Journal of Building Engineering 89 (2024) 109279

Contents lists available at ScienceDirect

Journal of Building Engineering

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

How to promote carbon emission reduction in buildings? Evolutionary analysis of government regulation and financial investment

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ARTICLE INFO

Keywords:
Carbon emission reduction
Government regulation
Construction enterprises
Market intervention
Evolutionary game
Numerical simulation

ABSTRACT

Buildings account for a significant portion of global carbon emissions, necessitating strategies to accelerate decarbonisation in the construction sector. This research aims to analyse the behavioural strategies and interactions among governments, construction enterprises, and financial institutions in promoting building carbon emission reduction (CER) through an integrated regulatory and market-driven approach. A novel three-party evolutionary game model is developed that incorporates government regulation policies, the profit-driven nature of construction enterprises, and the investment incentives of financial institutions. Numerical simulations using MATLAB were performed to evaluate the dynamic replication and evolutionary stabilities of stakeholder strategies under different scenarios. Residential project M in Beijing was chosen as a realistic environment for simulation and analysis. The results demonstrate that stringent government regulation can incentivize financial institutions to increase their investments in CER initiatives. However, construction enterprises may still resist decarbonisation efforts if the costs outweigh the economic benefits. A two-pronged approach combining "command-and-control" regulation and "market-facilitation" interventions is proposed to effectively align stakeholder interests. This study provides valuable insights into leveraging both regulatory instruments and market-based incentives to drive the transition towards sustainable construction practises. Policy recommendations are offered to create an enabling environment that encourages the active participation of all stakeholders in achieving net-zero emission targets for buildings. The novelty lies in the development of an integrated tripartite evolutionary game framework that coherently captures the dynamics among regulators, industry players, and financial institutions, thus supporting low-carbon policymaking in the construction domain.

1. Introduction

The escalating global challenges of climate change, energy consumption, and environmental degradation are inextricably intertwined with economic growth and urbanisation. At the heart of this intricate web lies the building sector, which is a significant driver of resource depletion, environmental harm, and greenhouse gas emissions fuelled by urban expansion [1,2]. According to a United

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https://doi.org/10.1016/j.jobe.2024.109279
Received 20 August 2023; Received in revised form 12 March 2024; Accepted 9 April 2024
Available online 12 April 2024
2352-7102/

Nations study [3], buildings consume a staggering 36 % of global energy and are responsible for a concerning 37 % of global carbon emissions by 2020. Remarkably, it is anticipated that more than 50 % of global carbon emission reduction (CER) efforts will stem from energy efficiency measures in the construction sector [4,5]. Building CER, therefore, is an intrinsic component of ensuring long-term steady economic growth and a green, healthy environmental development trajectory [6,7]. Consequently, the construction sector is widely regarded as holding the key to achieving long-term CER objectives and sustainable economic growth [8].

Currently, the construction sector's pivotal role in reducing energy consumption and greenhouse gas emissions is garnering significant attention from academia, government agencies, and businesses worldwide [9,10]. However, the growth of CER in buildings is encumbered by several barriers, including a lack of funding [11], inadequate awareness of CER [12], information asymmetry [13], and the availability of CER technologies [14]. To address these obstacles, governments have developed a myriad of regulatory measures aimed at guiding stakeholders in cooperatively promoting the adoption and development of building CER [15,16].

As the architect and enforcer of building CER regulations [17], the government has orchestrated a sequence of regulatory manoeuvres, serving as a guiding compass to oversee and propel the industry towards sustainable practises. This coherent approach aims not only to encourage but also to catalyse construction enterprises into actively implementing CER strategies, leveraging their advantages to the fullest [18]. However, this transition is not without its complexities. In the context of a low carbon-built environment, considering the entire lifecycle of a building, the CER decisions of stakeholders within the construction supply chain are influenced by an intricate interplay of various actors, including financial institutions, developers, consumers, contractors, and building material suppliers.

From the government's perspective, driven by a determination to alleviate cost impediments, thoughtfully devised incentive measures are designed to inspire construction entities to embrace building CER upgrades. This continuous dance of subsidies and penalties creates a conducive environment for enterprises to pursue sustainable growth [19–21].

Simultaneously, construction enterprises find themselves navigating uncharted territories as the constraints imposed by CER add layers of complexity to their management and operational routines. The implementation of CER policies prompts a reassessment of their operational frameworks and decision-making processes. From their standpoint, the more capital generated from the combination of construction income, government incentives, and penalty avoidance, the stronger their motivation to engage in CER initiatives [22]. Moreover, the power of building businesses' CER innovation increases in tandem with the magnitude of government subsidies [23,24].

Additionally, the support of financial institutions has emerged as one of the main factors influencing the development of sustainable construction [25]. These institutions, often viewed as strategic players in profit-seeking games, invest when the promise of building CER is enticing, the government is actively regulating, and construction companies are actively participating [26–28]. However, neither business can survive nor succeed in isolation; both depend on the resources and collaboration of other organisations [29,30]. Financial institutions, as investors in building CER, should also be regarded as incentive targets [31]. When the government extends certain incentives to these institutions, they will actively join the ranks of building CER, continuously promoting its adoption [31].

In reality, the players in the implementation of building CER are impacted by the diversity of needs and the intricate interaction of interests [32]. To investigate how to encourage the autonomous transformation of the building CER industry to sustain its long-term development through the collaborative efforts of these three key stakeholders, this research develops a tripartite evolutionary game model involving the government, financial institutions, and construction enterprises.

Early on in the implementation of building CER, the government offers incentives to pertinent parties to work together to advance building CER's sustainable growth. However, the lack of capital, technology, and talent in the initial building CER industry led to an imbalance in the income and expenditure of construction enterprises [33], which would not adopt CER technology. The implementation of the penalty system was seen as a successful way to lessen people's disobedient behaviour [34]. Wang et al. [35] argued that institutional punishment can be an effective deterrent to disobedient behaviour in businesses. They noted that penalties are frequently present in social and biological systems. The mechanism of punishment strongly encourages cooperation in the long-term evolutionary process, and the consequences of punishment are favourable to all system participants [19]. Including punishment in the incentive mechanism not only successfully reduces the system's volatility but also acts as the best evolutionarily stable strategy (ESS) [36]. While the development of building CER is efficiently promoted when the government provides sufficient subsidies to the interested parties, the government reaps only a certain number of environmental benefits. This research innovatively introduces a feedback subsidy mechanism in which construction enterprises give the government a certain amount of feedback subsidy after the building CER's energy efficiency retrofit becomes profitable, putting the tripartite game system into a positive cycle. However, it is uncertain how these two aspects would affect the evolution of building CERs' behaviour and strategy because few studies have considered their significance.

This study aims to address three objectives by using evolutionary game theory. These objectives are as follows:

(1) To construct and simulate a tripartite evolutionary game model of the government, financial institutions, and construction enterprises to explore how the building CER market can be transformed from a government-led to a tripartite dynamic mechanism to achieve a long-term sustainable and stable strategy for all parties under the premise of considering both government reward and punishment mechanisms and feedback subsidy mechanisms.
(2) To scrutinise the dynamic evolutionary trends of the three participants' strategic interactions and speculate on the dynamic tripartite ESSes of the building CER system under the two-wheel drive mechanism.
(3) To explore the impact of various key coefficients on stakeholder groups, propose targeted measures and recommendations that can be of guidance to policymakers related to building CER, and provide general insights for building CER policy analysis or design.

This research paper is structured as follows:

Section 2: Literature Review-reviews existing literature relevant to this research.

Section 3: Methodology: Tripartite Evolutionary Game Modeling of CER Behavioural Strategies: This section describes a tripartite evolutionary game model that is used to analyse the decision-making processes of government, financial institutions, and construction enterprises with building CER strategies.

Section 4: Simulation Analysis of the impact of important factors on each player's strategy while investigating the model's evolutionary process through numerical simulations. summarizes the results of the numerical simulations and discusses their theoretical and practical application value.

Section 5: Conclusion: This section provides the conclusions of the research and offers implications for stakeholders on how to adopt and build CER strategies.

2. Literature review

2.1. Reward and punishment mechanisms for building the CER

In-depth studies on government incentives and sanctions have recently been conducted by a few researchers. In terms of government subsidies, Chen and Hu [37] found that dynamic bilateral taxes and subsidies have a more pronounced incentive effect on enterprises' emissions reduction technology improvement than static single taxes and subsidies. Sung [23] confirmed a favourable two-way causal relationship between public subsidies and businesses' CER innovations. To study how subsidies affect the root causes of green innovation, Sun et al. [38] devised an evolutionary game theory model. The free-rider effect of suppliers and manufacturers in green innovation is lessened by subsidies within a fair range. In exchange for carbon emission permits, government-funded carbon emission subsidies can entice businesses to invest more and advance their technological innovation in emission reduction [39]. In terms of government penalties, Giri et al. [40] discovered that by providing CER subsidies and penalising excessive carbon emissions, governments can achieve net benefits and reduce environmental pollution. The majority of this research has concentrated on industries involved in production, such as manufacturing, power, and energy.

Current research on the multi-subject behaviour of building CER has focussed on the selection of technologies for building CER [41] or strategies to promote CER under mandatory environmental regulatory policies [42]. From the perspective of building users' energy consumption behaviour, previous studies have focussed on topics such as raising low-carbon awareness and improving behaviour management [43,44]. Few studies have combined government regulation and market support perspectives on the impact of CER behaviour in the building industry. To fulfil building CER targets and reduce energy problems and environmental governance pressures, awareness of construction enterprises' CER behaviours should be actively raised, and regulatory policies should be dynamically adjusted. However, few studies have incorporated feedback subsidies for enterprises into the government subsidy system.

2.2. Analysis of the evolutionary game of building the CER

The extensive association between CER participant subjects has attracted extensive attention from the research community, and the evolutionary game model has been widely used in these studies [45–48]. To promote the development of building CER, Na et al. [49] constructed a two-party evolutionary game model of enterprise and government and a three-party evolutionary game model of enterprise–enterprise–government. A comparative analysis of the models concluded that the behavioural decision of CER was influenced by the joint action of enterprises and government. In their research on the tripartite evolutionary game, Jing et al. [50] constructed a revenue matrix comprising three partners in the construction waste industry chain: the government, construction businesses, and recycling enterprises. They also found that reasonable control of the ratio of fines to subsidies resulted in a positive correlation between construction companies' construction waste recycling and government regulations. By dividing the development stages of GBs into three categories—realisation efficiency, financial efficiency and operational efficiency, He et al. [51] constructed a tripartite evolutionary game model consisting of the government and heterogeneous developers and explored how heterogeneous developers can further achieve the dual goals of carbon emission reduction and economic benefits in the carbon trading mechanism.

A game process can be used to describe the imitation and improvement processes in the dynamic evolution of the government, enterprises, and financial institutions developing the CER system. According to current demands and the industry's progress in developing CER, the government will continuously modify its regulation strategy to maximise environmental benefits in both its own and the businesses' interests. As a strategy to stimulate enterprises to improve their environmental performance, carbon emission restrictions have strong externalities and public interest, which cannot produce direct economic benefits to enterprises. Therefore, it is always an external constraint and a passive implementation strategy for enterprises. In contrast, in the current building CER market, the interaction among stakeholders has gradually become a strategic basis for deepening cooperation, thus facilitating the independent transformation of the CER construction industry. In this process, each subject imitates successful behaviour or calculates the best response to the current population by observing historical information about the success and failure of various options [52]. Thus, over time, each subject chooses a high-return strategy [53]. Evolutionary game theory can systematically explain this dynamic evolution in which parties continuously learn and modify their strategies through interactive observation, imitation, and information gathering under the assumption of limited rationality. Evolutionary game theory predicts the course of the building CER industry by revealing the equilibrium states of stakeholders' strategies and the corresponding stability conditions [54]. Supporting stakeholders' dynamic decision-making is better suited to research on incentive policy optimisation and stakeholder behaviour interaction [55].

