administration, University of Pardubice, Pardubice, Czech Republic
[c] Trinity Business School, Trinity College Dublin The University of Dublin, Dublin 2, Ireland
[d] School of Management, Swansea University, UK

ARTICLE INFO

Keywords:
Regulatory mechanism
Carbon reduction policies
Evolutionary game theory
The public

ABSTRACT

This paper aims to explore the influencing factors for the optimization of regulatory mechanisms in stimulating enterprises' implementation of carbon reduction policies, by establishing an evolutionary game model involving government, enterprises, independent regulators (IR) and the public. Results show that: (1) six equilibrium points exist satisfying stability criteria, including one ideal state where enterprises implement carbon reduction policies under IR supervision with the complementary force from the public, without government subsidizing. (2) Enterprises' positive policy implementation correlates closely with reduced supervision costs and increased economic costs caused by reputational losses, and the reduction in public participation costs can promote enterprises and IR to choose the positive strategy. (3) Enhanced government financial incentives and penalties can facilitate enterprises' carbon reduction implementation. This study evaluates multi-player cost-benefit trade-offs, providing evidenced references for the policy making to optimize the regulatory mechanism in China.

1. Introduction

In recent times, environmental concerns about carbon emission reduction have emerged as a global issue. To address this, tremendous countries and districts, including the United States, EU, China and Japan, have endeavored to achieve sustainable development goals. For effectively dealing with the question of curtailing carbon emissions to enhance environmental quality and foster green economic growth, countries have been introducing a series of low-carbon policies aimed at encouraging innovation and development within domestic enterprises (Jeon et al., 2015). Specifically, China, through the 14th Five-Year Plan, has clarified its aim to achieve low-carbon energy transformation, while accelerating the promotion and application of pollution and carbon reduction technologies, to realize green production and consumption patterns (Hepburn et al., 2021). To realize these targets, the Chinese government has adopted proactive measures to promote the sustainable development, such as encouraging enterprises to engage positively in the carbon trade market, augmenting the innovation of green technology, and utilizing energy-efficient technologies to enhance resource efficiency (Yang et al., 2023). All these approaches can help enterprises to accelerate the pace of reducing energy consumption and carbon emission.

* Corresponding author.
E-mail address: m.z.abedin@swansea.ac.uk (M.Z. Abedin).

https://doi.org/10.1016/j.ribaf.2025.102956
Received 9 January 2025; Received in revised form 10 May 2025; Accepted 11 May 2025
Available online 15 May 2025

However, problems exist. Due to the turbulence in the international energy market (Abedin et al., 2024a), China's energy transition is facing new challenges and uncertainties. Although Chinese government policies have substantially promoted the innovation and development of energy enterprises, there remains imperfections in regulatory frameworks, especially deficient supervision of state-affiliated corporations (Zhang et al., 2014; Bouteska et al., 2024), which has led to delays in the subsidy distribution, the subsidy abuse, and the corporate dishonesty in the process of subsidy issuance, application, and review (Song et al., 2022). In addition, problems need to be solved such as disparities and inequity in the Chinese Carbon Emission Trading System (Chai et al., 2022). Therefore, establishing a sound renewable energy fiscal policy system and strengthening the regulatory system can maximize the utility of fiscal funds in demand-side and stimulate innovative technology advancements in enterprises and research activities, accelerating the pace of reducing carbon emissions (Danish. et al., 2019).

At present, regulators overseeing Chinese energy enterprises mainly include national and local energy authorities, industry associations, and independent third-party testing and certification bodies. Existing studies have shown that Chinese energy regulation suffers from decentralization, lacking sufficient capacity for policy transformation (Wu et al., 2017). Therefore, there are great opportunities for the enhancement in Chinese energy management system and regulatory framework to construct the sustainable energy developing infrastructure (Schuman and Lin, 2012). Public participation has evolved as an important complementary force to Chinese industry supervision. It influences the formulation of government subsidy schemes and oversees regulators' supervision of enterprises' compliance (Tang et al., 2008). Therefore, public participation has become an indispensable part of ensuring the distribution of subsidies and curbing enterprise dishonesty. However, the role of public participation in the implementation of enterprise carbon reduction policies remains an underexplored question. The purpose of this study is to explore the influencing factors for the optimization of regulatory mechanisms in stimulating enterprises' implementation of carbon reduction policies.

This study applies Evolutionary Game Theory (EGT) as its theoretical basis to explore how different stakeholders interact in the implementation of enterprises' carbon reduction policies. Different from the traditional game theory, which assumes that players have complete rationality and the symmetric information (Nash, 1951), EGT holds that all players have the bounded rationality. Through trial-and-error learning, they utilize asymmetries to continuously adjust their strategies, ultimately reaching a state of dynamic equilibrium (Smith, 1984). Furthermore, EGT employs replicated dynamics equations to reflect the dynamic evolutionary paths of stakeholders' strategy adjustments (Weibull, 1997). The long-term tracking of the evolution of different strategies helps to comprehensively assess the positive and negative effects that various policy interventions exert on players, and to determine the equilibrium conditions for the system to converge towards the stable state. The main reason for choosing EGT is that its assumptions are closely in line with the interest conflicts and information gaps that exist among different groups in the real-world carbon reduction policy implementation. Therefore, EGT is used to include the government, enterprises, IR, and the public in a system as four boundedly rational players. It analyzes the interactions through cost-benefit analysis in an environment of information asymmetry and continuously adjusts the strategies based on the thresholds displayed in the system, to finally achieve an evolutionary equilibrium state.

The significance of this study is that it researches the dynamic relationship among multiple stakeholders to broaden the use of evolutionary game theory in the field of carbon reduction policy implementation. In practice, it provides a basis for formulating and optimizing Chinese carbon reduction policies and regulatory mechanisms, which is conducive to Chinese achievement of dual carbon goals. At the same time, it also provides ideas for other countries and regions to implement low-carbon transition strategies. The four-party dynamic perspective provides a new systematic approach for analyzing the sustainable implementation mechanism of carbon reduction policies. The research results will also benefit enterprises to enhance carbon reduction decision-making and promote the role of public engagement in social regulation.

This manuscript explores two main issues. The first is to study the influencing factors that affect the effective implementation of carbon reduction policies by enterprises and explore possible options for establishing an effective regulatory mechanism. The second is to seek the evolutionary stable equilibrium among the government, energy enterprises, IR and the public, and analyze the optimal strategy choices among stakeholders.

The innovation of this paper lies in introducing the public as a game player to build an evolutionary game model for the four party stakeholders, with a focus on how to improve the cooperative role of public engagement in regulatory mechanisms, enriching the research perspective of traditional regulatory mechanisms. The contributions of this paper are as follows: (1) This manuscript clarifies that stakeholders' cost motivations influence the probability of enterprises' implementing low-carbon practices, while the government's subsidies exert little influence. (2) It finds that public participation could be an complementary force in the regulatory mechanism, by focusing on the analysis of the dynamic impact of public regulatory cost variations. (3) This study establishes a quantitative analysis of enterprise carbon reduction decision-making and regulatory system formation process from the angle of evolutionary game theory to provide theoretical support for policy decision-making.

The remainder of this manuscript is organized below. Section 2 reviews relevant literature. Section 3 clarifies the methodology. Section 4 shows the results and offers a discussion. Section 5 comes to a conclusion.

2. Literature review

The literature review is divided into three subsections to comprehensively evaluate existing studies relevant to the regulatory mechanism on the implementation of enterprise carbon reduction policies. The first subsection reviews the influencing factors, which lays the groundwork for understanding the policy context and governance perspective. The second subsection examines the role of regulatory mechanisms in carbon reduction policy implementation, focusing on the governance dimension. The third subsection introduces evolutionary game theory as the theoretical framework, establishing the methodological approach.

2.1. Influencing factors of carbon reduction policies implementation

A review of the relevant literature reveals that domestic and foreign scholars have primarily examined the determinants influencing the implementation of carbon reduction policies. From the economic perspective, the tax policy can effectively regulate carbon emissions, because the appropriate taxation can avoid the excessive costs incurred by enterprises to reduce emissions (Kuo et al., 2016). Moreover, the carbon trade and environmental subsidies can positively improve enterprises' environmental performance and encourage more investments in innovative technology (Xia, et al., 2025). Additionally, green finance can effectively stimulate enterprises to carry out low-carbon production (Zhao et al., 2024). From the technological standpoint, technological innovation will not be affected by the carbon trading policy (Zhang et al., 2019), moreover, some argued that technological advancements could lower the expenses of carbon reduction and bring long-term and sustainable economic and environmental benefits, therefore enhancing policy incentives (Huisingh et al., 2015). In addition, social factors, such as public attitudes and preferences, will also have an impact on the making and implementation of policies. A high social support co-efficiency and high public participation can promote the popularization and acceptance of policies (Drews and van den Bergh, 2016; Wang et al., 2024).

On another side, scholars have found that government regulation has an incentive effect on the efficient implementation of policies, which in turn can improve the innovative performance of enterprises (Xia, 2022). Differentiated supervision can maximize the effect of human, material and financial resources and promote public participation in supervision (Zhou and Guo, 2022). In summary, these findings emphasize the role of regulation in promoting enterprises' innovation and optimizing resource allocation.

2.2. The Significance of Regulation in Carbon Reduction Policy Implementation

Studies have been conducted by researchers on the regulatory framework for the implementation of carbon reduction policies. The research, especially on OECD countries, pointed out that stricter regulation could enhance the efficiency of carbon reduction when combined with competitive policies (Asane-Otoo, 2016). The regulation called the European Union Emission Trading Scheme can stimulate enterprises to carry out sustainable development strategies (Lazzini et al., 2021). Moreover, specialized low-carbon regulatory departments can improve enterprises' compliance by setting standards and enhancing information disclosure systems (Zhang and Liu, 2020), which is a strong support for improving information spreading in the capital market (Abedin et al., 2024b). In addition, the collaboration between independent regulatory organizations and governments in jointly monitoring subsidies distribution to enterprises can largely standardize the allocation and improve the carbon reduction efficiency (Polzin et al., 2015). Carbon reporting regulation plays a significant role in standardizing enterprises' environmental behavior (Baboukardos et al., 2024). Besides, the enhanced national regulatory quality can standardize the market order and reduce the gaps in trading, which can further lower enterprises' equity costs, making them more competitive in carbon markets (Nasrallah et al., 2025). An effective regulatory mechanism can reconcile the information asymmetry between government and enterprises, further improving the policy execution (Zhang et al., 2022). Moreover, the high level of institutional quality can direct green finance funds to the renewable energy development and energy-saving technology innovation to promote the resource allocation, enhancing overall environmental benefits (Sun et al., 2025).

In the context of international carbon reduction policy practices, the public participation in supervision has played an indispensable role. For instance, researches by British scholars have found that the diversification of the public participation has accelerated the speed of the entire society's low-carbon energy transition (Chilvers et al., 2021). If the public can overcome the "information vacuum" to ensure a high level of participation in community green projects, it will facilitate the implementation of carbon reduction policies (Axon, 2016). In addition, the EU Emissions Trading System has received an increasing attention from the public, which is conducive to the formulation and implementation of relevant carbon reduction policies (Wei et al., 2021). In the United States, the active public participation in the environmental regulation helps to enhance citizens' governance effectiveness and prompt enterprises to increase their environmental awareness, thus having a positive impact on the formulation of the national carbon reduction policy mechanism (Sarzynski, 2015). Additionally, the institutional system in the Philippines provides a solid guarantee for the public participation in environmental governance, and the promotion and engagement of civil society organizations have vigorously promoted the continuous optimization of low-carbon policies (Gera, 2016). Furthermore, the public can collaborate with the public sector to form a collaboration in dealing with environmental issues. La Torre et al. (2024), based on the green finance field of the European public sector, demonstrated the crucial role of the public sector in solving sustainable development challenges, suggesting that the public sector should focus on promoting the implementation of green projects. Therefore, the public participation in the carbon reduction should be identified as a key support for the sustainable environmental governance (Fritz et al., 2024).

2.3. Evolutionary game theory

The regulatory mechanism for carbon reduction policies involves multiple stakeholders, including governments, enterprises, IR, and the public, with different objectives and constraints (Wu et al., 2022). This complex multi-party game environment results in great uncertainty in decision-making. This highlights the need to apply evolutionary game theory modeling in the complex system of carbon reduction regulation. Adopting an evolutionary game theory framework can simulate the decision-making patterns exhibited by various stakeholders in the information asymmetric environment, reveal the complex strategic interaction mechanism, and provide a theoretical basis for policy formulation (Yu et al., 2022).

Numerous researchers have utilized EGT to explore how government policies influence carbon reduction interactions among various stakeholders. Jamali et al. (2022) applied EGT to study the green transition of the high consumption industries in Iran, finding that government subsidies have a significant impact in promoting the low-carbon transformation of traditional industries. Kang and

Tan (2023), on the basis of EGT, studied the probabilities of the trading entities carrying out carbon reduction transactions in the supply chain, showing that cap and trade regulation has an important function in promoting the low-carbon business activities. Many other scholars have also adopted this theory to explore the issue about how government taxes and subsidies influence decision-making in the electricity and photovoltaic industries in countries such as Iran (Haghighi et al., 2021) and Thailand (Zhu et al., 2022). Lee and Tang (2017) found that the public participation efficiently lowered government regulatory expenses and substantially influenced the formulation of government policies. Yao and Fu (2021) believed that the government's regulatory measures standardized the implementation of industrial poverty alleviation policies. Zhou et al. (2022) designed an evolutionary game model to reveal that higher regulation severity from the government could inhibit environmental polluting behaviors and facilitate the efficient carbon reduction. Wu et al. (2024) employed EGT to assess the effects of different government policies, such as carbon tax and emission trading policy, on the performance of enterprises, showing that the combinations of policies could stimulate the enterprises to fulfill carbon reduction obligations.

