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Carbon Trading and Financial Innovation: Financing Mechanisms for CCUS Retrofitting in the Steel Industry

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ABSTRACT

On March 20, 2025, China's Ministry of Ecology and Environment issued “the Work Plan for Including the Steel, Cement, and Aluminum Smelting Industries in the National Carbon Emission Trading Market”, explicitly incorporating these three sectors into the national carbon market management framework, covering an additional 3 billion tons of CO_2 emissions. This move holds significant implications for the development of the carbon market and the application of CCUS technologies in these industries. Current research on CCUS investment incentives primarily focuses on sectors like power and oil & gas, with limited studies addressing policy mechanisms to promote CCUS adoption in steel enterprises. Moreover, due to the high costs of CCUS investments, existing research exhibits a pronounced "technology-oriented" bias, overemphasizing techno-economic analyses while neglecting financing-related policies and financial innovations, particularly the financing decisions of banks and other financial institutions.

To facilitate financing for steel plants' CCUS retrofits and ensure the implementation of emission reduction technologies, this study proposes a "government subsidy + bank green credit" financing incentive policy. A tripartite evolutionary game model is constructed involving steel enterprises, governments, and financial institutions. Banks decide whether to issue green credit based on risk-return assessments, governments determine their regulatory stance, and enterprises weigh retrofit costs against benefits to decide on CCUS adoption. Carbon allowance trading is introduced to examine the system’s evolutionary dynamics and stable strategies. Key findings include:

(1) Initial strategy proportions have minimal impact on simulation outcomes, with the stable equilibrium being (retrofit, grant green credit, proactive governance).

(2) Government subsidies and penalties are pivotal in incentivizing banks to extend green credit and enterprises to adopt retrofits, though excessive fiscal pressure may discourage proactive governance.

(3) Higher carbon social costs simultaneously strengthen government proactivity and bank lending willingness.

(4) Green credit returns drive bank lending, while rising lending costs, though dampening bank willingness, can pressure governments to act proactively and enhance enterprise retrofit motivation.

(5) Under carbon trading, enterprise willingness to retrofit increases with carbon prices.

Integrating game theory with carbon market mechanisms, this study proposes a dynamic CCUS financing decision framework for the steel industry, offering theoretical insights for quantifying policy synergies and designing green finance policies for high-emission sectors under the "dual carbon" goals.

Keywords: CCUS, financing decision, carbon policies, steel enterprise

NONMENCLATURE

Abbreviations

This is a paper for International CCUS Conference 2025 (ICCUSC 2025), May 28-29, 2025, Beijing, China.

CCUS	Carbon Capture, Utilization and Storage
Symbols	
η	Net capture rate
μ	Leakage rate

1. INTRODUCTION

On March 20, 2025, China's Ministry of Ecology and Environment (MEE) issued the Work Plan for Integrating the Steel, Cement, and Aluminum Smelting Industries into the National Carbon Market, incorporating these three energy-intensive sectors into the carbon trading system. This expansion adds approximately 3 billion tonnes of carbon emissions coverage.

China's steel industry accounts for over 15% of national carbon emissions, making its low-carbon transition critical for achieving Nationally Determined Contributions (NDC) targets. However, deep decarbonization technologies in this sector remain at the demonstration stage. Carbon Capture, Utilization, and Storage (CCUS) is regarded as a key transitional solution in the short term, yet its large-scale deployment faces systemic barriers including high technological costs, limited financing channels, and insufficient policy incentives.

Existing policy studies on CCUS promotion predominantly focus on traditional sectors like power and oil & gas (ZIEA, 2023), with notably inadequate attention to the steel industry—a stark contrast to its urgent decarbonization needs. Current research excessively prioritizes techno-economic analyses while neglecting financing mechanisms, a core industrial challenge (IEA, 2023). The World Bank reports that retrofitting steel plants with CCUS typically requires capital expenditures (CAPEX) exceeding ¥1 billion RMB, which cannot be supported solely by corporate funds (World Bank, 2023). Crucially, research on financial institutions' decision-making—particularly banks' roles in CCUS project financing—remains scarce, leading to policy designs that overlook supply-side financial constraints.