From the above literature, it can be said that game theory is mostly used in the current study to create two- or three-party CER strategies. Due to their dynamic features, evolutionary games are a useful tool for stakeholders in the construction industry to establish incentives and study decision-making behaviour [56]. The following drawbacks persist despite certain academic contributions to the study of CER decision-making using evolutionary game theory. First, few studies consider the influence of external financial institutions, which are crucial for creating and constructing CER, and instead only consider two or three stakeholders from the government, developers, contractors, or customers as game objects. Second, even though numerous academics have investigated how government subsidies affect CER, previous subsidy systems have rarely considered the feedback subsidy mechanism from construction enterprises to the government. The premise for this feedback subsidy mechanism is that the government has made substantial upfront investments in the construction industry to promote CER, such as incurring significant costs for raising public and corporate awareness. Initially, the government subsidises construction enterprises to produce and develop CER buildings. As these enterprises generate profits from CER initiatives, they provide feedback subsidies to the government, acknowledging the positive environmental benefits, improved energy efficiency, reduced resource waste, enhanced environmental protection, and reinforced ESG performance facilitated by their CER efforts. While a portion of the construction enterprises' profitability is involved, the feedback subsidies recognise the broader positive impacts their CER behaviour generates for the government, public and society at large. This feedback loop enables a joint effort among stakeholders to drive sustainable development and environmental conservation in the construction industry. Third, little emphasis has been given to CER in the construction sector in prior studies, which have mostly concentrated on industries such as manufacturing and energy. To address these research gaps, by considering the government's reward and punishment system and the feedback subsidy system of construction enterprises, this research aims to construct a novel tripartite evolutionary game model among the government, financial institutions, and construction enterprises to analyse their behavioural strategies and interactions in promoting building CER. It also examines the mutual influence and evolutionary trend of each party.

3. Methodology: Tripartite Evolutionary Game Modeling of CER behavioural strategies

As shown in Fig. 1, the government subsidises financial institutions that have invested in carbon emission reduction in buildings and uses reward and penalty contracts to encourage construction enterprises to reduce carbon emissions. At the same time, financial institutions will also invest in carbon emission reduction in buildings and form a "two-wheel drive mechanism" with the government to jointly promote carbon emission reduction in construction enterprises. This study innovatively introduces a feedback subsidy strategy to the government from construction enterprises that have made profits from carbon emission reduction, so that the three parties can form a joint effort to promote carbon emission reduction in the construction industry and sustainable development of the ecological environment.

In this study, the research question aims to understand how the reward and punishment coefficients and feedback subsidy coefficients of the building CER industry, and the strategic choice behaviour of stakeholders impact the upgrading of the traditional construction industry and the sustainable development of cities. Our hypotheses are as follows:

3.1. Basic assumptions of the model

Hypothesis 1. Each game participant is finite and rational, and all have limited information. As time passes, the game participants make decisions in their favour according to their cognitive ability and the information they have, but eventually, they will determine a stable strategy. Each participant has two strategies. Specifically, the probability that a construction enterprise engages in CER behaviour is x ($0 \leq x \leq 1$), and the probability that a construction enterprise engages in non-CER behaviour is 1-x. Similarly, the probability that a financial institution provides CER behaviour financial services or conventional financial services to a construction enterprise is y ($0 \leq y \leq 1$), and the probability that a financial institution does not invest is 1-y. The probability that the government actively regulates is z ($0 \leq z \leq 1$), and the probability that the government negatively regulates is 1-z. x, y and z are all functions of time t [57].

Hypothesis 2. To promote the development of CER in the construction industry, the government must ensure economic growth, environmental protection, and other social welfare, which represent the government's benefits. "Positive regulation" or "active

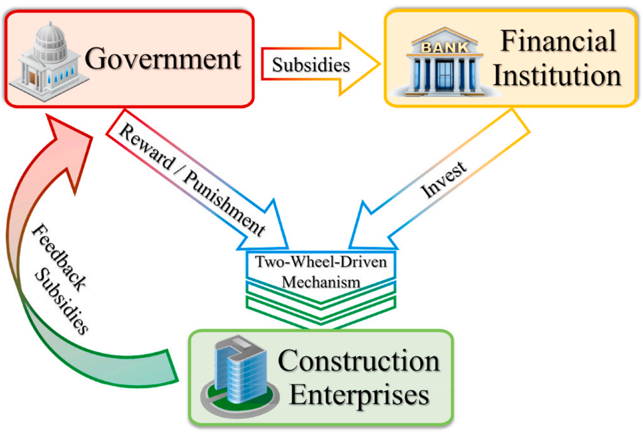


Fig. 1. Participants in the tripartite evolutionary game.

regulation” by the government refers to incentivizing measures that encourage construction enterprises to engage in CER activities. Examples include providing financial subsidies, tax credits, and other rewards for investments in low-carbon technologies, funding research on environmental technologies, and establishing stringent carbon emission standards with third-party certification. In contrast, “negative regulation” involves implementing restrictive measures aimed at deterring actions harmful to building CER. Examples of negative regulation include setting carbon emission limits and imposing fines on construction enterprises that exceed these limits, establishing carbon emission trading markets to incentivize CER, and mandating regular environmental audits with public disclosure of carbon emission data to enhance transparency and regulatory oversight. While positive regulation incentivizes CER adoption through rewards, negative regulation discourages non-compliance through punitive measures.

Hypothesis 3. Construction enterprises’ CER behaviour requires a large amount of upfront technical and financial investment, and there is a risk that the expected results will not be achieved. Both CER and non-CER behaviour construction enterprises can obtain financial support, such as conventional credit, from financial institutions.

Hypothesis 4. Financial institutions can independently choose whether to support investment in the CER behaviour of construction enterprises. Construction enterprise CER financial services include providing services such as investment and financing activities related to CER behaviours, trading of carbon emission rights and their carbon derivative products. Construction enterprise CER financial services require talent and capital investment, and there is a risk of credit loss caused by supporting low-carbon production projects that do not achieve their goals.

These hypotheses are developed to address the research question and contribute to the overall aim of the study by examining the key factors that influence the adoption of building CER strategies. By testing these hypotheses, we can gain a better understanding of how to promote the active adoption of CER strategies by different stakeholders in the construction industry.

3.2. Profit and loss variable selection and settings

The subjects of the game of CER behaviour evolution of construction enterprises are construction enterprises, financial institutions, and the government. According to the actual situation of CER behaviour of construction enterprises and the theory of the evolutionary game model [58], in the building CER behaviour system, all three participants have limited rational, incomplete information exchange and interactive influence of strategy choice. To explore the benefits and costs of different CER behavioural strategies of the three stakeholders. We set some relevant parameters and defined their meanings, as shown in Table 1.

$K(\alpha)$ **- Government Penalty Quota**: $K(\alpha)$ represents the penalty quota set by the government as a punitive measure against building companies failing to reduce carbon emissions. It is influenced by factors such as actual carbon emissions, government policy objectives, and stakeholder expectations. The penalty coefficient α is a multiplier that converts actual emissions into a specific penalty amount. There is typically a positive correlation between the penalty quota and the penalty coefficient, reflecting the government’s aim to tighten carbon emissions.

$I(\theta)$ **- Government Reward Quota**: $I(\theta)$ signifies the reward quota established by the government to incentivize building companies to reduce carbon emissions. The reward coefficient θ, another multiplier, is determined on the basis of factors such as CER efficiency, use of low-carbon technologies, and participation in carbon trading markets. Increasing reward quota I can lead to

Table 1
Meaning of the model parameters.

Participant	Parameters	Descriptions
Construction Enterprises	W_1, W_3	Earnings of construction enterprises that perform CER/non-CER when financial institutions invest.
	W_2, W_4	Earnings of construction companies that perform CER/non-CER when financial institutions do not invest. $W_1 > W_2 > W_3 > W_4$
	W_5	Value-added earnings of construction enterprises CER when the government is actively regulated, and financial institutions invest.
	C_C	Costs of construction enterprises when they perform CER.
Financial Institutions	G_1, G_2	Gains of financial institutions when they invest in CER/non-CER construction enterprises.
	G_3	Gains of financial institutions when they do not invest in CER construction enterprises.
	G_4	Value-added earnings of financial institutions when they invest in construction enterprises’ CER.
Government	C_P	Costs of the government raising awareness of financial institutions’ intentions to invest in building CER.
	C_R	Costs of government’s active regulation.
	$K(\alpha)$	The number of government penalties for non-CER construction enterprises (the penalty coefficient is α). $0 < \alpha < 1$
	$I(\theta)$	The number of government incentives for CER construction enterprises (the incentive coefficient is θ). $0 < \theta < 1$
	$S(\gamma)$	The number of government subsidies for financial institutions that have invested in CERs for construction enterprises (the subsidy coefficient is γ). $0 < \gamma < 1$
	ω	The feedback subsidy coefficient is obtained from the government from the construction enterprises when they are gaining value-added benefits from W_5. $0 < \omega < 1$

Note: The rationale for considering C_P is two-fold. First, by promoting building CER initiatives among financial institutions, the government aims to influence capital allocation towards supporting CER projects in the construction industry. This involves costs associated with awareness campaigns, training programmes and incentives to steer financial institutions’ investment decisions. Second, enhancing awareness about CER benefits enables financial institutions to develop sustainable financial products and services, such as green loans, carbon offset financing, and specialised investment vehicles. These offerings can provide additional revenue streams while supporting the construction industry’s transition towards lower emissions. Therefore, the government’s expenditure on raising CER awareness among financial institutions is a crucial factor influencing their investment decisions and the overall adoption of building CER strategies.

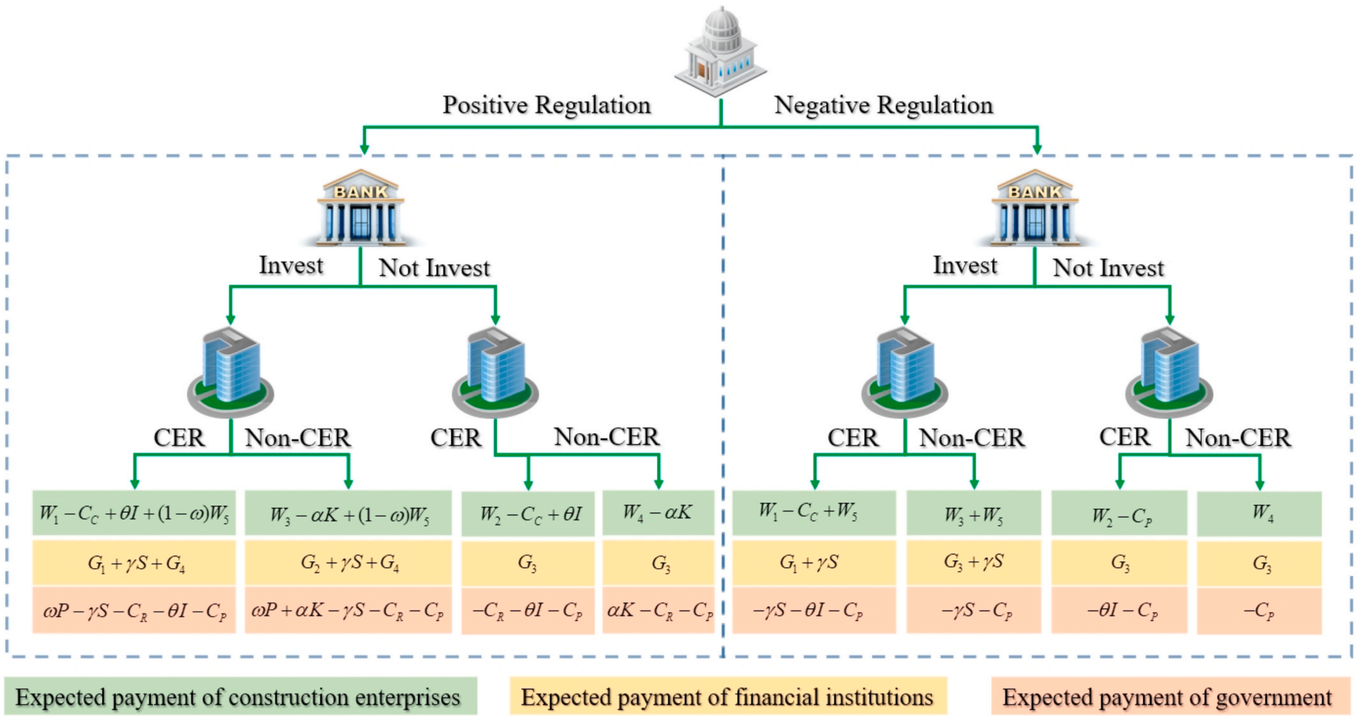


Fig. 2. Tripartite game payment matrix.

adjustments in reward coefficient θ to ensure that companies receive reasonable rewards.