However, existing researches have mainly focused on the impacts of government policies and the regulation on enterprises' carbon reduction behaviors, employing two-party or three-party game theory. Few researchers discuss the interactive regulatory mechanism between IR and the public, moreover, the issue of how to adjust different policies to optimize the regulatory mechanism for enterprises' low carbon transformation without government subsidies has not been fully explored. To address this research gap, this study will apply the evolutionary game theory to establish a four-party game model involving the government, enterprises, IR, and the public. By integrating IR and the public into a unified system, this study will analyze the complementary role of the public in the regulatory mechanism, as well as the effects of different variables on the strategic choices of stakeholders and the system's stability with no government subsidies. Based on this, regulatory optimization plans can be proposed, and theoretical and practical insights can be provided to enhance the effectiveness of carbon reduction policies.

3. Methods

3.1. Problem description

The government offers carbon reduction subsidies to enterprises to encourage the research and development of low-carbon technologies as part of their efforts to implement policies aimed at reducing carbon emissions. R&D and innovation of enterprises enabled by the subsidies can bring certain benefits to the government. IR supervises and coordinates the formulation and issuance of government subsidies. The government cooperates with the supervision of IR and provides financial supports. IR also supervises the enterprises and provides guidance. Enterprises respond to the supervision of IR and provide reports. The public plays a supervisory role

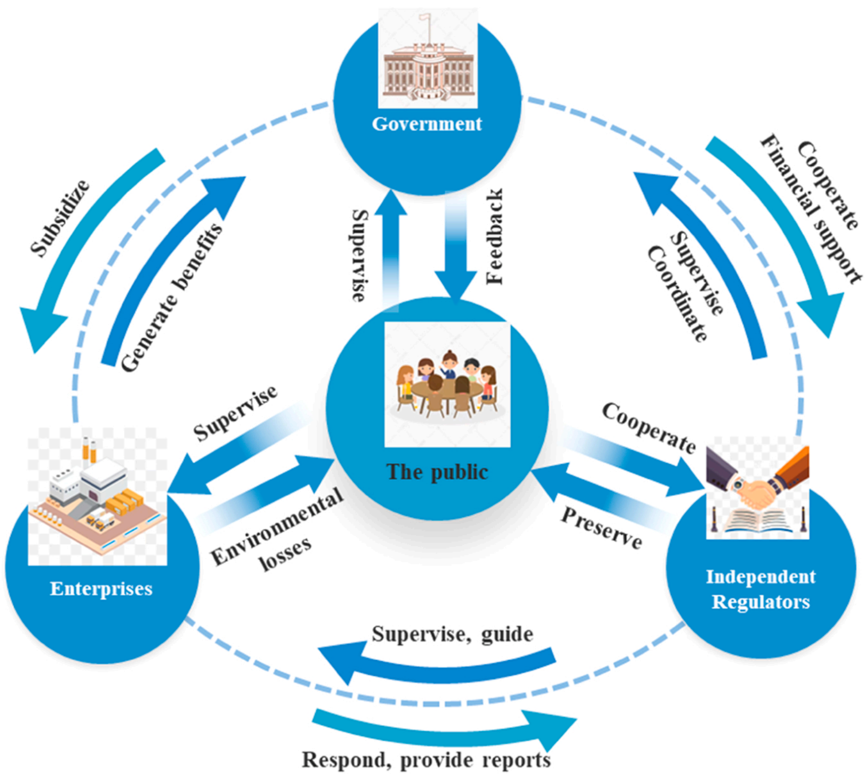

Fig. 1. Evolutionary game dynamics between government, enterprise, IR and the public.

in the formulation of subsidy schemes, which affects government policy making. The government regularly provides feedback to the public and is subject to public scrutiny. The public also supervises the enterprises carbon reduction policy implementation and reports non-compliant production, which causes enterprise reputational losses. The failure of enterprises to adopt low-carbon production practices will result in the public bearing the costs of pollution. The power of the public lies in its cooperation with the supervision of IR, which preserves the rights of public supervision. In evolutionary game theory, the government, enterprises, IR and the public exert mutual influence during the supervision process of carbon reduction policy implementation. Fig. 1 illustrates the evolutionary game dynamics between government, enterprise, IR and the public.

3.2. Assumptions

It is assumed that all the players of the four-party game have bounded rationality, and there is information asymmetry between the subjects. Based on the above basic assumptions, parameter selection and assumptions can be formulated as below:

Assumption 1. : strategy selection and probability. The government strategy set is $U_1 = \{S_1 subsidy; S_2 non-subsidy\}$. Enterprises strategy set is $U_2 = \{I_1 implementation; I_2 non-implementation\}$. IR strategy set is $U_3 = \{R_1 supervision; R_2 non-supervision\}$. The public strategy set is $U_4 = \{P_1 participation; P_2 non-participation\}$. Each of the four players has two strategies to select. The government has a probability of x for selecting the "subsidy" strategy, and a probability of $1-x$ for choosing the "non-subsidy" strategy. Enterprises have a probability of y for adopting the "implementation" strategy, and a probability of $1-y$ for opting for the "non-implementation" strategy. IR has a probability of z for choosing the "supervision" strategy, and a probability of $1-z$ for selecting the "non-supervision" strategy. The public has a probability of q for choosing the "participation" strategy, and a probability of $1-q$ for adopting the "non-participation" strategy, $(x, y, z, q \in [0, 1])$.

Assumption 2. : The government will provide subsidies and tax incentives to promote the carbon reduction activities, therefore the cost for the government is denoted as C_1. Meanwhile, the cost C_2 will be generated by the government for carrying out the environmental governance, which consists of technologies and manpower investment. When enterprises conduct the positive strategy, they should consider the expenses of the technology upgrading, therefore, the cost is denoted as C_3. Conversely, the cost for enterprises' choosing the negative strategy is C_6. Based on the regulatory cost theory (Stigler, 1971), the cost of regulation includes administrative expenses for maintaining regulatory agencies and executing regulatory tasks, as well as losses in social and economic welfares, thus we denote the cost for IR conducting supervision as C_4. For example, the Ministry of Ecology and Environment of China has established an online carbon emission monitoring system to oversee high carbon emitting enterprises such as thermal power plants. In this process, IR have invested significant funds to carry out integrated monitoring, which serves as real-world proof of C_4. Similarly, the public participating in supervision and reporting on enterprises' passive carbon production behaviors will lead to a cost C_5. For example, the Blue Map app developed by the Institute of Public and Environmental Affairs have tracked the environmental performances of nearly 20 million enterprises, and the public can use this app to access statistics and report to the official platforms. However, this APP requires continuous data updates, which will incur corresponding public supervision costs. Moreover, if enterprises select the negative strategy, they will be penalized by the government as F_1. Also, IR will be penalized for its inaction represented by F_2, which will lead to increased costs. This can be illustrated by the Chinese laws that if an energy regulatory agency neglects its duties, the higher authorities will order it to rectify and impose administrative sanctions on the responsible personnel.

Assumption 3. : The government can gain economic benefits B_1 brought by the carbon tax and the carbon trading market when enterprises actively implement policies to reduce carbon emission. Enterprises can gain benefits B_3 by positively participating in carbon trading activities and applying for government subsidies. Conversely, the income from enterprises' passive carbon reduction is denoted as B_4, which is obtained by cutting down the operating costs. Furthermore, the economic benefits obtained by enterprises can be allocated into improving the public welfare, which can be regarded as the public benefit B_2.

Assumption 4. : The government will use policy tools to motivate enterprises, IR and the public to participate in the carbon reduction activities positively. Therefore, when enterprises choose the active policy implementation strategy, they will be given financial incentives from the government M_1 to better support their low carbon transition. Similarly, financial supports from the government will be provided to IR for maintaining the independent operation, which is denoted as M_2. The reward M_3 from the government will be given to the public for their effective supervision and reporting, to form a cooperative regulation mechanism.

Assumption 5. : The public will take the environmental losses D_1 due to enterprises' failure to control carbon emissions, which is the reflection of negative environmental externalities (Picazo-Tadeo, 2009). According to the estimation from the World Bank, the losses caused by the environmental pollution account for approximately 10 % of China's GDP. Specifically, the excessive emissions of pollutants from energy enterprises have aggravated air pollution, leading to a rise in medical costs and a decline in the quality of the labor force. By contrast, the public distrust D_4 will be caused by IR failure to supervise enterprises' negative behaviors, leading to a decrease in enterprises' profits. This is the reflection of internalizing the externality. One example is that the international voluntary carbon market, due to the lack of effective regulatory review and supervision, has seen a large number of low-quality carbon credits flooding into the market, which has led to a decrease in market trading activities. This shows that the absence of regulatory supervision can lead to a decline in public trust towards carbon market transactions, resulting in huge economic losses. The reputational losses to enterprises D_2 will occur by IR supervision of exposing the environmentally harmful production. Enterprises should bear the reputational losses D_3 when the public supervises and discovers their passive implementation of policies.

The major parameters and their meanings are shown in Table 1. And Table 2 displays the payoff matrix.

3.3. Replicated dynamic equations construction

3.3.1. Replicated dynamic equation of the government

E_{11} stands for the anticipated benefit of the government's positive strategy. E_{12} stands for the anticipated benefit of the government's passive strategy. E_1 stands for the average anticipated benefit.

$$\begin{aligned}E_{11} &= yzq(B_1 - C_1 - M_1 - M_2) + (1-y)zq(C_1 - C_2 - M_2 - M_3)\\ &+yz(1-q)(B_1 - C_1 - M_1 - M_2) + (1-y)z(1-q)(C_1 - C_2 - M_2)\\ &+y(1-z)q(B_1 - C_1 - M_1) + (1-y)(1-z)q(C_1 - C_2 - M_3)\\ &+y(1-z)(1-q)(B_1 - C_1 - M_1) + (1-y)(1-z)(1-q)(C_1 - C_2)\end{aligned} \tag{1}$$

$$\begin{aligned}E_{12} &= yzq(B_1 - M_2) + (1-y)zq(-C_2 - M_2 - M_3)\\ &+yz(1-q)(B_1 - M_2) + (1-y)z(1-q)(-C_2 - M_2)\\ &+y(1-z)q(B_1) + (1-y)(1-z)q(-C_2 - M_3)\\ &+y(1-z)(1-q)(B_1) + (1-y)(1-z)(1-q)(-C_2)\end{aligned} \tag{2}$$

$$E_1 = xE_{11} + (1-x)E_{12} \tag{3}$$

The government strategy's replicated dynamic equation is calculated as

$$F_{(x)} = \frac{dx}{dt} = x\left(1-x\right)[C_1 - yM_1 - 2yC_1] \tag{4}$$

3.3.2. Replication dynamic equation of enterprises

E_{21}stands for the anticipated benefit of the enterprises' positive strategy. E_{22} stands for the anticipated benefit of the enterprises' passive strategy. E_2 stands for the average anticipated benefit.

$$\begin{aligned}E_{21} &= xzq(B_3 - C_3 + M_1) + xz(1-q)(B_3 - C_3 + M_1) + x(1-z)q(B_3 - C_3 + M_1)\\ &+(B_3 - C_3 + M_1)x(1-z)(1-q) + (B_3 - C_3)(1-x)zq + (B_3 - C_3)(1-x)z(1-q)\\ &+(B_3 - C_3)(1-x)(1-z)q + (B_3 - C_3)(1-x)(1-z)(1-q)\end{aligned} \tag{5}$$

$$\begin{aligned}E_{22} &= xzq(B_4 - C_6 - D_2 - D_3 - F_1) + xz(1-q)(B_4 - C_6 - D_2 - F_1)\\ &+x(1-z)q(B_4 - C_6 - D_3 - F_1) + x(1-z)(1-q)(B_4 - C_6 - F_1)\\ &+(1-x)zq(B_4 - C_6 - D_2 - D_3 - F_1) + (1-x)z(1-q)(B_4 - C_6 - D_2 - F_1)\\ &+(1-x)(1-z)q(B_4 - C_6 - D_3 - F_1) + (1-x)(1-z)(1-q)(B_4 - C_6 - F_1)\end{aligned} \tag{6}$$

$$E_2 = yE_{21} + (1-y)E_{22} \tag{7}$$

Enterprises strategy's replicated dynamic equation is calculated as

$$F_{(y)} = \frac{dy}{dt} = y(1-y)(B_3 - B_4 - C_3 + C_6 + F_1 + qD_3 + zD_2 + xM_1) \tag{8}$$

Table 1
Parameters and Meanings.