2. MATERIAL AND METHODS

2.1 Foundamental Assumptions

Assumption 1: If a steel enterprise chooses the strategy "Do Not Implement CCUS Technological Retrofitting", its products are all conventional types, yielding a revenue denoted as R_g. If the enterprise chooses the strategy "Implement CCUS Investment", its products qualify as green products. Due to factors such as product quality, environmental awareness, and green consumption economic policies, downstream enterprises (acting as consumers) demonstrate a preference for purchasing green products. Consequently, the enterprise's revenue becomes $(1+\alpha)*R_g$. Here, α represents the revenue growth rate attributable to the CCUS retrofitting, signifying the efficiency of the CCUS investment.

Assumption 2: Steel enterprises undertaking CCUS retrofitting require green credit financing from banks; otherwise, they must resort to alternative financing with higher costs.

Assumption 3: In carbon reduction governance, the government adopts either active or passive intervention strategies. Under active intervention: Non-retrofitting enterprises must purchase additional carbon allowances beyond their free allocation Q_e. Q represents CO_2 emissions without CCUS retrofitting. Q_0 represents CO_2 emissions with CCUS retrofitting.

Under passive intervention, enterprises face no carbon trading requirements. Notably, active government intervention incurs administrative costs C_2 for regulatory oversight. Considering the nascent development stage and public-good attributes of CCUS projects, the government primarily employs financial subsidies to incentivize participation. To broaden engagement, subsidies are allocated under a "participant-targeted" principle—only active participants receive subsidies.

2.2 Game Participants and Parameter Specification

Steel enterprises have two strategic choices: Implement CCUS Technological Retrofitting or Do Not Implement CCUS Technological Retrofitting. The probability of choosing retrofitting is denoted as X, and the probability of not retrofitting is $(1-X)$ When a steel enterprise chooses not to retrofit, its conventional products generate revenue R_S. It incurs a carbon allowance purchase cost $C_1 = (Q - Q_e) * P_e$, where P_e is the carbon trading price. If the bank implements a green credit policy, enterprises not retrofitting cannot obtain bank loans and must seek alternative financing, incurring an additional financing cost T.

When a steel enterprise chooses to implement CCUS retrofitting, its cost structure depends on bank credit policy. Since China's green credit practice supports financing for green projects and technological upgrades in traditional energy-consuming units, the retrofitting cost is F_1 if the bank provides green credit.

Without green credit, the enterprise faces a higher retrofitting cost F_2, where ($F_2 > F_1$). Due to factors such as enhanced product quality, environmental awareness, and green consumption policies, downstream enterprises (acting as consumers) demonstrate a greater willingness to purchase green products. Consequently, the enterprise's revenue from green products becomes (1 + α) * R_s , where α represents the revenue growth rate (α > 0). Additionally, the enterprise gains revenue $R_1 = P_e * (Q_e - Q_0)$ from selling surplus carbon allowances achieved through lower emissions.

Banks have two strategic choices: Implement Green Credit or Do Not Implement Green Credit. When implementing green credit, the bank receives a government subsidy $z * L$, where(0 < z < 1) is the subsidy coefficient and L is the green credit amount extended. Implementing green credit also yields green benefits R_g, which encompass reduced credit risk and long-term improvements in financial performance. However, the bank incurs costs C_3 for information gathering related to green loans and monitoring the green production activities of borrowing enterprises. If the bank chooses not to implement green credit, it earns revenue R_t from traditional credit activities. Under active government intervention, the bank faces penalty costs C_4 for failing to meet green credit performance evaluation standards.

The government has two strategic choices: Active Intervention or Passive Intervention. The probability of active intervention is z, and the probability of passive intervention is $(1 - z)$. When the government chooses active intervention, it incurs green policy and regulatory costs B_g associated with assessing bank green performance and monitoring enterprise carbon emissions. Enterprises exceeding their free carbon allowance allocation Q_e must purchase additional allowances. The government also provides a subsidy $z * L$ to banks implementing green credit and a subsidy S to steel enterprises undertaking CCUS retrofitting. Enterprises implementing CCUS retrofitting and engaging in low-carbon production generate socioeconomic benefits E (e.g., improved environment, public health) for the nation. Furthermore, the government imposes a penalty B_m on enterprises not implementing CCUS retrofitting.