$S(\gamma)$**- Government Subsidy Quota**: $S(\gamma)$ refers to the subsidy quota set by the government for financial institutions investing in the CER activities of building companies. The subsidy coefficient γ, a multiplier adjusted based on investment amounts, project categories, CER benefits, and sustainability indicators, aims to incentivize financial institutions towards CER initiatives. There is a positive correlation between the subsidy quota and the subsidy coefficient, with adjustments made based on actual emission reductions.

These parameters reflect different aspects of government interventions related to penalties, rewards, and subsidies aimed at promoting CER in buildings. They play crucial roles in shaping regulatory frameworks and financial incentives within the construction sector.

The tripartite game payment matrix between the government, construction enterprises, and financial institutions can be obtained on the basis of the behavioural decisions of CER of the three participating subjects, the aforementioned assumptions, and benefit– loss factors, as shown in Fig. 2.

The three players replicate the replication process outlined by the dynamic evolutionary game theory, continuously modifying their strategies through learning to increase their total efficacy. The replication dynamic equation, which is a dynamic differential equation, effectively establishes the frequency with which a specific tactic is adopted or approved by the populace [59,60]. The expected payoffs, average expected payoffs, and replication dynamic equations for the three participants' methods are listed below.

As can be seen from Fig. 2, the expected benefits of construction enterprises' CER and non-CER are denoted as E_x and E_{1-x}, respectively. The average expected benefits of construction enterprises are represented as $\overline{E_x}$.

$$\begin{cases} E_x = yz[W_1 - C_C + \theta I + (1-\omega)W_5] + (1-y)z(W_2 - C_C + \theta I) \\ +y(1-z)(W_1 - C_C + W_5) + (1-y)(1-z)(W_2 - C_P) \\ E_{1-x} = yz[W_3 - \alpha K + (1-\omega)W_5] + (1-y)z(W_4 - \alpha K) + y(1-z)(W_3 + W_5) + (1-y)(1-z)W_4 \\ \overline{E_x} = xE_x + (1-x)E_{1-x} \end{cases} \tag{1}$$

The replication dynamic equation of the construction enterprise is obtained from Eq. (1) as

$$F(x) = \frac{dx}{dt} = x(E_x - \overline{E_x}) = x(1-x)[y(W_1 - W_2 - W_3 + W_4) + z(\theta I + \alpha K) + W_2 - W_4 - C_P] \tag{2}$$

Equivalently, Eqs. (3) and (4) show the replication dynamics equations for financial institutions and the government, respectively

$$F(y) = \frac{dy}{dt} = y\left(E_y - \overline{E_y}\right) = y(1-y)[z(\gamma S + G_4) + x(G_1 - G_2) + G_2 - G_3] \tag{3}$$

$$F(z) = \frac{dz}{dt} = z(E_z - \overline{E_z}) = z(1-z)[\alpha K - x(\theta I + \alpha K) + y(\omega W_5 - \gamma S) - C_R] \tag{4}$$

3.3. Tripartite evolutionary stabilisation strategy analysis

Let $F(x) = 0$、$F(y) = 0$ and $F(z) = 0$, and we can obtain eight possible equilibrium points for the evolutionary stability of construction enterprises, financial institutions and government, including: $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1,1)$. Additionally, there may be a mixed strategy equilibrium point, $E_9(x', y', z')$ and $E_9(x', y', z')$ the equilibrium point should satisfy.

$$\begin{cases} y(W_1 - W_2 - W_3 + W_4) + z(\theta I + \alpha K) + W_2 - W_4 - C_P = 0 \\ (\gamma S + G_4) + x(G_1 - G_2) + G_2 - G_3 = 0 \\ \alpha K - x(\theta I + \alpha K) + y(\omega W_5 - \gamma S) - C_R = 0 \end{cases} \tag{5}$$

We will analyse the stability of the dynamic system evolution strategy for each subject and construction enterprise CER.

3.3.1. Asymptotic stability analysis of construction enterprises

Let, $F(x) = 0$ so that we have $x = 0$, $x = 1$ and $y^* = \frac{W_4 + C_C - W_2 - z(\theta I + \alpha K)}{W_1 - W_2 - W_3 + W_4}$ three solutions. By replicating the stability theorem of the dynamic equation, the probability of a construction enterprise choosing CER behaviour in a stable state must satisfy: $F(x) = 0$ and, $d(F(x))/dx < 0$ are $d(F(x))/dx = (1-2x)[y(W_1 - W_2 - W_3 + W_4) + z(\theta I + \alpha K) + W_2 - W_4 - C_P]$. That is, the positive and negative uncertainty $d(F(x))/dx$ is thus discussed in two steps.

(1) When, $y = y^*$ $F(x) \equiv 0$ and, $d(F(x))/dx \equiv 0$ the construction enterprise cannot determine the stability strategy.
(2) When $y \neq y^*$ it is known that $x = 0$ and $x = 1$ are two strategies for x. The following discussion is divided into two cases:
① when, $0 < y < y^*$ $x = 0$ and, $x = 1$ are substituted into, $d(F(x))/dx$ we can get $d(F(x))/dx|_{x=0} < 0$ and, $d(F(x))/dx|_{x=1} > 0$ then $x = 0$ the evolutionary stability point. When the investment probability of the financial institution is lower than that, y^* the construction enterprise chooses to conduct the CER strategy.
② When, $y^* < y < 1$ $d(F(x))/dx|_{x=0} > 0$ and, $d(F(x))/dx|_{x=1} < 0$ we know that $x = 1$ is the evolutionary stability point. When the investment probability of financial institutions is higher than that, y^* construction enterprises choose to conduct the CER strategy.

According to the above analysis, the replication dynamic phase diagram of the construction enterprise can be obtained as shown in Fig. 3.

Similarly, the replication dynamic phase diagrams of financial institutions and the government can be derived, as shown in Figs. 4

and 5.

3.3.2. Evolutionary stability analysis of the CER dynamic system for construction companies

Since $E_9(x', y', z')$ refers to a mixed strategy Nash equilibrium [61,62], we consider only the remaining $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$ and $E_8(1,1,1)$ eight pure strategy equilibrium points. The Jacobian matrix [63] of the replicated dynamic system of the construction enterprise CER can be obtained from equation (6):

$$J_0 = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$= \begin{bmatrix} (1-2x)\begin{bmatrix} y(W_1 - W_2 - W_3 + W_4) + W_2 + \\ z(\theta I + \alpha K) - W_4 - C_C \end{bmatrix} & x(1-x)(W_1 - W_2 - W_3 + W_4) & x(1-x)(\theta I + \alpha K) \\ y(1-y)(G_1 - G_2) & (1-2y)\begin{bmatrix} z(\gamma S + G_4) + G_2 + \\ x(G_1 - G_2) - G_3 \end{bmatrix} & y(1-y)(\gamma S + G_4) \\ -z(1-z)(\theta I + \alpha K) & z(1-z)(\omega W_5 - \gamma S) & (1-2z)\begin{bmatrix} \alpha K - x(\theta I + \alpha K) + \\ y(\omega W_5 - \gamma S) - C_R \end{bmatrix} \end{bmatrix} \quad (6)$$

The following is an example $E_1(0,0,0)$ to analyse its asymptotic stability, and its Jacobian matrix is shown in equation (7):

$$J_1 = \begin{bmatrix} W_2 - W_4 - C_C & 0 & 0 \\ 0 & G_2 - G_3 & 0 \\ 0 & 0 & \alpha K - C_R \end{bmatrix} \quad (7)$$

Therefore, the eigenvalues of $E_1(0,0,0)$ are, $\lambda_1 = W_2 - W_4 - C_C$ $\lambda_2 = G_2 - G_3$ and $\lambda_3 = \alpha K - C_R$. The stability analysis of the other equilibria is similar, and the eigenvalues of the Jacobian matrix are obtained by substituting each of the eight equilibria into the Jacobian matrix, as shown in Table 2.

To simplify the stability analysis without loss of generality when the interests of all parties are satisfied, the initial parameters must be consistent with, $\theta I + \alpha K + W_1 - W_3 - C_C > 0$ $\gamma S + G_4 + G_1 - G_3 > 0$ and $\theta I + C_R + \gamma S - \omega W_5 < 0$. Because the model parameters are complex, the stability of this evolutionary game is discussed below in three scenarios. The stability analysis of the local equilibrium point is shown in Table 3.

Scenario 1: When $W_2 - W_4 - C_C < 0$ $\alpha K - C_R < 0$ financial institutions do not invest in construction enterprises' CER, the difference between the benefits and costs obtained by construction enterprises performing CER is lower than the benefits obtained by construction enterprises performing non-CER; and the government penalties for construction enterprises performing non-CER are less than their regulatory costs. From Table 3, we can see that the equilibrium point $E_1(0,0,0)$ and $E_8(1,1,1)$ the corresponding Jacobian matrix eigenvalues are negative, so $E_1(0,0,0)$ and $E_8(1,1,1)$ are equilibrium points, {non-CER, no investment, negative regulation} and {CER, investment, positive regulation} are evolutionary stable strategies. The phase diagram of the evolutionary game model is shown in Fig. 6.

Scenario 2: When, $\theta I + \alpha K + W_2 - W_4 - C_C < 0$ $\gamma S + G_4 + G_2 - G_3 < 0$ and $\alpha K - C_R > 0$, the sum of government penalties for non-

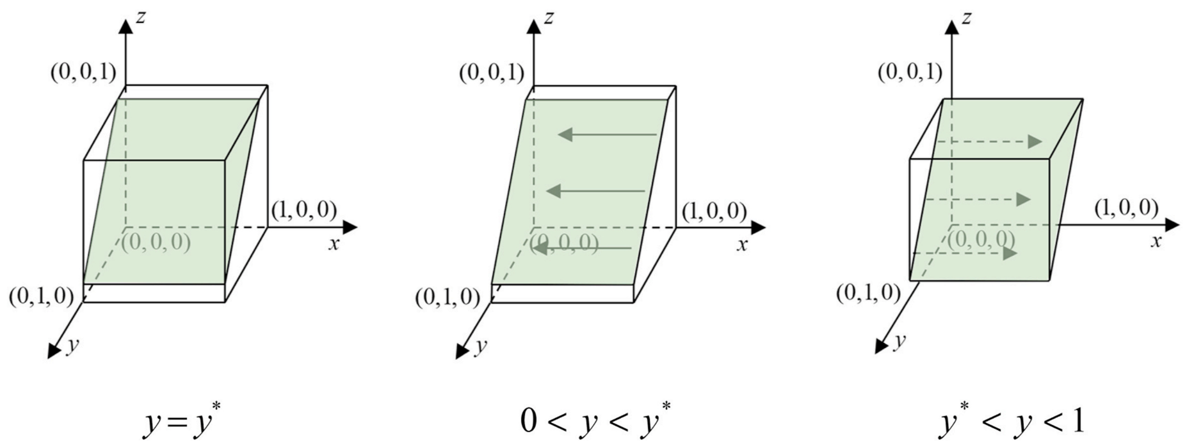


Fig. 3. Replication dynamic phase diagram of construction enterprises.