Parameters	Meaning
C_1	The cost for the government of facilitating carbon reduction activities.
C_2	The cost for the government of performing environmental governance.
C_3	The cost for enterprises of actively implementing carbon reduction policies.
C_4	The cost for IR of conducting supervision.
C_5	The cost incurred by the public in engaging in supervisory actions.
C_6	The cost for enterprises of not implementing carbon reduction production.
B_1	The environmental benefit for the government (when enterprises implement the policies).
B_2	Environmental benefits for the public from enterprises controlling carbon emissions.
B_3	The self-benefit gained by enterprises from carbon reduction production.
B_4	The economic benefit obtained by enterprises' passive implementation of the policy.
M_1	The financial incentives provided by the government to enterprises' active carbon reduction.
M_2	The financial support from the government for the operation of IR.
M_3	The reward offered by the government to the public for supervision and reporting.
D_1	Environmental losses to the public caused by enterprises' failure to control carbon emissions.
D_2	Reputational losses to enterprises through supervision by IR.
D_3	Reputational losses to enterprises when the public supervises production.
D_4	The public distrust caused by IR failure to supervise enterprise behaviors.
F_1	The government fines levied on enterprises for its negative implementation.
F_2	The penalties for IR's inaction.

Table 2
Payoff matrix.

Strategy selection		Public	Government			
			Subsidy *x*		Non-subsidy *1-x*	
			Enterprises' Implementation *y*	Enterprises non-implementation *1-y*	Enterprises implementation *y*	Enterprises non-implementation *1-y*
, Independent Regulators (IR)	Supervision *z*	Participation *q*	$B_1 - C_1 - M_1 - M_2$, $B_3 - C_3 + M_1$, $-C_4 + M_2$, $B_2 - C_5$	$C_1 - C_2 - M_2 - M_3$, $B_4 - C_6 - D_2 - D_3 - F_1$, $-C_4 + M_2$, $-C_5 + M_3 - D_1$	$B_1 - M_2$, $B_3 - C_3$, $-C_4 + M_2$, $B_2 - C_5$	$-C_2 - M_2 - M_3$, $B_4 - C_6 - D_2 - D_3 - F_1$, $-C_4 + M_2$, $-C_5 + M_3 - D_1$
		non-participation *1-q*	$B_1 - C_1 - M_1 - M_2$, $B_3 - C_3 + M_1$, $-C_4 + M_2$, B_2	$C_1 - C_2 - M_2$, $B_4 - C_6 - D_2 - F_1$, $-C_4 + M_2$, $-D_1$	$B_1 - M_2$, $B_3 - C_3$, $-C_4 + M_2$, B_2	$-C_2 - M_2$, $B_4 - C_6 - D_2 - F_1$, $-C_4 + M_2$, $-D_1$
	Non-supervision *1-z*	Participation *q*	$B_1 - C_1 - M_1$, $B_3 - C_3 + M_1$, $-F_2 - D_4$, $B_2 - C_5$,	$C_1 - C_2 - M_3$, $B_4 - C_6 - D_3 - F_1$, $-F_2 - D_4$, $-C_5 + M_3 - D_1$	B_1, $B_3 - C_3$, $-F_2 - D_4$, $B_2 - C_5$	$-C_2 - M_3$, $B_4 - C_6 - D_3 - F_1$, $-F_2 - D_4$, $-C_5 + M_3 - D_1$
		non-participation *1-q*	$B_1 - C_1 - M_1$, $B_3 - C_3 + M_1$, $-F_2$, B_2	$C_1 - C_2$, $B_4 - C_6 - F_1$, $-F_2$, $-D_1$	B_1, $B_3 - C_3$, $-F_2$, B_2	$-C_2$, $B_4 - C_6 - F_1$, $-F_2$, $-D_1$

3.3.3. Replication dynamic equation of IR

E_{31} stands for the anticipated benefit of IR positive strategy. E_{32} stands for the anticipated benefit of IR passive strategy. E_3 stands for the average anticipated benefit.

$$\begin{aligned} E_{31} &= xyq(M_2 - C_4) + x(1-y)q(M_2 - C_4) \\ &+(1-x)yq(M_2 - C_4) + (1-x)(1-y)q(M_2 - C_4) \\ &+xy(1-q)(M_2 - C_4) + x(1-y)(1-q)(M_2 - C_4) \\ &+(1-x)y(1-q)(M_2 - C_4) + (1-x)(1-y)(1-q)(M_2 - C_4) \end{aligned} \tag{9}$$

$$\begin{aligned} E_{32} &= xyq(-F_2 - D_4) + x(1-y)q(-F_2 - D_4) \\ &+(1-x)yq(-F_2 - D_4) + (1-x)(1-y)q(-F_2 - D_4) \\ &+xy(1-q)(-F_2) + x(1-y)(1-q)(-F_2) \\ &+(1-x)y(1-q)(-F_2) + (1-x)(1-y)(1-q)(-F_2) \end{aligned} \tag{10}$$

$$E_3 = zE_{31} + (1-z)E_{32} \tag{11}$$

IR strategy's replicated dynamic equation is calculated as

$$F_{(z)} = \frac{dz}{dt} = z(1-z)(F_2 - C_4 + M_2 + qD_4) \tag{12}$$

3.3.4. Replication dynamic equation of the public

E_{41} stands for the anticipated benefit of the public positive strategy. E_{42} stands for the anticipated benefit of the public passive strategy. E_4 stands for the average anticipated benefit.

$$\begin{aligned} E_{41} &= xyz(B_2 - C_5) + x(1-y)z(M_3 - C_5 - D_1) \\ &+(1-x)yz(B_2 - C_5) + (1-x)(1-y)z(M_3 - C_5 - D_1) \\ &+xy(1-z)(B_2 - C_5) + x(1-y)(1-z)(M_3 - C_5 - D_1) \\ &+(1-x)y(1-z)(B_2 - C_5) + (1-x)(1-y)(1-z)(M_3 - C_5 - D_1) \end{aligned} \tag{13}$$

$$\begin{aligned} E_{42} &= xyzB_2 + x(1-y)z(-D_1) \\ &+(1-x)yzB_2 + (1-x)(1-y)z(-D_1) \\ &+xy(1-z)B_2 + x(1-y)(1-z)(-D_1) \\ &+(1-x)y(1-z)B_2 + (1-x)(1-y)(1-z)(-D_1) \end{aligned} \tag{14}$$

$$E_4 = qE_{41} + (1-q)E_{42} \tag{15}$$

The public strategy's replicated dynamic equation is calculated as

$$F_{(q)} = \frac{dq}{dt} = q(1-q)(M_3 - yM_3 - C_5) \tag{16}$$

3.4. Stability analysis of strategies

3.4.1. Equilibrium points

Lyapunov's first stability theorem (Cong et al., 2015) essentially states that, for a given equilibrium point, if there exists a situation where at the equilibrium point, all the eigenvalues have negative real part, then the equilibrium point is stable and constitutes an ESS (evolutionarily stable strategy). ESS refers to a state where most individuals in a population adopt a specific strategy, making it impossible for a small number of mutants with alternative strategies to invade (Smith and Price, 1973). In a multi-party evolutionary game, a stable solution is required to be a strict Nash equilibrium, which in turn must be a pure strategy (Wang et al., 2021). When $F_{(x)} = F_{(y)} = F_{(Z)} = F_{(q)} = 0$, there are 16 pure strategic equilibrium solutions of the equations. They are $E_1(0,0,0,0)$, $E_2(0,1,0,0)$, $E_3(0,0,1,0)$, $E_4(0,1,1,0)$, $E_5(1,0,0,0)$, $E_6(1,1,0,0)$, $E_7(1,0,1,0)$, $E_8(1,1,1,0)$, $E_9(0,0,0,1)$, $E_{10}(0,1,0,1)$, $E_{11}(0,0,1,1)$, $E_{12}(0,1,1,1)$, $E_{13}(1,0,0,1)$, $E_{14}(1,1,0,1)$, $E_{15}(1,0,1,1)$, $E_{16}(1,1,1,1)$. Based on the replicated dynamic system constructed by formulas 1–16, the Jacobian matrix J is constructed as:

$$J = \begin{pmatrix} \frac{\partial f(x)}{\partial x} & \frac{\partial f(x)}{\partial y} & \frac{\partial f(x)}{\partial z} & \frac{\partial f(x)}{\partial q} \\ \frac{\partial f(y)}{\partial x} & \frac{\partial f(y)}{\partial y} & \frac{\partial f(y)}{\partial z} & \frac{\partial f(y)}{\partial q} \\ \frac{\partial f(z)}{\partial x} & \frac{\partial f(z)}{\partial y} & \frac{\partial f(z)}{\partial z} & \frac{\partial f(z)}{\partial q} \\ \frac{\partial f(q)}{\partial x} & \frac{\partial f(q)}{\partial y} & \frac{\partial f(q)}{\partial z} & \frac{\partial f(q)}{\partial q} \end{pmatrix} = \begin{pmatrix} J_{11} & x(1-x)(-2C_1-M_1) & 0 & 0 \\ y(1-y)M_1 & J_{22} & y(1-y)D_2 & y(1-y)D_3 \\ 0 & 0 & J_{33} & z(1-z)D_4 \\ 0 & q(1-q)(-M_3) & 0 & J_{44} \end{pmatrix} \tag{17}$$

And

$$J_{11} = (1-2x)[C_1 - yM_1 - 2yC_1]$$

$$J_{22} = (1-2y)(B_3 - B_4 - C_3 + C_6 + F_1 + D_3t + D_2z + M_1x)$$

$$J_{33} = (1-2z)(F_2 - C_4 + M_2 + D_4q)$$

$$J_{44} = (1-2q)(M_3 - M_3y - C_5)$$

3.4.2. Stability condition analysis

We bring E_1-E_{16} into Equation (17), to obtain the eigenvalues of the equilibrium and judge their positive or negative values. See Table 3. Since $C_1 > 0$, $C_1 + M_1 > 0$, $C_5 > 0$, Based on the signs of the real parts, 6 stable points can be obtained, which are $E_2(0,1,0,0)$, $E_4(0,1,1,0)$, $E_5(1,0,0,0)$, $E_7(1,0,1,0)$, $E_{11}(0,0,1,1)$, $E_{13}(1,0,0,1)$, $E_{15}(1,0,1,1)$.

3.4.2.1. Situation 1. When the stability conditions $-C_5 < 0$, $-C_1 - M_1 < 0$, $F_2 - C_4 + M_2 < 0$, $B_4 - B_3 + C_3 - C_6 - F_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_2(0,1,0,0)$, which represents that the government does not subsidize, enterprises implement the carbon reduction policy, IR do not supervise, and the public do not participate in supervision. This situation reflects the cost-effective drive of stakeholders. Specifically, the cost of public participation in supervision must be greater than 0, therefore the public will choose the passive strategy. The government must pay the cost of subsidizing enterprises; thus, the government will also

Table 3
Equilibriums and Eigenvalues.

Equilibrium	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	Eigenvalue λ_4
$E_1(0,0,0,0)$	C_1	$M_3 - C_5$	$F_2 - C_4 + M_2$	$B_3 - B_4 - C_3 + C_6 + F_1$
$E_2(0,1,0,0)$	$-C_5$	$-C_1 - M_1$	$F_2 - C_4 + M_2$	$B_4 - B_3 + C_3 - C_6 - F_1$
$E_3(0,0,1,0)$	C_1	$M_3 - C_5$	$C_4 - F_2 - M_2$	$B_3 - B_4 - C_3 + C_6 + D_2 + F_1$
$E_4(0,1,1,0)$	$-C_5$	$-C_1 - M_1$	$C_4 - F_2 - M_2$	$B_4 - B_3 + C_3 - C_6 - D_2 - F_1$
$E_5(1,0,0,0)$	$M_3 - C_5$	$-C_1$	$F_2 - C_4 + M_2$	$B_3 - B_4 - C_3 + C_6 + F_1 + M_1$
$E_6(1,1,0,0)$	$C_1 + M_1$	$-C_5$	$F_2 - C_4 + M_2$	$B_4 - B_3 + C_3 - C_6 - F_1 - M_1$
$E_7(1,0,1,0)$	$M_3 - C_5$	$-C_1$	$C_4 - F_2 - M_2$	$B_3 - B_4 - C_3 + C_6 + D_2 + F_1 + M_1$
$E_8(1,1,1,0)$	$C_1 + M_1$	$-C_5$	$C_4 - F_2 - M_2$	$B_4 - B_3 + C_3 - C_6 - D_2 - F_1 - M_1$
$E_9(0,0,0,1)$	C_1	$C_5 - M_3$	$D_4 - C_4 + F_2 + M_2$	$B_3 - B_4 - C_3 + C_6 + D_3 + F_1$
$E_{10}(0,1,0,1)$	C_5	$-C_1 - M_1$	$D_4 - C_4 + F_2 + M_2$	$B_4 - B_3 + C_3 - C_6 - D_3 - F_1$
$E_{11}(0,0,1,1)$	C_1	$C_5 - M_3$	$C_4 - D_4 - F_2 - M_2$	$B_3 - B_4 - C_3 + C_6 + D_2 + D_3 + F_1$
$E_{12}(0,1,1,1)$	C_5	$-C_1 - M_1$	$C_4 - D_4 - F_2 - M_2$	$B_4 - B_3 + C_3 - C_6 - D_2 - D_3 - F_1$
$E_{13}(1,0,0,1)$	$C_5 - M_3$	$-C_1$	$D_4 - C_4 + F_2 + M_2$	$B_3 - B_4 - C_3 + C_6 + D_3 + F_1 + M_1$
$E_{14}(1,1,0,1)$	C_5	$C_1 + M_1$	$D_4 - C_4 + F_2 + M_2$	$B_4 - B_3 + C_3 - C_6 - D_3 - F_1 - M_1$
$E_{15}(1,0,1,1)$	$C_5 - M_3$	$-C_1$	$C_4 - D_4 - F_2 - M_2$	$B_3 - B_4 - C_3 + C_6 + D_2 + D_3 + F_1 + M_1$
$E_{16}(1,1,1,1)$	C_5	$C_1 + M_1$	$C_4 - D_4 - F_2 - M_2$	$B_4 - B_3 + C_3 - C_6 - D_2 - D_3 - F_1 - M_1$

adopt the passive strategy. IR will receive government penalties for non-supervision, that is, the cost of not implementing the positive strategy is lower than that of implementing supervision. The high expenses of supervision by IR prevents it from gaining benefits. Therefore, IR will adopt the non-supervision strategy. For enterprises, the profits from not controlling carbon emissions after deducting penalties for passive implementation are lower than the profits from implementing low-carbon policies. It indicates that penalties for passive implementation have affected enterprises' profits. Therefore, from the perspective of gaining profits, enterprises will still positively carry out carbon reduction policies without the supervision of IR or the public. The conditions of Situation 1 reflect the cost-and benefit connection of various players in the system under certain circumstances, as well as the interactions among the government, enterprises, IR and the public.