When the government chooses passive intervention, it gains reduced socioeconomic benefits $\gamma * E$,(0 < γ < 1) if an enterprise implements CCUS retrofitting. Concurrently, passive intervention leads to negative economic consequences C_g , such as a weakened environmental ethos and lagging industrial structure, due to inadequate policy enforcement.

Table 1. Notation

Agents	Notation	Theoretical Essence
Government	B_g	Governmental policy and regulatory costs
	C_g	Economic losses under passive governance, including environmental ethos degradation and industrial structure stagnation
	Z	Government subsidy coefficient for green credit amount
	E	Socioeconomic benefits from enterprise CCUS retrofitting under active governance
	γ	Environmental benefit attenuation coefficient
	P_e	Unit carbon trading price
Banks	C_3	Green credit operational costs : information collection and monitoring expenditures
	R_t	Traditional credit revenue
	R_g	Green benefits: credit risk reduction and long-term financial performance enhancement
	C_4	Green credit performance penalty
Steel Enterprises	α	Green product revenue growth rate
	R_s	Conventional product revenue
	T	Alternative financing cost for non-retrofitting enterprises under green credit policy
	F_1	Enterprise CCUS retrofitting cost with green credit
	F_2	Enterprise CCUS retrofitting cost without green credit
	C_1	Carbon allowance purchase cost
	Q_e	Free carbon allowance allocation
	Q	Cumulative CO_2 emissions without CCUS retrofitting
	Q_0	Post-retrofitting CO_2 emissions
	S	Government retrofit subsidy
	R_1	Carbon allowance sales revenue post-retrofitting
	L	Retrofitting financing amount
	B_m	Non-retrofitting penalty

2.3 Payoff Matrix

Based on the preceding analysis, the payoff matrix for the constructed tripartite evolutionary game model is presented in Table 2:

Table 2. Payoff Matrix of the Three Stakeholders

		Steel Enterprises	
Government	Bank	Retrofit Z	Not retrofit $1-Z$
Active action X	Implement Y	$E-B_g-zL-S$ R_g+zL-C_3 $(1+\alpha)R_s+R_1+S-F_1$	B_m-B_g-zL $Rg+zL-C_3$ $R_s-C_1-T-B_r$
	Not implement $1-Y$	$E-B_g-S$ R_t-C_4 $(1+\alpha)R_s+R_1+S-F_2$	B_m-B_g R_t-C_4 $R_s-C_1-B_m$
Inactive action $1-X$	Implement Y	$\gamma E-C_g$ R_g-C_3 $(1+\alpha)R_s-F_1$	$-C_g$ R_g-C_3 R_s-T
	Not implement $1-Y$	$\gamma*E-C_g$ R_t $(1+\alpha)R_s-F_2$	$-C_g$ R_t R_s

Based on Table 2, the government's strategic choices in the game are (Active Intervention, Passive Intervention). When opting for Active Intervention, its expected payoff is denoted as $E(x_1)$; when choosing Passive Intervention, the expected payoff is $E(x_2)$. The government's average payoff is $E(\bar{x})$。

$$\begin{aligned}E(x_1)=Y*Z*(E-B_g-z*L-S)+\\ Y*Z*(B_m-B_g-z*L)\\ +(1-Y)*Z*(E-B_g-S)+\\ (1-Y)*(1-Z)*(B_m-B_g)\end{aligned}\quad(1)$$

$$E(x_2)=Z*(\gamma*E-C_g)+(1-Z)(-C_g)\quad(2)$$

$$E(\bar{x})=X*E(x_1)+(1-X)*E(x_2)\quad(3)$$

Based on the game structure, the bank's strategic choices are (Extend Green Credit, Do Not Extend Green Credit). When opting to extend green credit, its expected payoff is $E(y_1)$; when choosing not to extend green credit, the expected payoff is $E(y_2)$. The bank's average payoff is denoted as $E(\bar{y})$.