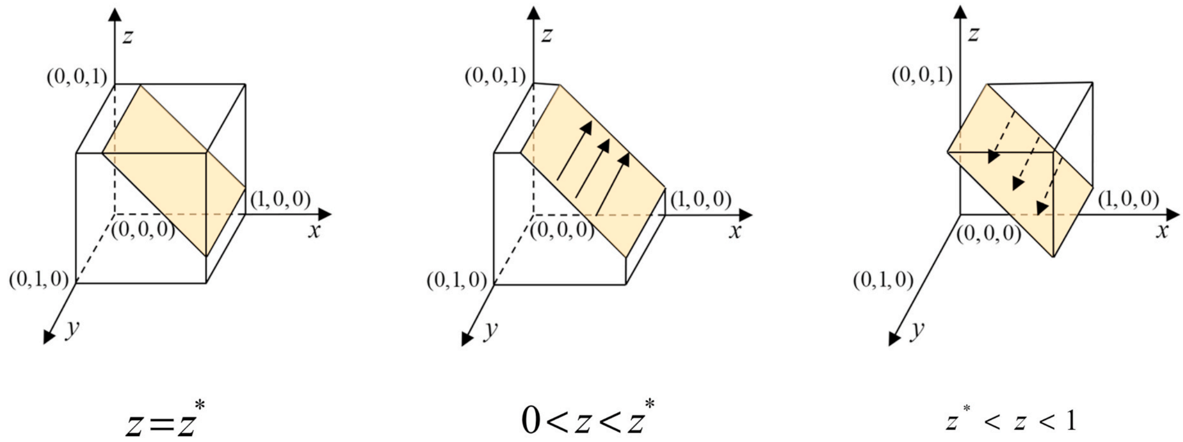


Fig. 4. Replication dynamic phase diagram of financial institutions.

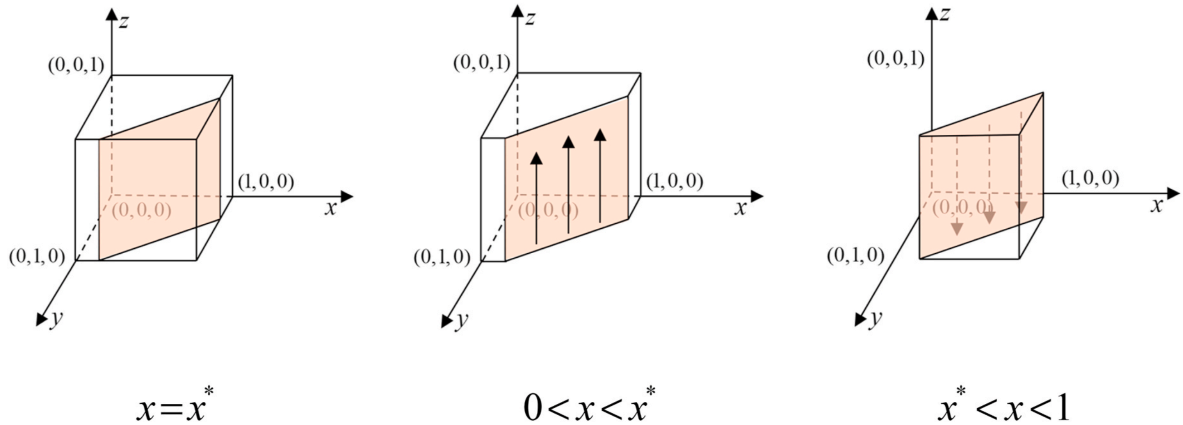


Fig. 5. Replicated dynamic phase diagram of the government.

Table 2
Eigenvalues of the Jacobian matrix.

Balancing point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1(0,0,0)$	$W_2 - W_4 - C_C$	$G_2 - G_3$	$\alpha K - C_R$
$E_2(0,0,1)$	$\theta I + \alpha K + W_2 - W_4 - C_C$	$\gamma S + G_4 + G_2 - G_3$	$-(\alpha K - C_R)$
$E_3(0,1,0)$	$W_1 - W_3 - C_C$	$-(G_2 - G_3)$	$\alpha K + \omega W_5 - \gamma S - C_R$
$E_4(0,1,1)$	$\theta I + \alpha K + W_1 - W_3 - C_C$	$-(\gamma S + G_4 + G_2 - G_3)$	$-(\alpha K + \omega W_5 - \gamma S - C_R)$
$E_5(1,0,0)$	$-(W_2 - W_4 - C_C)$	$G_1 - G_3$	$-(\theta I + C_R)$
$E_6(1,0,1)$	$-(\theta I + \alpha K + W_2 - W_4 - C_C)$	$\gamma S + G_4 + G_1 - G_3$	$\theta I + C_R$
$E_7(1,1,0)$	$-(W_1 - W_3 - C_C)$	$-(G_1 - G_3)$	$-(\theta I + C_R + \gamma S - \omega W_5)$
$E_8(1,1,1)$	$-(\theta I + \alpha K + W_1 - W_3 - C_C)$	$-(\gamma S + G_4 + G_1 - G_3)$	$\theta I + C_R + \gamma S - \omega W_5$

CER construction enterprises and subsidies for CER construction enterprises is lower than the sum of the difference between the costs and benefits of CER construction enterprises when financial institutions do not invest and the benefits of construction enterprises derive when they do not. The sum of government subsidies to financial institutions that invest in CERs for construction enterprises, the proceeds from financial institutions' profits when the government actively regulates, and the benefits of financial institutions investing in CERs for construction enterprises when construction enterprises do not engage in CERs is lower than the benefits of financial institutions not investing in CERs for construction enterprises. Government penalties for construction enterprises that do not engage in CER are lower than the cost of active government regulation. From Table 3, we can see that the equilibrium points $E_2(0,0,1)$ and $E_8(1,1,1)$, corresponding to the Jacobian matrix eigenvalues, are negative, so $E_2(0,0,1)$ and $E_8(1,1,1)$ are the equilibrium points, {non-CER, no investment, active regulation} and {CER, investment, active regulation} are the ESSes. The phase diagram of the evolutionary game model is shown in Fig. 7.

Scenario 3: When $W_2 - W_4 - C_C > 0$ or $G_2 - G_3 > 0$, financial institutions do not invest in CER for construction enterprises, the

Table 3
Local equilibrium point stability analysis.

Balancing point	Scenario 1		Scenario 2		Scenario 3	
	Eigenvalue symbols	Stability	Eigenvalue symbols	Stability	Eigenvalue symbols	Stability
$E_1(0,0,0)$	$(-,-,-)$	ESS	$(\pm,-,+)$	Saddle	$(\pm,\pm,\pm)$	Saddle
$E_2(0,0,1)$	$(\pm,\pm,\pm)$	Saddle	$(-,-,-)$	ESS	$(\pm,\pm,\pm)$	Saddle
$E_3(0,1,0)$	$(\pm,+,+)$	Saddle	$(\pm,+,+)$	Saddle	$(\pm,+,+)$	Saddle
$E_4(0,1,1)$	$(+,\pm,-)$	Saddle	$(\pm,\pm,-)$	Saddle	$(+,\pm,-)$	Saddle
$E_5(1,0,0)$	$(+,+,-)$	Instability	$(\pm,+,-)$	Saddle	$(\pm,+,-)$	Saddle
$E_6(1,0,1)$	$(\pm,+,+)$	Saddle	$(+,+,+)$	Instability	$(\pm,+,+)$	Saddle
$E_7(1,1,0)$	$(\pm,-,+)$	Saddle	$(\pm,-,+)$	Saddle	$(+,-,+)$	Saddle
$E_8(1,1,1)$	$(-,-,-)$	ESS	$(-,-,-)$	ESS	$(-,-,-)$	ESS

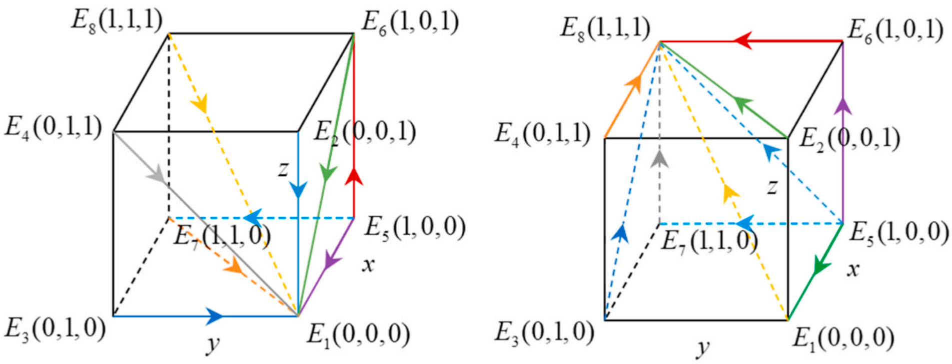


Fig. 6. Phase diagrams of $W_2 - W_4 - C_C < 0$ and $\alpha K - C_R < 0$.

difference between the benefits and costs of CER for construction enterprises is higher than the benefits of CER for construction enterprises without CER. The benefits to financial institutions of investing in construction enterprises that do not engage in CER are higher than those of not investing in CER for construction enterprises. The equilibrium point $E_8(1,1,1)$ corresponding to the Jacobian matrix eigenvalues is negative, so $E_8(1,1,1)$ is the equilibrium point, {CER, investment, active regulation} is the ESS, and the phase diagram of the evolutionary game model is shown in Fig. 8.

4. Simulation Analysis

To visualise the dynamic evolution path of the three stakeholders and the entire replication dynamic system in terms of CER, we utilised the MATLAB R2021 programme to conduct the simulation based on the replication dynamic equations and constraints. Specifically, we analysed the effects of the penalty coefficient, α subsidy coefficient, γ reward coefficient θ and feedback complement coefficient ω on the evolutionary process of CER behaviour of construction enterprise. However, relevant empirical data are difficult to obtain in a short time, and the experimental method of numerical simulation with [57,64] powerful iterative and interactive quantitative analysis has proved to be widely used to solve many problems of multi-subject games.

Note that *the Implementing Rules for the Management of Demonstration Projects for Green Development Incentive* Funds *for Buildings in Beijing (Trial)* issued by the Beijing Municipal Commission of Housing and Urban-Rural Development stipulates that "the incentive for

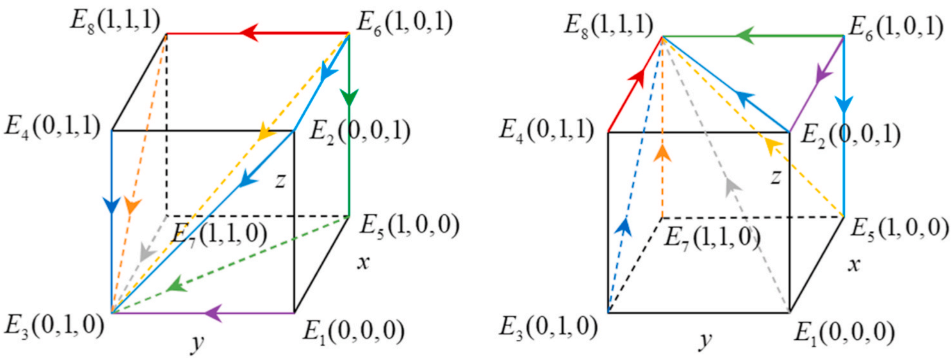


Fig. 7. Phase diagrams of, $\theta I + \alpha K + W_2 - W_4 - C_C < 0$ $\gamma S + G_4 + G_2 - G_3 < 0$ and $\alpha K - C_R > 0$.