3.4.2.2. Situation 2. When the stability conditions $-C_5 < 0$, $-C_1 - M_1 < 0, C_4 - F_2 - M_2 < 0, B_4 - B_3 + C_3 - C_6 - D_2 - F_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_4(0,1,1,0)$, which represents that the government does not subsidize, enterprises implement carbon reduction policy, IR supervise, and the public do not participate in supervision. This situation indicates that public participation in supervision will definitely incur costs, leading to the public choosing the passive strategy. The government also incurs the expense of subsidizing; thus, it chooses the strategy of not implementing carbon reduction subsidies. Although IR needs to bear certain costs, the costs can be compensated by the government's funds. Moreover, the punitive measures from government can incentivize IR to carry out its supervisory duties. Therefore, IR will choose the supervision strategy. If enterprises do not control carbon emissions, they will need to bear reputational losses caused by IR supervision and penalties imposed by the government, resulting in net income less than that with the implementation strategy. As a result, enterprises will opt to implement the carbon reduction policy. Situation 2 illustrates how the four parties form a coordinated and stable state through a cost-benefit exchange mechanism under different policy environments, to ensure the successful execution of carbon policy objectives.

3.4.2.3. Situation 3. When the stability conditions $M_3 - C_5 < 0$, $-C_1 < 0, F_2 - C_4 + M_2 < 0, B_3 - B_4 - C_3 + C_6 + F_1 + M_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_5(1,0,0,0)$, which represents the government subsidizes, enterprises do not implement carbon reduction policy, IR do not supervise, and the public do not participate in supervision. In this state, public participation in supervision may be nonexistent due to the higher costs involved compared to the government rewards offered. The expense of IR supervision is higher than the penalties for choosing the passive strategy, together with the financial support provided by the government. Thus, IR lack the motivation to select the positive strategy. In addition, the profits of enterprises not choosing carbon reduction policy are higher than those of choosing low-carbon production, even excluding government fines. That is, the net income of enterprises' positive strategy is less than that of the passive strategy, with relative net income less than 0. From the perspective of the principle of revenue maximization, enterprises should choose the passive strategy. In this situation, although the government carries out carbon reduction subsidies, it is difficult to promote multi-party participation due to the inability to effectively control costs. High costs cause the demotivation of IR and public participation, as well as the lack of internal motivation for enterprises to implement policies, therefore the system has fallen into an undesirable state of inertia (Tang et al., 2021).

3.4.2.4. Situation 4. When the stability conditions $M_3 - C_5 < 0, -C_1 < 0, C_4 - F_2 - M_2 < 0, B_3 - B_4 - C_3 + C_6 + D_2 + F_1 + M_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_7(1,0,1,0)$, which represents that the government subsidizes, enterprises do not implement the carbon reduction policy, IR supervise, and the public do not participate. Under these conditions, the government's incentive for increased public participation is less than the public's supervision cost, which means the public's net benefit from supervision is negative. Therefore, the public have no motivation to select the strategy of participation. The cost of supervision paid by IR minus the government funds is lower than the penalties for IR inaction. Since the actual expenditure on supervision is lower than the penalties for adopting the passive strategy, IR will have a tendency to choose the supervision strategy. The net income of enterprises choosing not to implement the strategy is still higher than that from implementing, even after deducting reputational losses and government penalties caused by supervision. That is, the net income for enterprises choosing the passive strategy minus the net income for choosing the positive strategy is greater than 0, with a relative net income greater than 0. Based on the principle of revenue maximization, enterprises should select a negative strategy. Therefore, when the government offers subsidies, IR, stimulated by government policy incentives, will choose to positively supervise. However, enterprises and the public will opt for negative strategies due to net incomes. Situation 4 shows how each player will choose the strategy driven by cost-effectiveness, forming a stable but suboptimal equilibrium point.

3.4.2.5. Situation 5. When the stability conditions $C_5 - M_3 < 0, -C_1 < 0, F_2 - C_4 + D_4 + M_2 < 0, B_3 - B_4 - C_3 + C_6 + F_1 + D_3 + M_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_{13}(1,0,0,1)$, which represents that the government subsidizes, enterprises do not implement the carbon reduction policy, IR do not supervise, and the public participate in supervision. Under this situation, the public's rewards received from the government for reporting outweigh the expenses for engaging in supervision, indicating the public's net income from participation is greater than 0. Therefore, the public will choose a positive strategy. Due to the fact that the external cost generated by the passive strategy is lower than the internal costs by the positive strategy, IR will adopt the non-supervision strategy. Excluding various costs and losses that may occur during policy implementation, the net income for enterprises choosing the positive strategy minus choosing the passive one is less than 0, with a relative net income less than 0. As a result, enterprises will adopt the passive strategy. The equilibrium point under Situation 5 is a reflection of the cost-effectiveness motivation of the government, IR, enterprises and public in different policy environments.

3.4.2.6. Situation 6. When the stability conditions $C_5 - M_3 < 0$, $-C_1 < 0$, $C_4 - D_4 - F_2 - M_2 < 0$, $B_3 - B_4 - C_3 + C_6 + F_1 + D_2 + D_3 + M_1 < 0$ are met, the only asymptotically stable equilibrium point is $E_{15}(1,0,1,1)$, which represents that the government subsidizes, enterprises do not implement the carbon reduction policy, IR supervise, and the public participate in supervision. As in Situation 5, due to the fact that the reward offered by the government for public reporting surpasses their expenses, the public will opt for the strategy of participation. The internal cost incurred by supervising enterprises is lower than the negative externalities such as penalties and reputational losses incurred by non-supervision, therefore, IR will select the strategy of supervision. Even if enterprises are penalized and endure reputational losses for not implementing the policy, opting for the passive strategy still results in a higher net income compared to choosing the positive strategy. Consequently, enterprises will not implement the strategy. Under these conditions, the government subsidy cannot generate direct returns. The interests of various players cannot be coordinated due to cost factors, leading to the system forming an unideal state.

4. Results and discussion

From a theoretical perspective, the importance of stability points analysis lies in the fact that we choose the stable point of $E_4(0,1,1,0)$ because it is an idealized equilibrium state, where enterprises will actively implement carbon reduction policies without the government subsidy, under IR supervision, while avoiding excessive public intervention. Analyzing this stable point can help us understand how to optimize regulatory mechanisms to incentivize enterprises' reduction, which is of great significance for alleviating government financial burdens and formulating efficient policies. In addition, this stability point also indicates that public participation can function as a complementary force. This provides guidance for adjusting the intensity and approaches of public participation in regulation, contributing to reducing social costs and achieving effective resource allocation.

In practical application, stability point analysis reveals how various stakeholders interact and form equilibrium strategies under different parameter changes in the implementation of carbon reduction policies. Under specific conditions, the government, enterprises, IR and the public will each select the optimal strategy to maximize their own benefits. As time evolves, various parties continuously adjust their strategies, and the system will ultimately reach an ideal stable state. Once this stable mode is formed, we can predict the long-term strategic trends of stakeholders based on this stable point, providing support for the policy formulation. In the real world, by constructing and improving regulatory frameworks, we can motivate enterprises to actively implement emission reduction policies and stimulate the cooperation among all stakeholders to achieve environmental goals, even without direct economic incentives from the government.

4.1. Results

From the above analysis, it can be seen that in the case where the stability conditions are satisfied, $E_4(0,1,1,0)$ (the government does not subsidize, enterprises implement carbon reduction policy, IR supervise, the public do not participate in supervision) becomes the ideal state. The four parties can form beneficial interactions by enterprises implementing the positive carbon reduction strategy, under the active supervision of IR, even without government subsidies or excessive participation of the public. We assign values to the parameters to dynamically analyze the evolutionary game process and change the key parameters to analyze their different effects on the system.

4.1.1. Initial settings

Initially, we set the probability of government providing subsidy as x_0, the probability of enterprises implementing low-carbon policy as y_0, the probability of IR conducting supervision as z_0, and the probability of the public participating as q_0, $x_0 = 0.5$, $y_0 = 0.5$, $z_0 = 0.5$, $q_0 = 0.5$. Based on the reasonable estimations, we give numerical values to $C_1 = 20$, $C_2 = 15$, $C_3 = 8$, $C_4 = 3$, $C_5 = 5$, $C_6 = 12$, $B_1 = 10$, $B_2 = 16$, $B_3 = 12$, $B_4 = 22$, $M_1 = 18$, $M_2 = 2$, $M_3 = 5$, $D_1 = 10$, $D_2 = 3$, $D_3 = 6$, $D_4 = 7$, $F_1 = 5$, $F_2 = 6$. Fig. 2 displays the initial state and the paths.

Fig. 2(a) shows that, to begin with the initial probabilities, the ESS for the government, enterprises, IR and the public are passive, positive, positive and passive, respectively, verifying the equilibrium point $E_4(0,1,1,0)$. The reason for this equilibrium is that considering potential negative externalities, the government's convergency speed towards the passive strategy accelerates, and its strategic choice tends to be stable at $t = 0.2$. Before $t = 0.15$, the speed of enterprises evolving towards the positive strategy is higher than that of IR towards the positive strategy. However, as regulatory intensity increases, the convergency speed of enterprises slows down but continues evolving towards the stable state. Considering the rising participation costs, the public's strategy evolves towards non-participation, but the convergency speed was relatively slow, gradually reaching the stable state at $t = 1$. Through iterations, the expected returns of the four parties reach a consistent equilibrium balance, forming the stable state of $E_4(0,1,1,0)$.

Then we set the initial probabilities of the government, enterprises, IR and the public as $x_0 = 0.1, 0.2, 0.5, 0.9$, $y_0 = 0.1, 0.2, 0.5, 0.9$, $z_0 = 0.1, 0.2, 0.5, 0.9$, $q_0 = 0.1, 0.2, 0.5, 0.9$, respectively. Fig. 2(b1), Fig. 2(b2), Fig. 2(b3), and Fig. 2(b4) display the impacts of initial probability changes on paths. It can be seen that the higher the initial probability is, the faster enterprises and IR converge towards the positive strategy, while the lower the initial probability is, the faster government and the public converge towards the negative strategy. Specifically, if $x_0 = t_0 = 0.1$, the government and the public display the quickest convergency speeds towards the negative strategic selection. If $y_0 = z_0 = 0.9$, enterprises and IR show the fastest paces of converging to the positive strategy. And Fig. 2 (c) is 3D evolutionary paths of the players evolving towards $E_4(0,1,1,0)$ under the initial settings, which verifies the results of the theoretical analysis. It shows that different initial values of x_0, y_0, z_0, q_0 will make the system finally evolve towards $E_4(0,1,1,0)$. This