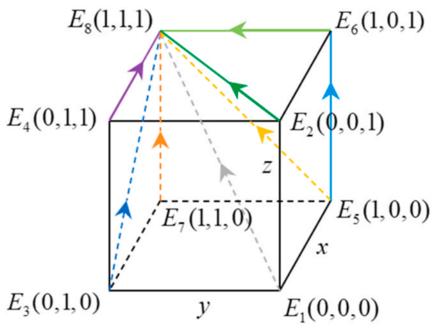


Fig. 8. Phase diagram of $W_2 - W_4 - C_C > 0$ and $G_2 - G_3 > 0$.

energy-saving green transformation of public buildings shall not exceed 20 yuan per square metre", so $S = 15$. According to the data of the Department of Standards and Quotas of the Ministry of Housing and Urban-Rural Development of China, the incremental cost of a one-star green building in hot summer and cold winter areas is 12–40 yuan per square metre so it is set at $C_c = 19$. Similarly, we refer to Refs. [1,65], *the China Statistical Yearbook*, *the China Energy Statistical Yearbook*, and its residential project M as a realistic environment for simulation and analysis. Other relevant documents to describe the initial value of this study: $C_R = 10$, $C_P = 6$, $K = 23$, $I = 13$, $W_5 = 35$, $W_1 = 60$, $W_2 = 45$, $W_3 = 51$, $W_4 = 41$, $G_4 = 8$, $G_1 = 21$, $G_2 = 8$, $G_3 = 15$, where, α, θ, γ, ω are taken as 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, respectively.

4.1. Effect of the initial strategy on system evolution

Let $z = 0.5$ be a constant value $y|_{t=0} = 0.5$, and the image of the initial investment strategy of financial institutions evolving with different initial CER strategies of construction enterprises is shown in Fig. 9(a), and similarly in Fig. 9(b). As shown in Fig. 9, the initial CER strategy of construction enterprises has little to no influence on how financial institutions and governments change over time. Accordingly, regardless of the likelihood that construction enterprises will opt for a volume-based or aggressive CER strategy, the government and financial businesses will do so. However, in the early stage of the CER strategy, the government and financial institutions will first choose a negative CER strategy because the CER technology, equipment, and related management experience and market environment are not mature, or the urgency to implement CER strategy in the construction industry is not yet high. With the implementation of China's carbon peaking and carbon neutrality goals [66] and the announcement of related regulations, the construction industry, which accounts for the bulk of carbon emissions, has slowly moved towards a positive CER strategy. As shown in Fig. 9(a), the higher the probability that construction companies implement positive CER strategies, the faster the financial institutions invest in CER and the faster the government chooses to actively regulate them. As can be observed in Fig. 9(b), the government's decision is largely unaffected by the willingness of construction enterprises to cut carbon emissions, demonstrating the government's hegemonic role in CER in the construction industry.

Let $z = 0.5$ be a constant value and $x|_{t=0} = 0.5$. The images of the initial CER strategies of construction enterprises evolving with different initial investment strategies of financial institutions are shown in Fig. 10(a) and similarly in Fig. 10(b). As seen in Fig. 10, when $x > 0.3$, both construction enterprises and the government eventually choose a positive CER strategy; when $x \leq 0.3$, construction

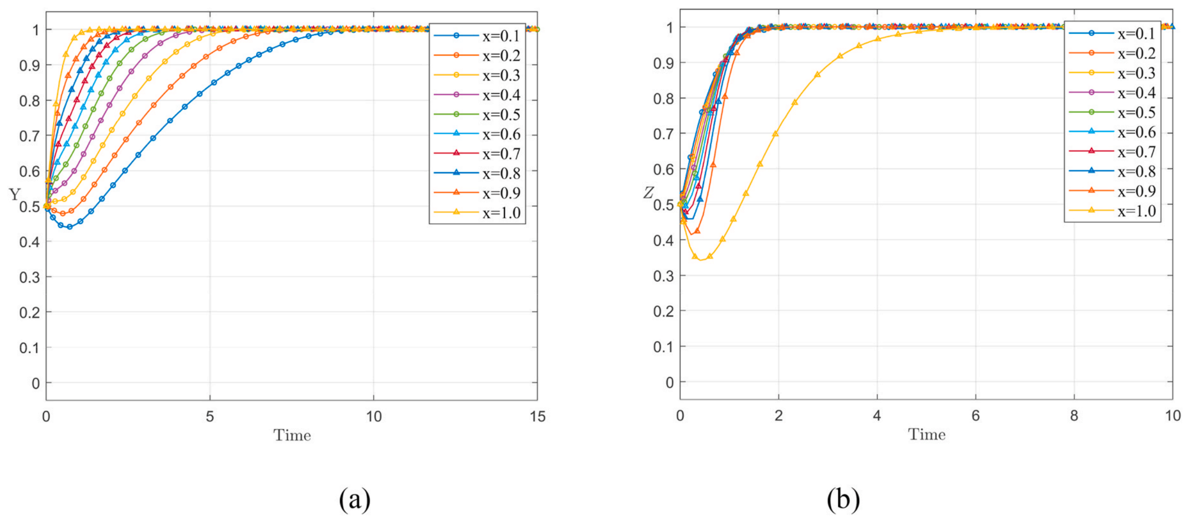


Fig. 9. Evolutionary effects of changes in x on y and z.

enterprises choose negative CER and the government chooses negative regulation. This behaviour arises from financial institutions, motivated by profit, being unable to attain positive returns in the previous period and, consequently, choosing not to invest. This scenario illustrates the significance of determined capital inflow in shaping CER decisions within the construction supply chain. In the later stages of industry development, as seen by the comparison of Fig. 10(a) and (b), the government adopts positive CER strategies at a faster pace than construction enterprises, which further proves that the government is in the leading position in construction CER.

Let $y = 0.5$ be a constant value and $x|_{t=0} = 0.5$. Fig. 11(a) and (b) depict the evolution of construction enterprises' initial CER strategies under different initial value regulation strategies implemented by the government. Observing Fig. 11, when $x > 0.3$, both construction enterprises and financial institutions eventually choose a positive CER strategy. Conversely, when $x \leq 0.3$, construction enterprises choose negative CER and financial institutions choose not to invest. These behaviours stem from the inclination of construction enterprises to align their CER choices with the government's stance. Fig. 11(a) illustrates that construction enterprises will only select a positive building CER strategy when the probability of positive government regulation is high. This decision is driven by the impact of implementing the building CER strategy on the profitability of construction enterprises. The reduction in profits prompt hesitation, but a high probability of proactive government regulation mitigates concerns. Conversely, Fig. 11(b) demonstrates a distinct pattern. When the probability of active government regulation surpasses 0.5, the astute business acumen of financial institutions prompts immediate investment in CER initiatives for construction enterprises.

4.2. Effects of relevant parameters on system evolution

4.2.1. Effect of penalty coefficient α

The simulation results of the evolutionary game when the penalty coefficient α of the government for construction enterprises without CER takes different values are shown in Fig. 12 and Fig. 13. Fig. 13 Illustrates the evolutionary trajectory of the tripartite game involving construction enterprises' CER under varying penalty coefficients. When α is too small, the choice of the three parties is {non-CER, no investment, negative regulation}. As α increases, the willingness of construction enterprises to participate in CER behaviour exhibits minimal change, but there is a noticeable shift in the willingness of financial institutions to invest in CER projects and the government's inclination towards positive regulation. Ultimately, as the penalty coefficient increases, the three-party evolution converges towards the outcome of {CER, investment, and positive regulation}, leading to a steady state. This dynamic evolution simulation diagram verifies that $E_1(0,0,0)$ and $E_8(1,1,1)$ inferred in scenario 1 of 3.3.2 are indeed the ESSes in the system.

To elaborate further, the reasoning behind the ESSes can be elucidated. On the one hand, financial institutions abstain from investing in construction enterprises' CER initiatives because of the discrepancy between the benefits and costs associated with CER. The potential profitability from not engaging in CER surpasses the net benefits obtained by conducting CER ($W_2 - C_C < W_4$). Consequently, construction enterprises prioritise profitability over carbon reduction efforts. On the other hand, the government's penalty for construction enterprises that neglect CER falls short of the regulatory costs ($\alpha K - C_R < 0$). Thus, the government opts for negative regulation. However, as the penalty coefficient increases, the government intensifies penalties for non-compliance ($\alpha K - C_R <$ 0), which aligns more closely with the cost of regulation. As a result, the government transitions to proactive regulation. Simultaneously, penalised construction enterprises recognise that the net benefits of participating in CER, when supported by financial institutions, exceed the benefits of abstaining from CER ($W_1 - C_C > W_4 - \alpha K$). Consequently, they seek collaboration with financial institutions to drive CER initiatives within the construction industry. With higher penalty coefficients, the tripartite game evolves towards the optimal outcome of a flourishing CER culture in the construction sector.

4.2.2. Effect of the subsidy coefficient γ

The simulation results of the evolutionary game, considering various values of the government subsidy coefficient γ for financial

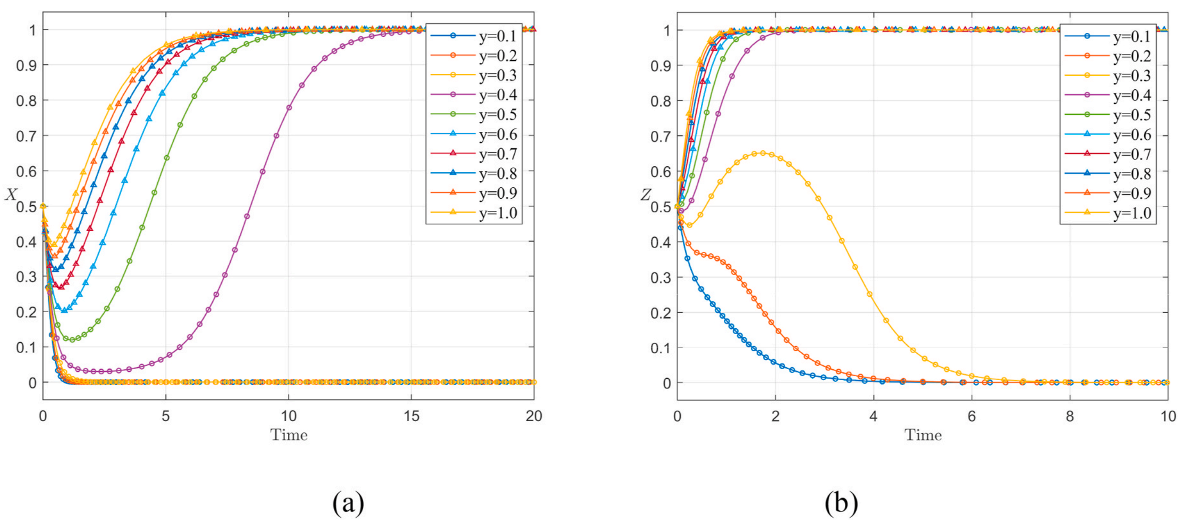


Fig. 10. Evolutionary effects of changes in y on x and z.

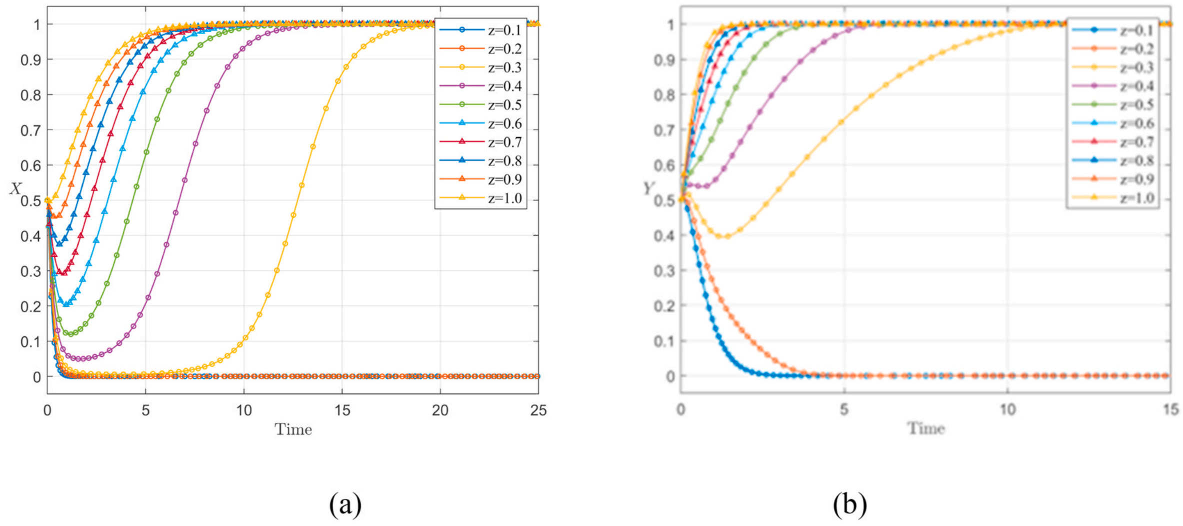


Fig. 11. Evolutionary effects of changes in z on x and y.

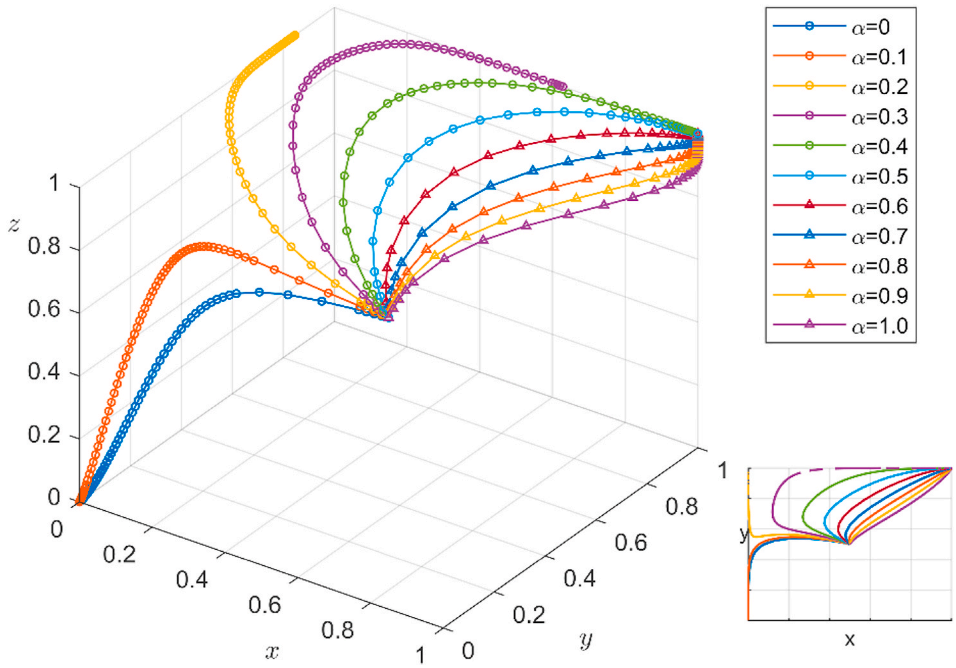
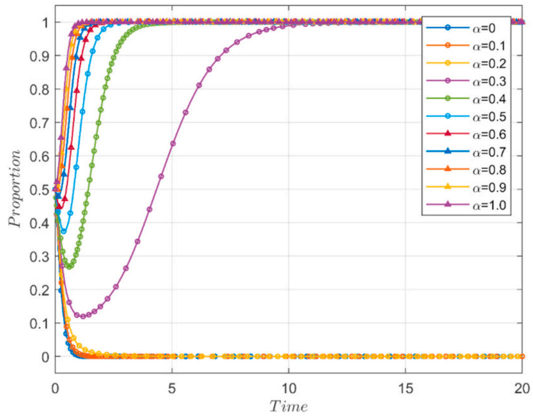


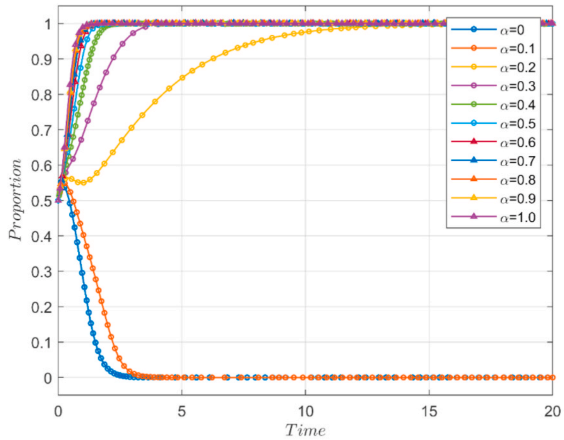
Fig. 12. Game trajectory of building CER under different α.

institutions investing in construction enterprises' CER decisions, are illustrated in Figs. 14 and 15. Fig. 14 displays the evolutionary trajectory of the tripartite game concerning construction enterprises' CER under different subsidy coefficients. To incentivize financial institutions to help construction enterprise CERs, the government will subsidise financial institutions that invest in construction enterprise CERs, and financial institutions' choices are significantly influenced by the government subsidy coefficient. Without government subsidies, financial institutions refrain from investing in construction enterprise CERs, and construction enterprises do not engage in CER initiatives. However, when the subsidy coefficient is at a moderate level, financial institutions evolve towards investing in construction enterprise CERs, and construction enterprises also progress towards implementing CERs. The stabilisation process becomes swifter as the subsidy coefficient increases until it eventually reaches equilibrium. Conversely, if γ becomes too large, financial institutions shift their focus solely towards investing in construction enterprise CERs, while the government opts for negative regulation due to excessive expenditure. Conversely, if γ becomes too large, financial institutions shift their focus solely towards investing in construction enterprise CERs, while the government opts for negative regulation due to excessive expenditure.

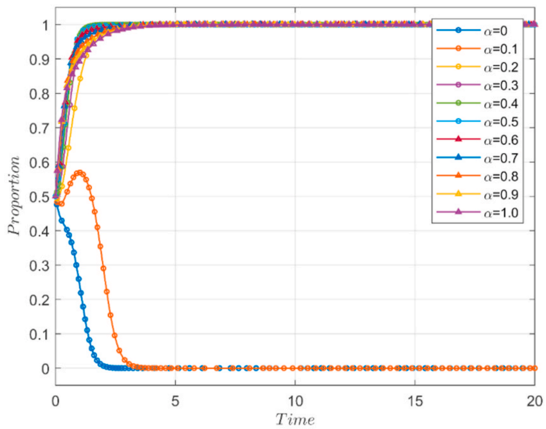
More specifically, when $\gamma = 0$, the government initially adopts a positive regulation, attempting to implement CERs in the con-



(a) Construction Enterprises.



(b) Financial Institutions.



(c) Government.

Fig. 13. Effect of changes α on the evolutionary trajectories of x, y, and z.

struction industry without subsidising financial institutions. However, financial institutions lacking investment do not engage in CER investments within construction enterprises, leading to the government's failure to achieve its CER objectives. Consequently, the government transitions to negative regulation. However, once subsidies are introduced, financial institutions promptly evolve towards investing in construction enterprise CERs, and the rate of evolution accelerates as the subsidy coefficient increases, eventually reaching a steady state. When γ becomes excessively large, it stimulates financial institutions to invest in construction enterprises, but the government fails to reach a steady state due to strategic choices driven by excessive expenditure. Therefore, the optimal evolution of CER in the construction industry occurs only when the government's subsidy coefficient to financial institutions is regulated within an appropriate range. This approach mobilises construction enterprises' enthusiasm for CER initiatives and promotes their evolution towards CER adoption. Conversely, excessively high subsidy levels hamper the flourishing development of CERs in the construction industry.

4.2.3. Effect of the incentive coefficient θ

The simulation results of the evolutionary game with different values of the government incentive coefficient θ for CERs of construction enterprises are shown in Figs. 16 and 17. The evolutionary trajectory of the tripartite game of CER of construction enterprises under different incentive coefficients is shown in Fig. 16. The government rewards construction enterprises' CER behaviour to motivate them to reduce their carbon emissions. When θ is small, financial institutions abstain from investing in construction enterprises' CER behaviour, and construction enterprises opt for negative CER actions. However, with a moderate incentive coefficient, financial institutions evolve towards investing in construction enterprises' CER behaviour, and construction enterprises progress towards implementing CERs, eventually reaching a state of stability. In contrast, when θ becomes too large, the government shifts

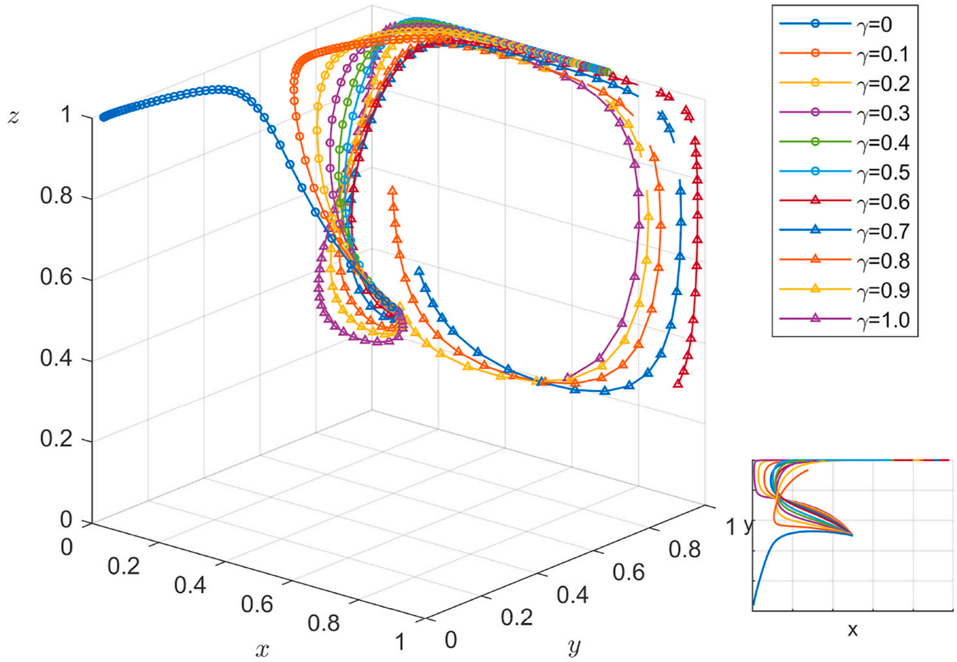


Fig. 14. Game trajectory of building CER under different γ.