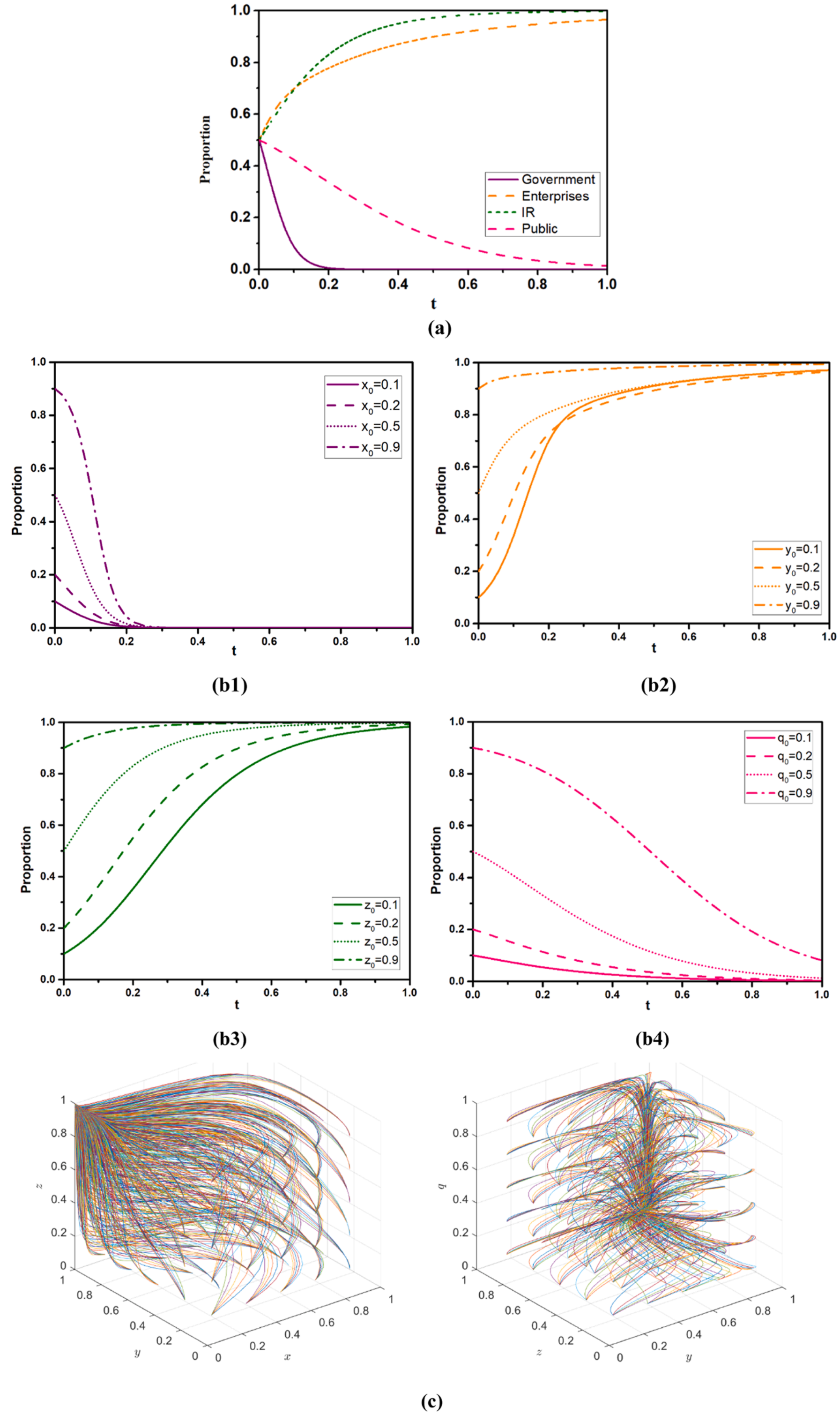

Fig. 2. (a) Initial state of the system, (b1) $x_0 = 0.1, 0.2, 0.5, 0.9$,(b2) $y_0 = 0.1, 0.2, 0.5, 0.9$, (b3) $z_0 = 0.1, 0.2, 0.5, 0.9$, (b4) $q_0 = 0.1, 0.2, 0.5, 0.9$ (c)3D evolution paths of the system.

reveals that if there is only one ESS in the system, the alterations of initial values have no impact on the outcome of the system, while just affect the speeds at which players reach the stable point.

4.1.2. The effects of parameter alternations on stability

Firstly, the impact of government subsidy intensity changes will be analyzed. We set the values of $M_1 = 2$ and $M_1 = 30$, and their evolutionary paths are shown in Fig. 3(a) and Fig. 3(b), respectively. Fig. 3(c) depicts the overall evolutionary paths of the players, and it is evident that when $M_1 = 2, 18, 30$, for enterprises and IR, both their curves converge to 1, and the convergence rate of enterprises increases as the value of M_1 goes up. But the curves of IR almost overlap. This suggests that the increasing value of the government financial incentives obviously encourages enterprises to choose the positive strategy, and also exerts a positive but minimal effect on the strategic choice of IR. In contrast, for the government and the public, their convergency rates accelerate towards the negative strategies with the rising value of M_1, which indicates that the higher the government financial incentive is, the larger possibilities the government and the public choose the negative strategy. This is because if financial incentives prove to be effective in stimulating enterprises' carbon reduction, there will be less need for the government to provide additional subsidies to enterprises. Therefore, higher financial incentives prompt the government to provide no subsidies, quickening the speed of the government evolving toward the passive strategy. Because of enterprises' good performance in carbon reduction, the public does not need to provide additional supervision. So the public tend to choose non-participation strategy as the government financial incentives rise. Based on this, it can be concluded that the government financial incentives should be increased to facilitate enterprises' carbon reduction activities.

Secondly, we set the values of $C_3 = 2$ and $C_3 = 12$, and their evolutionary paths are shown in Fig. 4(a) and Fig. 4(b), respectively. And the overall evolutionary paths of the players are depicted in Fig. 4(c). It is clear that, for enterprises and IR curves at $C_3 = 2, 8$, all continue to converge towards 1, but the evolutionary processes exhibit a relatively slower convergence towards the positive strategy. What should be pointed out is that when the value of C_3 reaches a certain threshold, like 12, it will alter enterprises' convergency path towards the negative strategy and totally change the equilibrium state. This indicates that higher policy implementation cost will damage the willingness of enterprises to choose the positive strategy. At this stage, the curves of IR, at values of 8 and 12, show overlapped paths, which displays that the exceedingly high carbon reduction cost for the enterprises will trigger an increase in regulation expenses, eventually dampening the enthusiasm of IR choosing the positive strategy. By contrast, though the curves of the public and the government still evolve towards 0, the convergences occur at much slower paces with the increasing value of C_3. This shows that the rising implementation cost for enterprises will decrease the possibility of the government and the public choosing the negative strategy. This is because the government will seek the balance between the subsidy provision and the carbon reduction, thus slowing down the pace of adopting the non-subsidy policy. The public will take more consideration into supervision to ensure the interest of themselves, which also decreases their non-participation strategic selection. In conclusion, to prevent C_3 from exerting a negative effect on the players reaching the equilibrium points, the value should be decreased.

Thirdly, the impact of reputational losses will be analyzed. We set the value of D_2 to 1.5 and 10, and their evolutionary paths are shown in Fig. 5(a) and Fig. 5(b), respectively. The reputational loss D_3 of the enterprise caused by public supervision is set to 0.5 and 15, as shown in Fig. 5(c) and Fig. 5(d). In Fig. 5(e), the curves for enterprises at $D_2 = 1.5, 3, 10$ converge towards 1 at an increasing pace, and those curves for IR also evolve to 1, but display in overlapped paths. This suggests that the rise in enterprises' reputational losses caused by IR supervision accelerates the speeds at which enterprises select the positive strategy. But it has no obvious effect on the convergency speeds of IR in choosing the supervision strategy. This can be explained by the fact that the enterprises' economic income will be reduced due to the reputational losses, which is the major driving force for their accelerating paces to choose the positive carbon reduction strategy. For the public and the government, as D_2 changes from 1.5 to 10, their tendencies to move towards negative strategies become more pronounced, with a more rapid acceleration in the convergence rate. In conclusion, enterprises' reputational losses caused by IR supervision should be enhanced to prompt the system to move towards the equilibrium state. Fig. 5(f) displays the similar evolutionary paths of the four players, which are brought about by the changes in D_3. We can come to the conclusion that higher reputational losses caused by the public supervision have a positive influence on the system evolution towards the equilibrium.

Fourthly, the impact of supervision cost by IR will be analyzed. We set C_4 to 1 and 10, and their evolutionary paths are shown in Fig. 6(a) and Fig. 6(b), respectively. From Fig. 6(c), it can be seen that when $C_4 = 1, 3, 10$, the curves for enterprises converge towards 1, but show a declining speed. Although IR keep evolving toward 1 when $C_4 = 1, 3$, the path alters to converge towards 0 as C_4 reaches the threshold of 10. This demonstrates that rising costs of IR supervision will slow down the paces of enterprises and IR selecting the positive strategy, failing to stimulate enterprises and IR to positively participate in the carbon reduction activity. Moreover, excessively high costs associated with IR supervision could diminish IR enthusiasm, even completely alter its strategic choice to the negative alternative. In contrast, the overlapping curves for the government and the public at $C_4 = 1, 3, 10$ show converging trends towards 0, which indicates that the alterations in IR supervision costs have little influence on the strategic selections of them. Therefore, the cost for IR supervision should be reduced and controlled within a certain range.

Then, the impact of penalties incurred by enterprises' non-implementation of the policy will be analyzed. We set the value of F_1 as 8 and 12, and their evolutionary paths are shown in Fig. 7(a) and Fig. 7(b) respectively. From Figure7(c), the curves for enterprises at $F_1 = 5, 8, 12$ exhibit convergency tendencies towards 1, at an ever-increasing speed. This shows that stricter government penalties increase enterprises' possibility to choose the positive strategy. This is because enterprises will implement the carbon reduction strategy actively to maximize their benefits when faced with the increased non-compliant punishment. The overlapped paths for IR also converge towards 1, indicating a minimal influence of value variations on the IR strategic selection. Nevertheless, such penalties can still incentivize IR to select the positive supervision strategy. By contrast, for F_1 values of 5, 8, and 12, both the public and the government curves converge toward 0, with all convergence rates accelerating. This illustrates that the alterations in the government penalties can affect the convergence speeds of the public and the government, without altering their selections towards the negative strategy. In summary, government penalties on enterprises' non-compliance should be increased to make the system evolve to the equilibrium more quickly and stably.

Finally, the impact of public participation costs will be analyzed. We set C_5 to 0.5 and 20, and the evolutionary paths are displayed in Fig. 8(a) and Fig. 8(b), respectively. In Fig. 8(c), it is clearly observed that curves for enterprises and IR at $C_5 = 0.5, 5, 20$ show convergency trends towards 1, albeit with diminishing speeds. This indicates that the increased public supervision cost can negatively influence the rates at which enterprises and IR evolve, reducing the possibilities of them choosing the positive strategy. By contrast, when C_5 is set to 0.5, the public decelerates the convergency speed towards 0 and exhibits the lowest willingness to select the negative strategy, the situation of which also applies to the government. This indicates that lower public participation costs can slow down the public convergency pace of choosing the non-participation strategy. Due to the increased possibility of the public participating in supervision under lower costs, enterprises will be motivated to choose the positive strategy. And IR will also be encouraged to choose supervision strategy supported by the public complementary force. This demonstrates that variations in the public participation cost can obviously affect the stability equilibrium. Whether the cost is too high or too low, it can hinder players' speeds from moving towards the optimal strategy. In conclusion, the public cost in supervision should be limited in a certain range to ensure the system stability.

4.2. Discussion

This study explores the influencing factors of the regulatory mechanism on the effective implementation of enterprises carbon reduction policies, involving the government, enterprises, IR and the public. According to the simulations, key parameters have

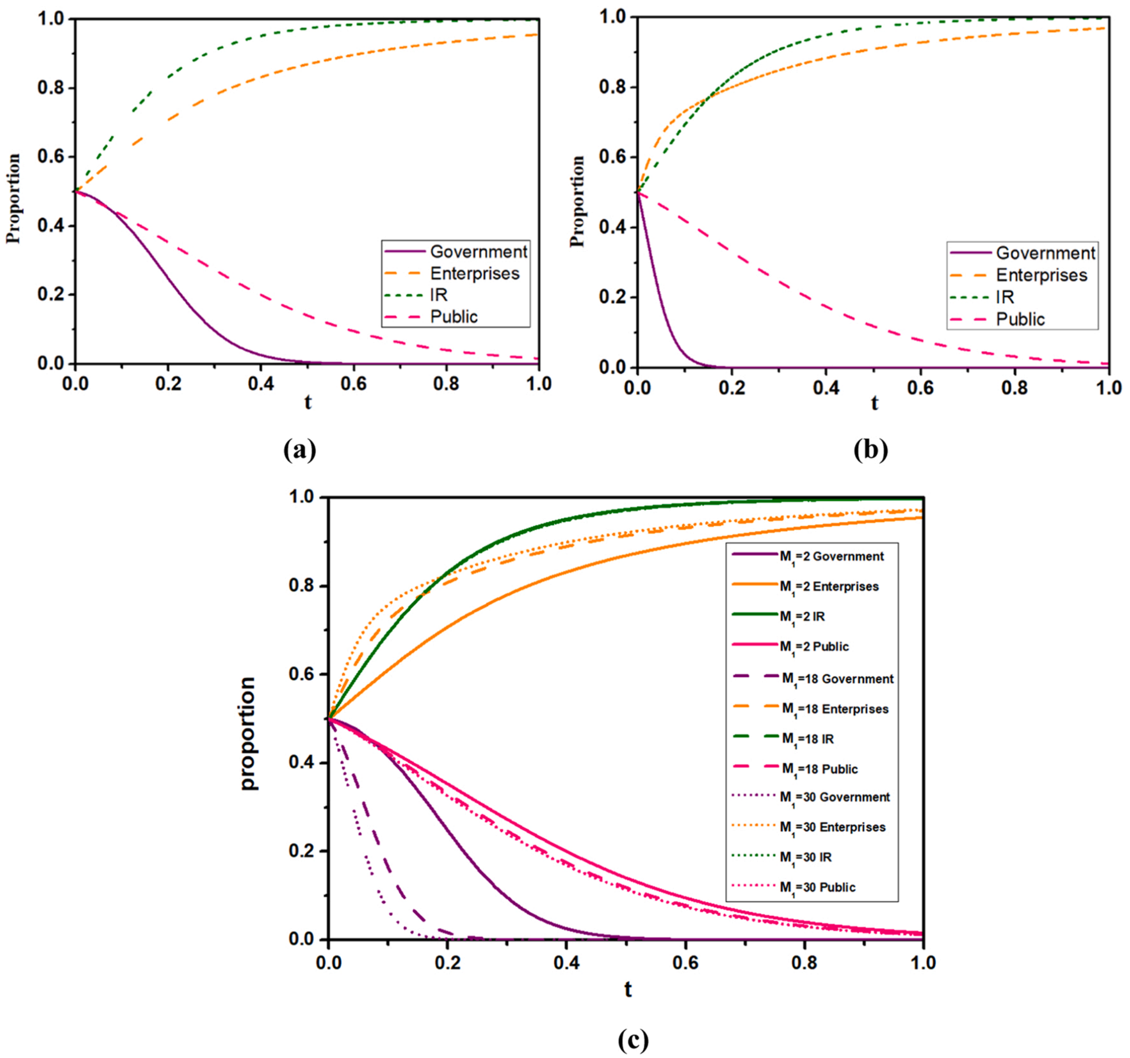

Fig. 3. The Impact of Government Financial Incentives: **(a)** $M_1 = 2$, **(b)** $M_1 = 30$, **(c)** M_1 changes on the equilibrium of the system.

differentially influenced the strategic choices of the players.

Firstly, our study demonstrates that the cost and benefit analysis functions as a major element in enterprises' implementation of carbon reduction policies. Specifically, the increase in the government financial incentives will stimulate enterprises to choose the positive strategy. However, higher financial incentives will speed up the government's willingness to choose non-subsidy strategy. This result differs from previous studies, in which policy factors were typically considered as the main driving force. Furthermore, the possibility of enterprises opting for the positive strategy goes up as the severity of punitive consequences increases. Penalties can regulate enterprises' conduct by compelling technical upgrades, which, in turn, can affect their benefits. Thus, the punishment for enterprises' non-compliance should be moderately strengthened, combined with financial incentives such as tax preferential, to achieve the balance between the regulation and enterprises' profits.

Secondly, rising reputational losses caused by supervision from IR and the public will push enterprises to choose the positive strategy. According to cost-benefit analysis, reputational losses will reduce the enterprises' market share and increase operating costs, leading to a decline in revenues. Therefore, it is necessary to establish a sound regulatory mechanism to increase the cost in reputational losses, thus promoting the carbon reduction compliance of enterprises.

Thirdly, rising costs of IR supervision and the public participation will both dampen enterprises' enthusiasm for selecting the positive strategy. Higher cost of IR supervision will lower their possibility to choose the active strategy but exert no obvious effect on the strategic selection of the public. However, rising cost of the public participation not only quickens the speed of the public adopting the non-participation strategy but also makes IR possibility of choosing the supervision strategy decline. These results show that high supervision costs can lead to passive evolutions of all players, especially the rising public participation cost. Therefore, a cooperative mechanism between IR and the public should be established to make the public a complementary force in the supervision, reducing the

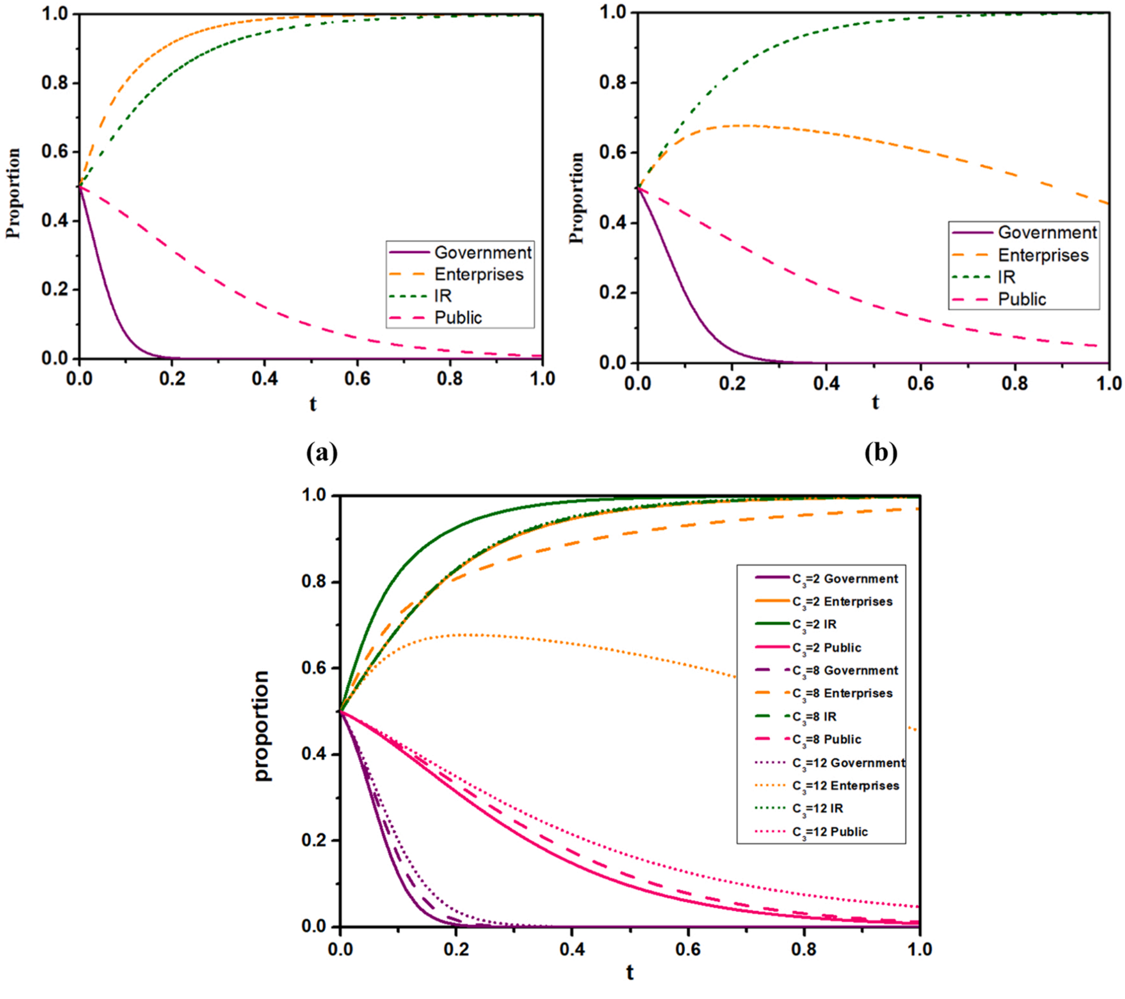

Fig. 4. Impact of Enterprise Costs for Actively Implementing Carbon Reduction Policies: (a) $C_3 = 2$, (b) $C_3 = 12$, (c) C_3 changes on the equilibrium of the system.

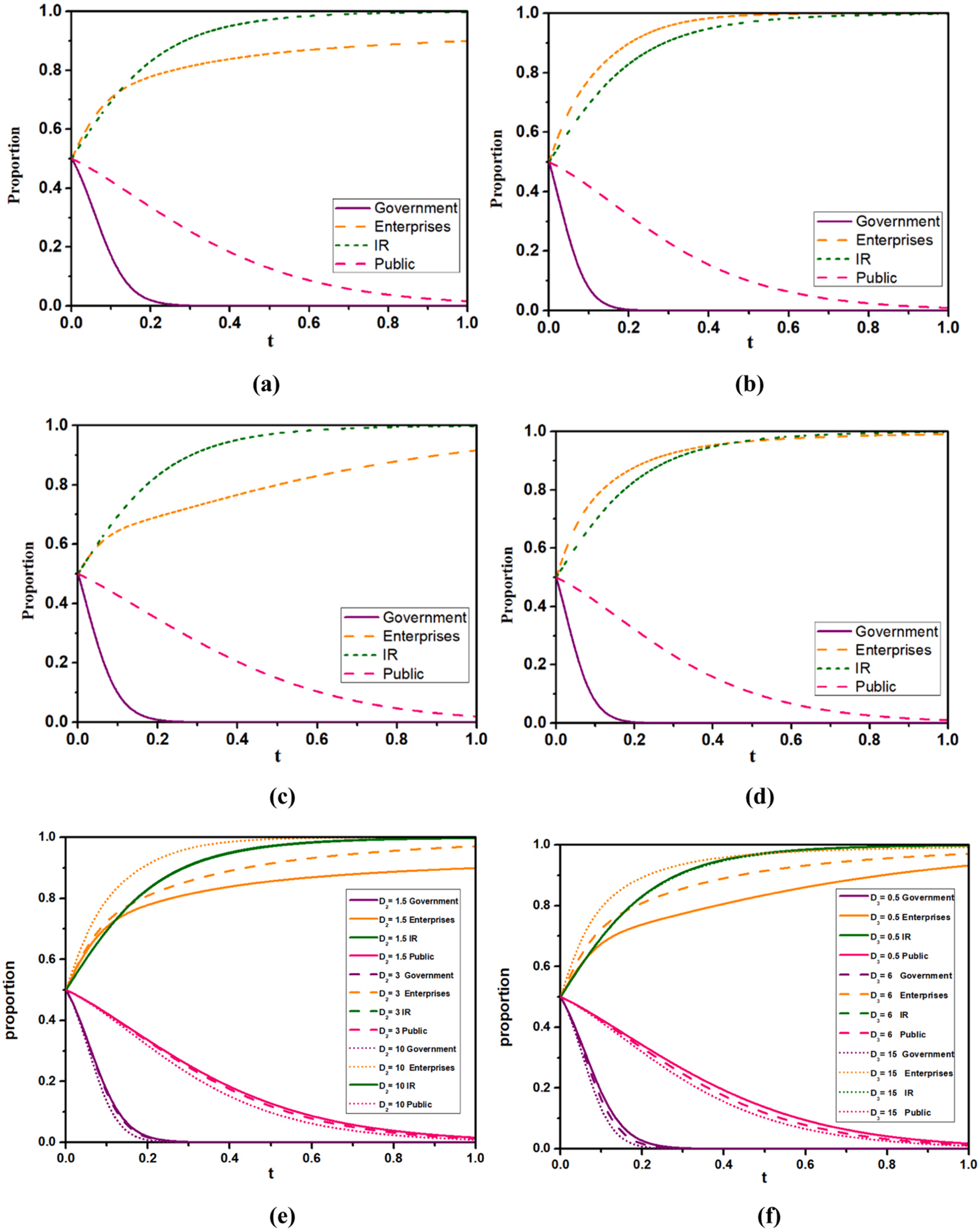

Fig. 5. Impact of reputational loss: (a) $D_2 = 1.5$, (b) $D_2 = 10$,(c) $D_3 = 0.5$, (d) $D_3 = 15$, (e) D_2 changes on the equilibrium of the system; (f) D_3 changes on the equilibrium of the system.

cost in supervision and jointly enhancing the possibility of enterprises actively performing carbon reduction policies.

In conclusion, the selected parameters have significant meanings. The cost rises in IR and the public supervision have negative effects on enterprises' adopting the carbon reduction strategy, deterring the system's evolution towards the ideal state. Increases in financial incentives and penalties have positive effects on enterprises' strategic selection, promoting the system to evolve. Reputational losses caused by IR and the public supervision also have positive influences. Furthermore, the initial willingness of four players have positive effects on their strategic selections towards the equilibrium points. The results indicate that reasonable adjustments of relevant parameters can reduce the cost while boosting the benefits of enterprises' green transformation, thus expediting the carbon reduction policy implementation.

5. Conclusion

This manuscript establishes a four-party evolutionary game model comprising government, enterprises, IR and the public. It examines the influence of key parameters variations on the strategic selections and the stability of the system. Results offer a theoretical support for the regulatory mechanism optimization in China and also provide references for the policy making of other nations' low-carbon development. The conclusions of this manuscript are as follows:

Firstly, there are 16 pure strategy equilibrium points in the system, of which 6 meet the asymptotic stability conditions. The ideal state $E_4(0,1,1,0)$ is the government does not subsidize, enterprises implement carbon reduction policies, IR supervise, and the public does not participate, which can be achieved under the conditions that IR active supervision cost is lower than its government financial support, and the net benefits of enterprises' positive strategy exceed those of passive strategies, taking into account penalties for enterprises' negative strategy and reputational losses caused by IR supervision.