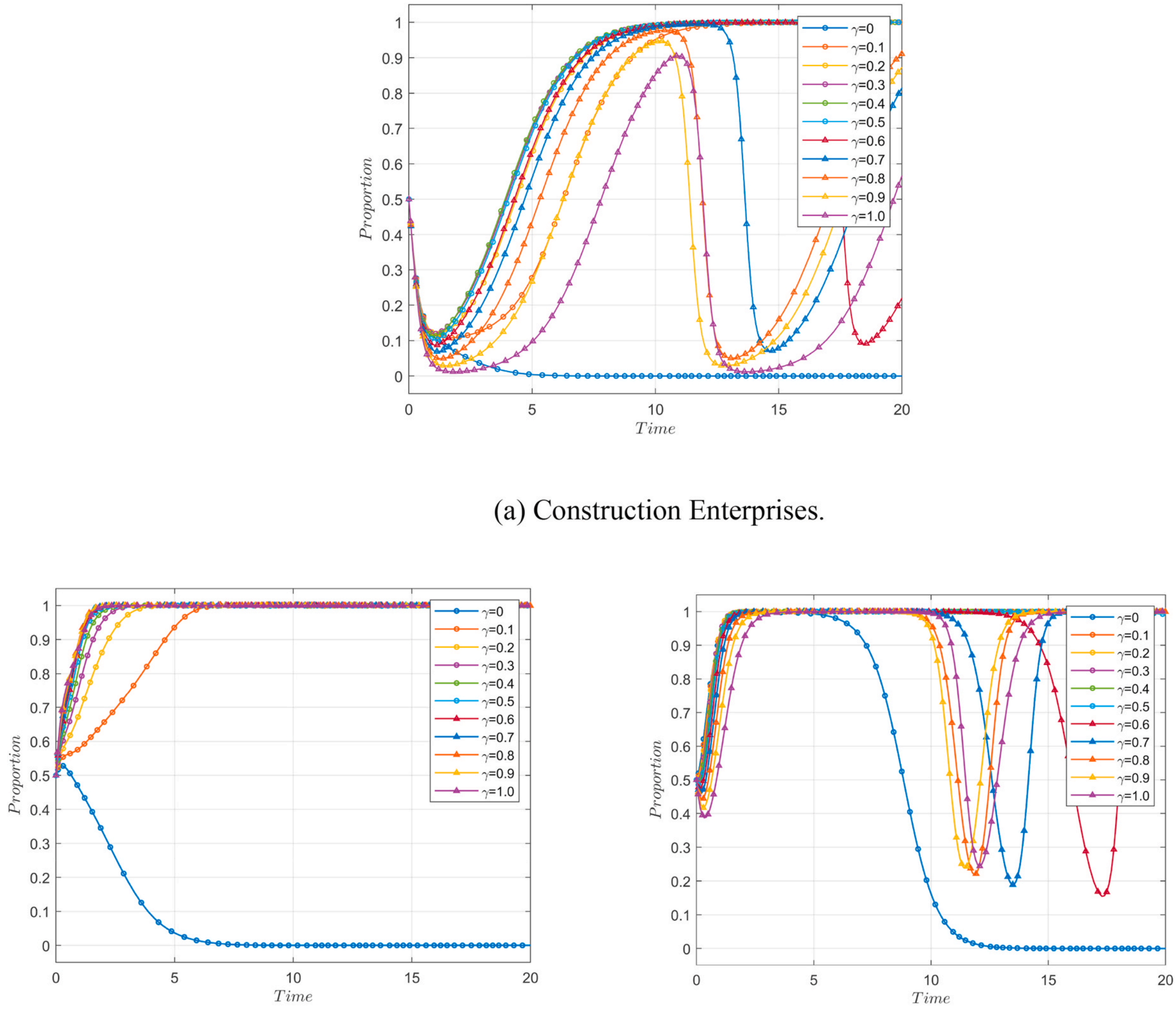
towards negative regulation, construction enterprises and financial institutions engage in an unstable process, and the tripartite game of construction enterprises' CERs fails to reach a stable state.

To delve deeper, when $\theta \leq 0.2$, the government subsidies provided for construction enterprises' CER behaviours are insufficient to offset the incremental costs. Consequently, both financial institutions and construction enterprises choose negative CER actions. In the short term, government subsidies for construction enterprises are not compelling enough to motivate them to adopt CER practises. This reluctance stems from the requirement of advanced expertise, skilled R&D talent, and high abatement costs associated with construction CERs. Likewise, financial institutions, hesitant due to the reluctance of construction enterprises and investment risks, refrain from investing in CERs for construction companies. As $0.3 \leq \theta \leq 0.7$ time progresses, construction enterprises begin to recognise the benefits of CERs and evolve towards adopting CER practises. The rate of evolution is positively correlated with the incentive coefficient until a stable state is achieved. This dynamic evolution leads to the establishment of a stable positive CER strategy within the construction industry. However, when the reward coefficient becomes excessively large ($\theta > 0.7$), the government's strategic choices become uncertain, preventing the attainment of a steady state. Consequently, this uncertainty also affects construction enterprises' ability to reach stability. In summary, very low incentive coefficients fail to mobilise the enthusiasm of financial institutions and construction enterprises for CERs. Conversely, excessively high incentive coefficients hinder the government and construction enterprises from reaching a stable state. Only moderate incentive coefficients can effectively drive the stable development of the tripartite game towards a positive CER direction.

4.2.4. Effect of the feedback subsidy coefficient ω

The simulation results of the evolutionary game for different values of the feedback subsidy coefficients ω to the government from the construction enterprises that have gained value-added benefits are shown in Figs. 18 and 19. When the government actively regulates, financial institutions invest in the CER behaviour of construction enterprises to generate additional benefits. Consequently, construction enterprises provide feedback subsidies to the government as a means of acknowledging the benefits received. When $\omega \leq 0.5$ the building CER systems all choose a negative CER. When $\omega > 0.5$ the building CER systems all choose a positive CER. Finally, the entire tripartite evolutionary game system reaches stability.

Specifically, when ω is small, the government pursues a negative regulation strategy. This decision arises from the feedback subsidy being lower than the cumulative subsidies provided to financial institutions and the incentives offered to construction enterprises. In turn, construction enterprises opt for negative CER behaviour, as it is not penalised for posing risks associated with investing in CER initiatives. Consequently, financial institutions refrain from investing in construction enterprises' CER activities. However, as the feedback subsidy coefficient (ω) increases, the government's revenue gradually rises, prompting a shift from the original wait-and-see attitude towards a positive regulation approach. At this stage, the negative CER behaviour of construction enterprises incurs significant penalties. Consequently, construction enterprises have evolved towards adopting CER practices driven by the deterrence of punitive measures. Financial institutions, influenced by positive government regulations and construction enterprises' adoption of CER, increase their investments in CER behaviour. The rate of evolution accelerates with higher subsidy coefficients, ultimately leading to a state of equilibrium.



(a) Construction Enterprises.

(b) Financial Institutions.

(c) Government.

Fig. 15. Effect of changes in γ the evolutionary trajectories of x, y, and z.

4.3. Dynamic evolution of the building CER system

The range of stable values of the four influence coefficients is derived from 4.2. In this section, $\alpha = 0.3$, $\gamma = 0.2$, $\theta = 0.5$, $\omega = 0.6$ are selected for numerical simulations to verify whether the equilibrium points $E_1(0,0,0)$ and $E_8(1,1,1)$ are stable in the evolutionary model. MATLAB software was used to generate 100 randomized groups with different initial strategy points x, y, and z to run the numerical simulations. The various lines in different colours, as depicted in Fig. 20, show the evolution of the CER tripartite for 100 unfixed initial strategy conditions. The lines converge $E_1(0,0,0)$ when both y and z are small; when both y and z are large, the lines eventually converge $E_8(1,1,1)$. Specifically, when the willingness of financial institutions to invest is small and the government is less aggressive in regulating building CER, construction enterprises will not be aggressive in building CER. Only when the cash flow from government active regulation and financial institutions flows into the building CER system will the tripartite evolutionary game finally converge to a three-way active CER steady state.

4.4. Discussion and policy applications

Based on the overall comparison of the simulation results presented in this paper, the CER behaviour of building enterprises is most sensitive to the subsidy coefficient, followed by the penalty and reward coefficients, while it is less sensitive to the feedback assistance coefficient. The research findings offer vital theoretical guidance and practical insights for the government to further adjust and optimise CER strategies in the construction industry based on current policies. First, the government should intensify the promotion of building CER for financial institutions, providing them with a relatively smaller proportion of subsidies to invest in CER initiatives. Second, the government can further develop "negative regulation" measures, establishing carbon emission trading markets, conducting

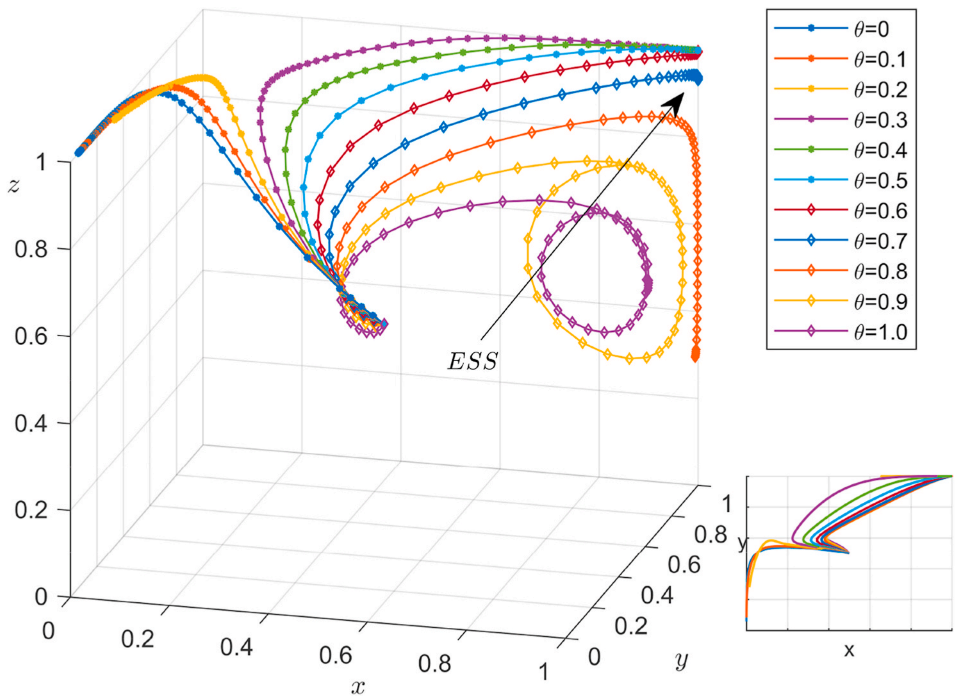


Fig. 16. Game trajectory of building CER under different θ.

regular environmental audits, and publicly disclosing carbon emission data.

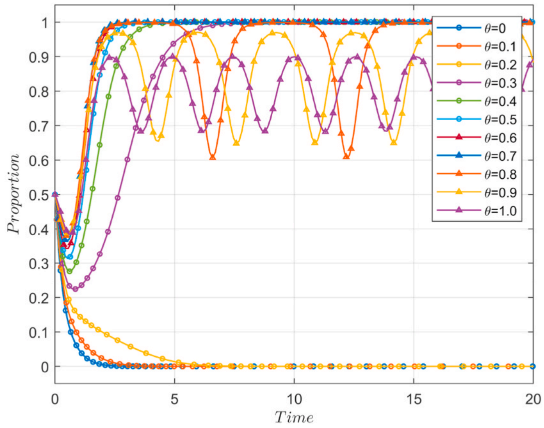
Specifically, concerning the promotion of CER behaviour in building enterprises, the simulation results depicted in Fig. 13(a) and 17(a) provide quantitative evidence, indicating that building enterprises show similar sensitivity to government rewards and penalties. Both reward and penalty coefficients must be greater than 0.3 for building enterprises to actively adopt CER measures. This indirectly highlights the challenging task for the government in raising awareness about CER. From the perspective of building enterprises, this low sensitivity may stem from differences in their awareness and understanding of CER measures. It may also be constrained by technological and financial limitations. The former requires the government to strengthen promotion and training for building companies, elevating their awareness, and understanding of building CER. Additionally, it is crucial to align these efforts with national strategies and market conditions both regulatory measures discussed in this paper to drive the development and implementation of CER initiatives. The latter necessitates leveraging the power of financial institutions to heavily invest in low-carbon technologies for buildings, including, but not limited to, designing green building materials optimising ventilation and air conditioning systems, developing carbon footprint assessment and management strategies, and researching intelligent building management systems.