Secondly, reducing regulatory costs is the key to promoting enterprises low-carbon emissions reduction. A decrease in IR supervision costs drives enterprises to choose positive strategies, moreover, the reduction in public participation costs not only promotes enterprises' positive carbon emission, but also encourages active IR supervision, which fully demonstrates the complementary force of the public participation. In addition, enhancing economic costs caused by reputational losses significantly advances the implementation of enterprises' carbon reduction strategies, which indicates that stricter supervision can regulate enterprises' compliant behaviors. Therefore, a collaborative regulatory mechanism between the public and IR should be formed to facilitate a stable situation

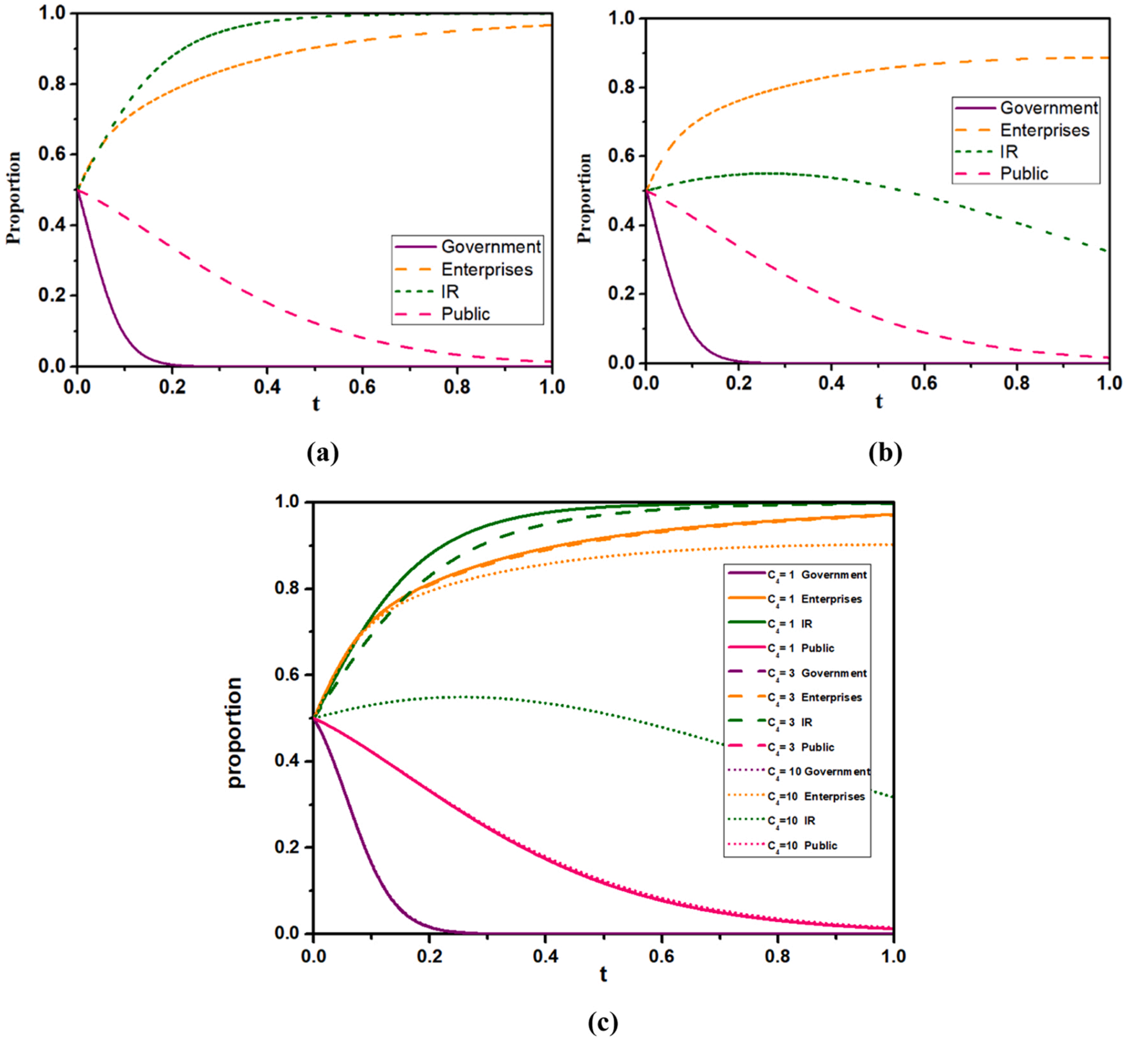

Fig. 6. Impact of supervision cost by IR: (a) $C_4 = 1$,(b) $C_4 = 10$,(c) C_4 changes on the equilibrium of the system.

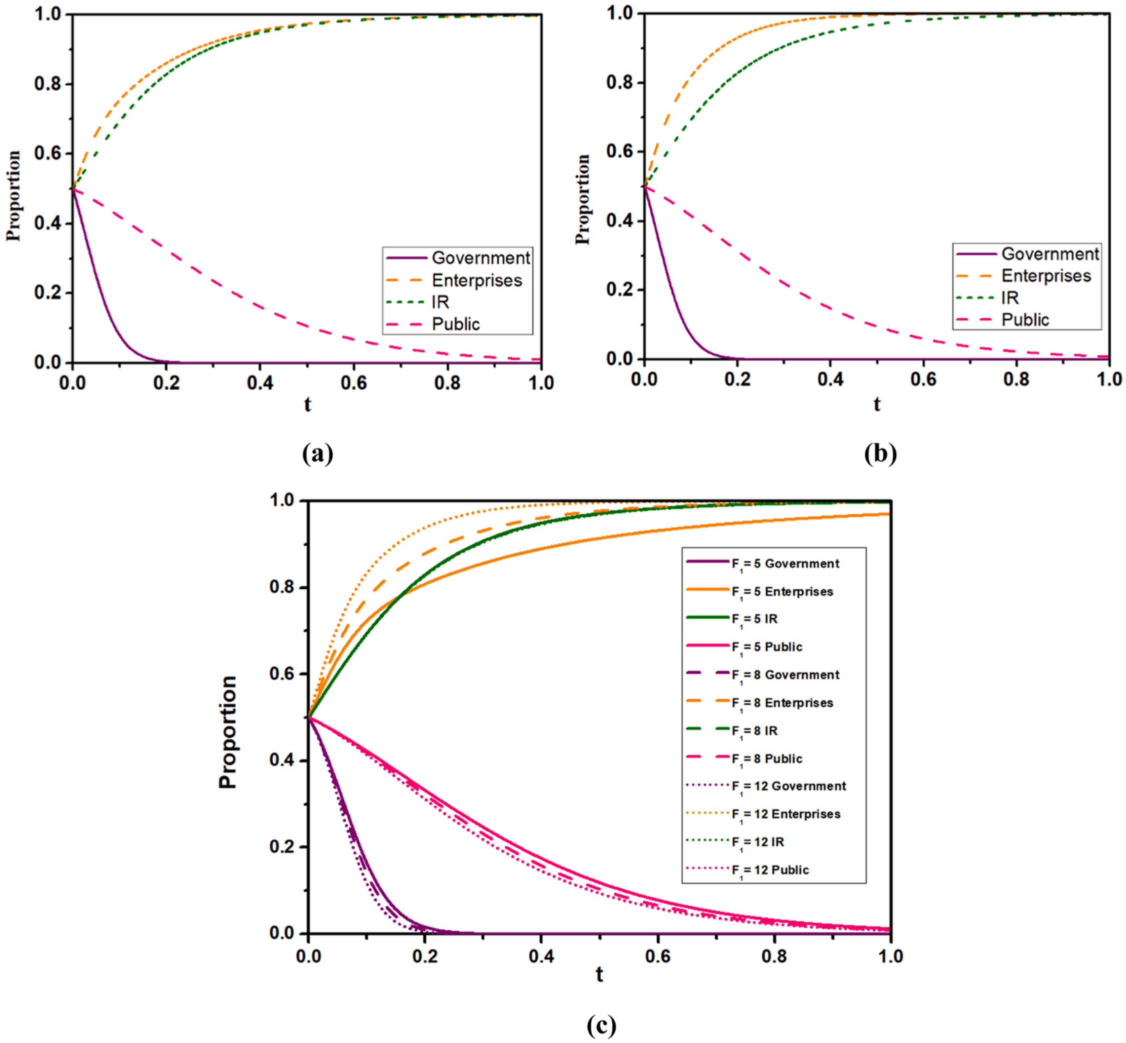

Fig. 7. Impact of penalties incurred by enterprises' non-implementation of the policy: (a) $F_1 = 8$, (b) $F_1 = 12$, (c) F_1 changes on the equilibrium of the system.

where enterprises actively implement low-carbon production without government subsidies, through improving the supervision framework and reducing costs. For example, the big energy data center in Zhejiang Province allows the public and regulatory agencies to view the energy consumption and carbon emission data of enterprises. Under the collaborative supervision, enterprises are motivated to regulate their carbon emissions to enhance their social reputation. This effectively reduces the supervision cost and enhances regulatory efficiency.

Finally, enhanced government financial incentives and penalties can facilitate enterprises' carbon reduction policy implementation. For example, the substantial fines caused by exceeding emissions limits prompted Hefei Iron and Steel Group to invest heavily in product modernization. Such updates enabled low-carbon manufacturing and won the government financial support, making the enterprise a benchmark for green production. Additionally, the initial probability levels of government, enterprises, IR, and the public strategies do not affect the directions of their strategic selection evolution but only affect the time for the system reaching the stable state.

In summary, our study has testified that by optimizing the regulatory mechanism together with dynamic incentives and punishments, the system can achieve the optimal equilibrium without government subsidies.

Based on the conclusions, the policy implications are as follows.

(1) The government should establish a dynamic incentive mechanism. By setting clear indicators to quantify the carbon emissions and cost inputs of enterprises, moderate financial incentives such as tax preferential, and innovation subsidies should be provided to reduce the implementation expenses of enterprises and avoid the excessive financial burden on the government. Furthermore, an increase in the punishment can significantly stimulate enterprises' carbon reduction compliance. Therefore, a

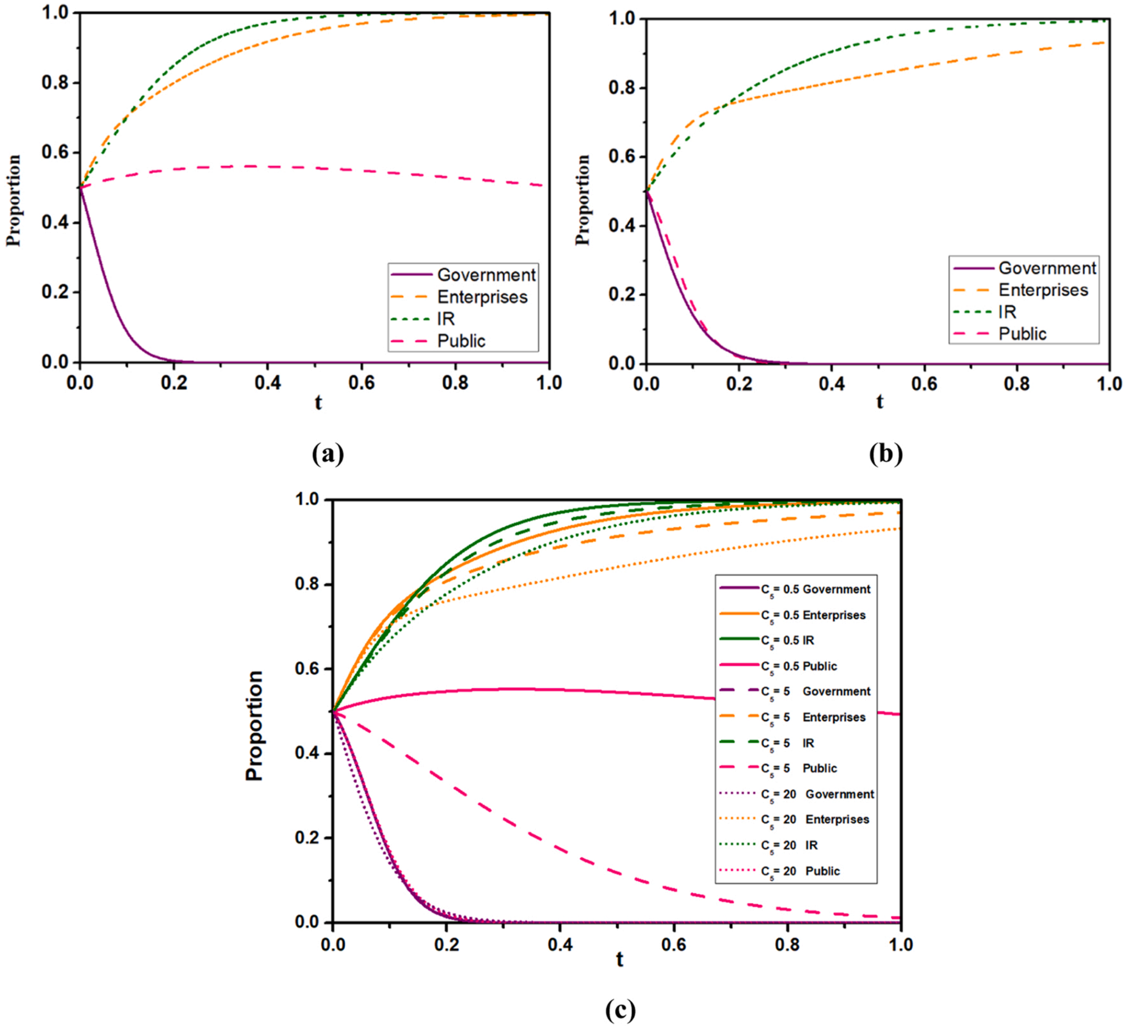

Fig. 8. Impact of public participation cost: (a) $C_5 = 0.5$, (b) $C_5 = 20$, (c) C_5 changes on the equilibrium of the system.

differentiated punishment system should be built based on the enterprises' carbon reduction performance. Specifically, high emission enterprises will be fined heavily and forced to suspend production for rectification. While low emission enterprises should be rewarded and encouraged to continue improving. The above measures can strengthen the government's economic incentives and constraints on enterprises, encouraging them to adopt positive carbon reduction strategies.

(2) An effective interaction mechanism should be built between the public participation and IR to reduce the regulatory costs. Firstly, in areas where traditional energy enterprises gather with high energy consumption, an online digital supervision platform can be established with reporting and information disclosure functions. By integrating the forces of the public and IR, a comprehensive supervision system can be formed to enhance cooperative efficiency, mitigating the supervision cost. Secondly, in regions where renewable energy enterprises such as photovoltaics and wind power develop fast, it is crucial to promote the integration of the green electricity certificate and the carbon trading system and introduce third-party regulatory agencies to ensure that every stage from data generation to transaction completion is under strict supervision. An example is that, in 2024, two new energy enterprises, Ningfeng and Ningyang, in Nanjing, applied for GEC and completed the city's first batch of distributed photovoltaic green power transactions, which was under the effective supervision from regulatory agencies and the public.

(3) Market regulatory measures should be flexibly utilized to optimize the coordination between regulatory agencies and the public. In developed regions, a green carbon emission credit system can be formed to disclose the blacklist of non-compliant enterprises, reducing their reputation among the public and augmenting the losses of violations. In undeveloped areas, regulatory agencies can collaborate with communities to conduct public activities of illegal carbon emissions, enhancing the sensitivity of public supervision. This will make the public participate actively to fill the blind spot in the market regulation. The

first public interest litigation case of ecological compensation for carbon sink subscription in Anhui has functioned as a typical example to raise the public awareness of the environmental and resource protection.

However, limitations exist in this study which should be addressed in future research: (1) This model is built on the bounded rationality of the stakeholders, whereas stakeholders will be guided by subjective factors in the real policy-making process. Therefore, the model and variable settings should fully consider the complex dynamic relationship among game players. (2) The focus of this study remains on carbon reduction, and future research can extend to more fields to increase referencing values. (3) The selection of the main strategy is idealized, and more research should be conducted to explore other strategy combinations. In the future study, introducing dynamics like policy uncertainty would enhance the analysis.

CRediT authorship contribution statement

Mohammad Zoynul Abedin: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Petr Hajek:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Brian Lucey:** Writing – review & editing, Supervision, Conceptualization. **Xi Zhang:** Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Qingyuan Zhu:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Consent for publication

All authors are very positive to publish this manuscript on this journal.

Ethics approval and consent to participate

Not applicable.

Funding

This paper was supported by the Major Program of the National Social Science Foundation of China (Grant No. 23&ZD175), the National Natural Science Foundation of China (Grant Nos. 72173096, 72303139, 71873103).

Declaration of Competing Interest

There is no competing interest among the authors.

Acknowledgements

Mohammad Zoynul Abedin acknowledge the generous support of Global Wales Partnership for funding the project ‘Small Business Decarbonisation Programme’.

Data availability

Data will be made available on request.

References

Abedin, M.Z., Goldstein, M., Huang, Q., Zeng, H., 2024a. Forward-looking disclosure effects on stock liquidity in China: evidence from MD&A text analysis. Int. Rev. Financ. Anal. 95, 103484.
Abedin, M.Z., Goldstein, M., Malhotra, N., Yadav, M., 2024b. Middle East conflict and energy companies: the effect of air and drone strikes on global energy stocks. Financ. Res. Lett. 69, 106009.
Asane-Otoo, E., 2016. Competition policies and environmental quality: empirical analysis of the electricity sector in OECD countries. Energ. Policy 95, 212–223.
Axon, S., 2016. The Good Life": engaging the public with community-based carbon reduction strategies. Environ. Sci. Policy 66, 82–92.
Baboukardos, D., Kopita, A., Ranegaard, C., Demetriades, E., 2024. Carbon reporting regulation: real effects, external pressures, and internal policies. Bus. Strateg. Environ. 33, 4871–4886.
Bouteska, A., Ha, L.T., Bhuiyan, F., Sharif, T., Abedin, M.Z., 2024. Contagion between investor sentiment and green bonds in China during the global uncertainties. Int. Rev. Econ. Financ. 93 (A), 469–484.
Chai, S., Yang, X., Zhang, Z., Abedin, M.Z., Lucey, B., 2022. Regional imbalances of market efficiency in China's pilot emission trading schemes (ETS): a multifractal perspective. Res. Int. Bus. Financ 63, 101758.
Chilvers, J., Bellamy, R., Pallett, H., Hargreaves, T., 2021. A systemic approach to mapping participation with low-carbon energy transitions. Nat. Energy 6, 250–259.
Cong, N., Doan, T., Siegmund, S., Tuan, H., 2015. Linearized asymptotic stability for fractional differential equations. Electron. J. Qual. Theo 2016, 1–13.
Danish, Ulucak, R., Khan, S., Baloch, M., Li, N., 2019. Mitigation pathways toward sustainable development: is there any trade-off between environmental regulation and carbon emissions reduction? Bus. Strateg. Environ. 28, 813–822.
Drews, S., van den Bergh, J., 2016. What explains public support for climate policies? A review of empirical and experimental studies. Clim. Policy 16, 855–876.
Fritz, L., Baum, C., Low, S., Sovacool, B., 2024. Public engagement for inclusive and sustainable governance of climate interventions. Nat. Commun. 15, 4168.

Gera, W., 2016. Public participation in environmental governance in the Philippines: the challenge of consolidation in engaging the state. Land. Use Policy 52, 501–510.
Haghighi, R., Yektamoghadam, H., Dehghani, M., Nikoofard, A., 2021. Generation expansion planning using game theory approach to reduce carbon emission: a case study of Iran. Comput. Ind. Eng. 162, 107713.
Hepburn, C., Qi, Y., Stern, N., Ward, B., Xie, C., Zenghelis, D., 2021. Towards carbon neutrality and China's 14th Five-Year Plan: clean energy transition, sustainable urban development, and investment priorities. Environ. Sci. Ecotechnol. 8, 100130.
Huisingh, D., Zhang, Z., Moore, J., Qiao, Q., Li, Q., 2015. Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling. J. Clean. Prod. 103, 1–12.
Jamali, M., Rasti-Barzoki, M., Khosroshahi, H., Altmann, J., 2022. An evolutionary game-theoretic approach to study the technological transformation of the industrial sector toward renewable electricity procurement: a case study of Iran. Appl. Energ. 318, 119083.
Jeon, C., Lee, J., Shin, J., 2015. Optimal subsidy estimation method using system dynamics and the real option model: photovoltaic technology case. Appl. Energ. 142, 33–43.
Kang, K., Tan, B., 2023. Carbon emission reduction investment in sustainable supply chains under cap-and-trade regulation: an evolutionary game-theoretical perspective. Expert. Syst. Appl. 227, 120335.
Kuo, T., Hong, I., Lin, S., 2016. Do carbon taxes work? Analysis of government policies and enterprise strategies in equilibrium. J. Clean. Prod. 139, 337–346.
La Torre, M., Leo, S., Palma, A., Zapata, J., 2024. Public spending and green finance: a systematic literature review. Res. Int. Bus. Financ 68, 102197.
Lazzini, S., Occhipinti, Z., Parenti, A., Verona, R., 2021. Disentangling economic crisis effects from environmental regulation effects: implications for sustainable development. Bus. Strateg. Environ. 30, 2332–2353.
Lee, H., Tang, C., 2017. Socially and environmentally responsible value chain innovations: new operations management research opportunities. Manag. Sci. 64, 983–996.
Nash, J., 1951. Non-cooperative games. Ann. Math. 54, 286–295.
Nasrallah, N., Khoury, R., Atayah, O., Marashdeh, H., Najaf, K., 2025. The impact of carbon awareness, country-governance, and innovation on the cost of equity: evidence from oil and gas firms. Res. Int. Bus. Financ 73, 102640.
Picazo-Tadeo, A., Prior, D., 2009. Environmental externalities and efficiency measurement. J. Environ. Manag. 90, 3332–3339.
Polzin, F., Migendt, M., Täube, F.A., von Flotow, P., 2015. Public policy influence on renewable energy investments—A panel data study across OECD countries. Energ. Policy 80, 98–111.
Sarzynski, A., 2015. Public participation, civic capacity, and climate change adaptation in cities. Urban. Clim. 14, 52–67.
Schuman, S., Lin, Alvin, 2012. China's renewable energy law and its impact on renewable power in China: progress, challenges and recommendations for improving implementation. Energ. Policy 51, 89–109.
Smith, J., 1984. Game theory and the evolution of behaviour. Behav. Brain. Sci. 7, 95–125.
Smith, J., Price, G., 1973. The logic of animal conflict. Nature 246, 15–18.
Song, D., Jia, B., Jiao, H., 2022. Review of renewable energy subsidy system in China. Energies 15, 7249.
Stigler, G., 1971. The theory of economic regulation. Bell J. Econ. Manag. Sci. 2, 3–21.
Sun, X., Meng, Z., Zhang, X., Wu, J., 2025. The role of institutional quality in the nexus between green financing and sustainable development. Res. Int. Bus. Financ 73, 102531.
Tang, B., Wong, S., Lau, M., 2008. Social impact assessment and public participation in China: a case study of land requisition in Guangzhou. Environ. Impact Asses 28, 57–72.
Wang, H., Chen, L., Liu, J., 2021. An evolutionary game theory analysis linking manufacturing, logistics, and the government in low-carbon development. J. Oper. Res. Soc. 73, 1014–1032.
Wang, X., Han, Y., Shi, B., Abedin, M.Z., 2024. The impacts of green credit guidelines on total factor productivity of heavy-polluting enterprises: a quasi-natural experiment from China, 2025 Ann. Oper. Res 347, 41–68. https://doi.org/10.1007/s10479-024-05973-y.
Wei, Y., Gong, P., Zhang, J., Wang, L., 2021. Exploring public opinions on climate change policy in "Big Data Era"—a case study of the european union emission trading system (EU-ETS) based on Twitter. Energ. Policy 158, 112559.
Weibull, J., 1997. Evolutionary game theory. MIT press.
Wu, X., Liu, P., Wei, Q., 2022. Analysis on evolutionary stability strategies of carbon emission of logistics enterprises based on carbon tax. Math. Probl. Eng. 2021, 9941243.
Wu, X., Liu, P., Yang, L., Shi, Z., Lao, Y., 2024. Impact of three carbon emission reduction policies on carbon verification behavior: an analysis based on evolutionary game theory. Energy 295, 130926.
Wu, J., Zuidema, C., Gugerell, K., Roo, G., 2017. Mind the gap! Barriers and implementation deficiencies of energy policies at the local scale in urban China. Energ. Policy 106, 201–211.
Xia, Y., 2022. The impact of R&D subsidies on firm innovation in different supervision situations: analysis from pharmaceutical companies in China. Technol. Forecast. Soc. 177, 121491.
Xia, X., Li, J., Wei, W., Benkraiem, R., Abedin, M.Z., 2025. Emission reduction levels of manufacturers under carbon trading policies. Energ. Econ. 141, 108111.
Yang, L., Song, S., Liu, C., 2023. Green signals: the impact of environmental protection support policies on firms' green innovation. Bus. Strateg. Environ. 33, 3258–3278.
Yao, H., Fu, J., 2021. Analysis of smooth implementation of Industry Poverty Alleviation considering government supervision. Math. Probl. Eng. 2021, 1–13, 5554595.
Yu, N., Chen, J., Cheng, L., 2022. Evolutionary game analysis of carbon emission reduction between government and enterprises under carbon quota trading policy. Int. J. Env. Res. Pub. He. 19, 8565.
Zhang, H., Li, L., Zhou, D., Zhou, P., 2014. Political connections, government subsidies and firm financial performance: evidence from renewable energy manufacturing in China. Renew. Energ. 63, 330–336.
Zhang, Y., Liu, J., 2020. Overview of research on carbon information disclosure. Front. Eng. Manag 7, 47–62.
Zhang, Y., Shi, W., Jiang, L., 2019. Does China's carbon emissions trading policy improve the technology innovation of relevant enterprises? Bus. Strateg. Environ. 29, 872–885.
Zhang, B., Zhang, B., Di, J., Han, Q., 2022. The strategic behavior of Chinese enterprises using R&D subsidies: game model and empirical research. Appl. Econ. 54, 4187–4202.
Zhao, X., Benkraiem, R., Abedin, M.Z., Zhou, S., 2024. The charm of green finance: can green finance reduce corporate carbon emissions? Energ. Econ. 134, 107574.
Zhou, W., Guo, F., 2022. Precise supervision of enterprise environmental protection behavior based on Boolean Matrix Factorization under low carbon background. Int. J. Env. Res. Pub. He. 19, 7739.
Zhou, K., Wang, Q., Tang, J., 2022. Evolutionary game analysis of environmental pollution control under the government regulation. Sci. Rep. 12, 474.
Zhu, T., Tang, W.H., Wang, W., 2022. Analyzing government subsidies for residential solar photovoltaics poverty alleviation programs using evolutionary game theory. Renew. Sust. Energ. Rev. 152, 111856.