From the government's standpoint, substantial investments are required for the promotion of awareness about building CER, providing subsidies for financial institutions to invest in building enterprises' CER initiatives, and rewarding building enterprises for their CER efforts. It is worth acknowledging that government penalties and incentives can significantly drive the development of building CER. However, financial subsidies are merely initial incentives and boosters for promoting CER behaviour. The combination of economic and non-economic measures would be a more effective choice for addressing issues related to building CER. If the government aims to stimulate the construction industry towards low-carbon sustainability while avoiding the "path dependence" and "crowding-out effects" caused by high subsidies, it must gradually reduce financial subsidies and guide building enterprises into a new phase characterised by a shift in CER motivation.

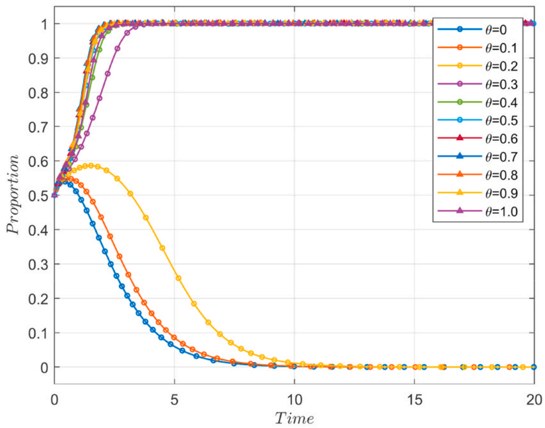
From the perspective of financial institutions, the low sensitivity to government subsidies, as shown in Figs. 14 and 15, indicates the government's dominant role in the field of CER and its intention to actively guide the flow of financial capital. This reflects the government's recognition of the CER potential in the construction industry and its emphasis on CER projects. Financial institutions should consider the advantages and potential returns of building CER, develop detailed investment strategies, heavily invest in building enterprises' CER initiatives, contribute to the national "Carbon Peak and Carbon Neutrality" goals, achieve effective allocation of financial assets, and lay the foundation for further establishing a green financial market.

5. Conclusion

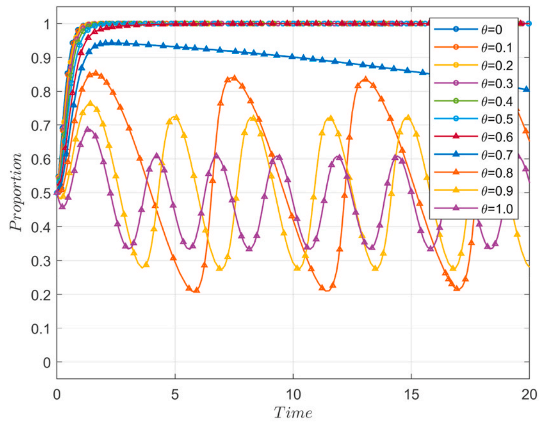
This research contributes to the field of building carbon emission reduction (CER) strategies by employing evolutionary game theory to analyse the strategic choices of the government, construction enterprises, and financial institutions. The two-pronged mechanism combining “government regulation and market intervention”, with financial institutions as a player in the game, has been innovatively constructed. This study explores the reward and punishment coefficients and feedback subsidy coefficients as



(a) Construction Enterprises.



(b) Financial Institutions.



(c) Government.

Fig. 17. Effect of changes in θ the evolutionary trajectories of x, y, and z.

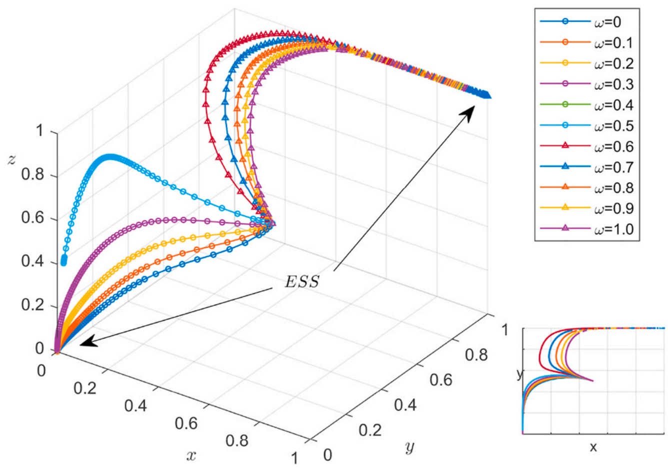
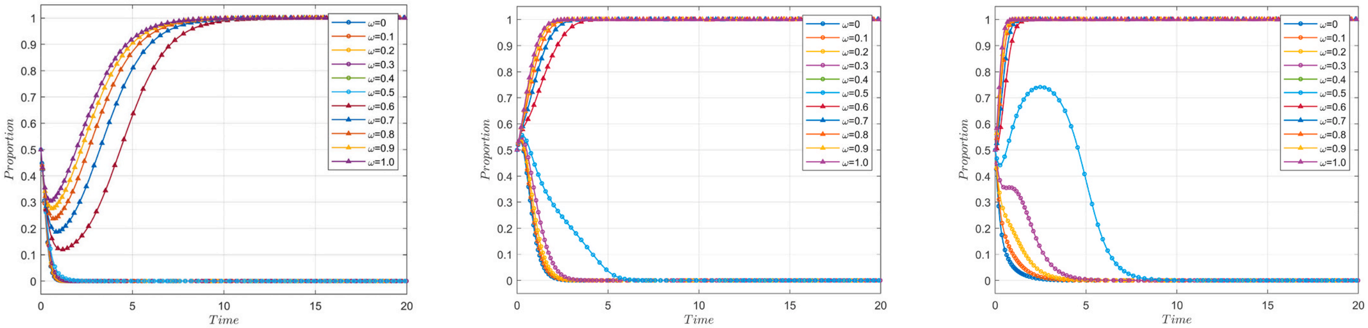


Fig. 18. Game trajectory of building CER under different ω.



(a) Construction Enterprises. (b) Financial Institutions. (c) Government.

Fig. 19. Effect of changes ω on the evolutionary trajectories of x, y, and z.

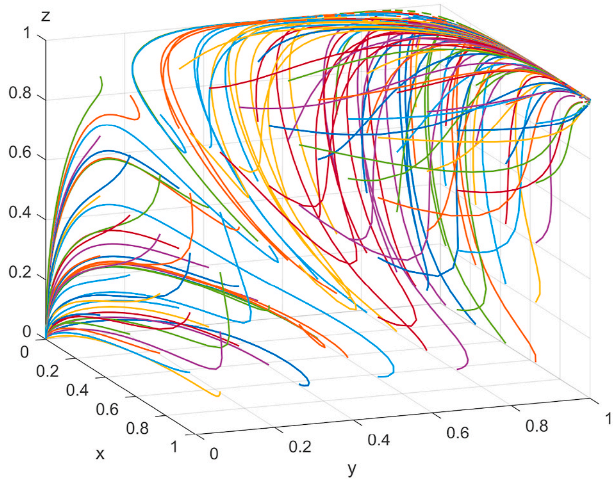


Fig. 20. Dynamic evolution of the building CER system.

influencing factors in the evolution game model. By considering construction enterprises' CER behaviour, the investment dilemma of financial institutions and the negative regulation issue of government agencies, a tripartite evolutionary model of CER behaviour is constructed.

The core contribution lies in meticulously examining the intricate interaction effects between government regulation and market dynamics in the context of promoting sustainable building CER strategies. By developing a tripartite evolutionary game model involving the government, financial institutions, and construction enterprises, this research provides a nuanced understanding of how these stakeholders influence and respond to each other's actions.

Specifically, this study sheds light on the interplay between government incentives, penalties, and the strategic decision-making processes of financial institutions and construction enterprises. This study explores how these interactions shape the evolutionary trajectories of building CER adoption, ultimately leading to the identification of dynamically stable strategies for all parties.

By emphasising the interactive effects of government interventions and market forces, this study offers valuable insights into the collaborative efforts required to drive sustainable transformation in the built environment. These findings can inform policymakers in designing effective regulatory frameworks that harmonise with market dynamics and guide industry stakeholders in aligning their strategies for mutually beneficial outcomes.

Based on these findings, several implications for promoting the active adoption of building CER strategies by the government, financial institutions, and construction enterprises are proposed:

➢ The government should develop region-specific regulatory policies that consider the stage of the construction industry, its development status, and its advantages. This will effectively guide traditional construction enterprises in adopting CER behaviour.
➢ Financial institutions should develop detailed strategies for investing in building CER, considering the advantages and potential returns of such investments.
➢ Construction enterprises should recognise the benefits of adopting CER and collaborate with the government and financial institutions to implement CER strategies.

In summary, this study highlights the significance of active government regulation, moderate subsidies and rewards, and collaboration between stakeholders in promoting the adoption of building CER strategies. However, excessive subsidies and rewards can hinder progress. Increasing awareness and understanding of CER among financial institutions is crucial, and construction enterprises play a vital role in providing feedback subsidies to the government. These suggestions guide policymakers and stakeholders in the construction industry, facilitating the active adoption of CER strategies and contributing to the sustainable development of cities.

While this study contributes valuable insights into promoting sustainable building CER through collaborative efforts, it is crucial to acknowledge certain limitations and propose improvements over past research.

First, previous studies have often relied on simplified parameters or assumptions that may not fully capture the complex reality of building CER dynamics. This study addresses this limitation by incorporating both real-world data and elements derived from previous experiences into the model parameters. However, certain parameters, such as government subsidies to financial institutions, are based on policy incentives rather than direct economic subsidies, making quantification challenging. Future research could explore quantification methods, such as fuzzy clustering analysis and fuzzy comprehensive evaluation, to integrate a broader range of parameters and enhance the accuracy of the model.

Second, while existing research often treats government "positive regulation" (incentives) and "negative regulation" (penalties) as opposing forces, this study acknowledges the nuanced approach adopted by governments in practise. Governments may employ a strategy that combines both encouraging and restrictive measures to effectively promote CER development. By incorporating this understanding into the tripartite evolutionary game model, this study provides a more realistic representation of the interplay between stakeholders. However, future studies could further refine the model by considering the dynamic adjustments made by governments in response to the evolving strategies of construction enterprises and financial institutions.

Third, previous studies have primarily focussed on specific regions or countries, overlooking the potential regional variations in building CER dynamics. This study addresses this limitation by applying the model to a case study in China. However, future research could further validate and enhance the model's stability by applying it to multiple cases across different countries, capturing diverse regional contexts and regulatory environments. Cross-cultural comparisons and the integration of socioeconomic factors could yield additional insights into the generalizability of the proposed model.

By addressing these limitations and proposing improvements over past work, this study contributes to a more comprehensive understanding of the collaborative efforts required to promote sustainable building CER strategies among governments, financial institutions, and construction enterprises. The insights derived from this research can inform policymakers, industry stakeholders, and future academic endeavours in this crucial domain.

CRediT authorship contribution statement

Wei Wang: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. **Shaojie Hao:** Formal analysis, Software, Visualization, Writing – original draft. **Hua Zhong:** Data curation, Project administration. **Zhi Sun:** Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was supported by Project 1448824: Constructing A Digital Environment Expert Network UK Natural Environment Research Council.

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