$$\begin{aligned}E(y_1)=X*(Rg+z*L-C3)+(1-X)*(Rg-C3)+\\ x*(Rg+z*L-C3)+(1-X)*(Rg-C3)\end{aligned}\quad(4)$$

$$E(y_1)=X*(R_t-C_4)+(1-X)*(R_t)\quad(5)$$

$$E(\bar{y})=Y*E(y_1)+(1-Y)*E(y_2)\quad(6)$$

The steel enterprise's strategic choices in the game are (Implement CCUS Technological Retrofitting, Do Not Implement CCUS Technological Retrofitting). When opting to implement retrofitting, its expected payoff is $E(z_1)$; when choosing not to implement retrofitting, the expected payoff is $E(z_2)$. The steel enterprise's average payoff is denoted as $E(\bar{z})$.

$$\begin{aligned}E(z_1)=X*Y*((1+\alpha)*R_s+R_1+S-F_1)+\\ (1-X)*Y*((1+\alpha)*R_s-F_1)+\\ (1-X)*(1-Y)*((1+\alpha)*R_s-F_2)+\\ (1-Y)*X*((1+\alpha)*R_s+R_1+S-F_2)\end{aligned}\quad(7)$$

$$\begin{aligned}E(z_2)=X*Y*(R_s-C_1-T-B_m)+\\ X*(1-Y)*(R_s-C_1-B_m)+\\ Y*(1-X)*(R_s-T)+(1-X)*(1-Y)*R_s\end{aligned}\quad(8)$$

$$E(\bar{z})=Z*E(z_1)+(1-Z)*E(z_2)\quad(9)$$

2.4 Replication Dynamic Equations

A replication dynamic system is constructed to analyze strategy stability. The replication dynamic equations for the steel enterprise, bank, and government are respectively defined as follows:

Replication Dynamic Equation for the Steel Enterprise:

$$\begin{aligned}F(X)=\frac{dX}{dt}=X*(X-1)*\\ (B_g-B_m-C_g+B_m*Z-E*Z+\\ S*Z+L*z*y+E*\gamma*Z)\end{aligned}\quad(10)$$

Replication Dynamic Equation for the Bank:

$$\begin{aligned}F(Y)=\frac{dY}{dt}=-Y*(Y-1)*\\ (R_g-C_3-R_t+C_4*X+L*z*X)\end{aligned}\quad(11)$$

Replication Dynamic Equation for the Government:

$$\begin{aligned}F(Z)=\frac{dZ}{dt}=-Z*(Z-1)*\\ (R_s*\alpha-F2+B_m*X+C_1*X-F_1*Y+F_2*Y\\ +R_1*X+S*X+T*Y)\end{aligned}\quad(12)$$

According to Friedman's analytical approach, the evolutionarily stable strategy (ESS) can be determined by analyzing the local stability of the Jacobian matrix for the system of differential equations. Evolutionary game theory posits that an equilibrium point becomes an evolutionarily stable strategy (ESS) when all eigenvalues of the Jacobian matrix are negative. If all eigenvalues are positive, the equilibrium is unstable. When eigenvalues exhibit both positive and negative values, the equilibrium constitutes a saddle point.

$$J = \begin{bmatrix} \frac{\partial F(X)}{\partial x} & \frac{\partial F(X)}{\partial y} & \frac{\partial F(X)}{\partial z} \\ \frac{\partial F(Y)}{\partial x} & \frac{\partial F(Y)}{\partial y} & \frac{\partial F(Y)}{\partial z} \\ \frac{\partial F(Z)}{\partial x} & \frac{\partial F(Z)}{\partial y} & \frac{\partial F(Z)}{\partial z} \end{bmatrix} \quad (13)$$

Table 3. Stability Analysis of Local Equilibrium Points

Equilibrium Point	Eigenvalue	Asymptotically Stable
E1(0, 0, 0)	$\lambda_{11} = B_m - B_g + C_g$	Indeterminate
	$\lambda_{12} = R_g - C_3 - R_t$	Indeterminate
	$\lambda_{13} = \alpha * R_s - F_2$	Indeterminate
E2(1, 0, 0)	$\lambda_{21} = B_g - B_m - C_g$	Indeterminate
	$\lambda_{22} = C_4 - C_3 + R_g - R_t + L * z$	Indeterminate
	$\lambda_{23} = B_m + C_1 - F_2 + R_1 + S + \alpha * R_s$	Indeterminate
E3(0, 1, 0)	$\lambda_{31} = B_m - B_g + C_g - L * z$	Indeterminate
	$\lambda_{32} = C_3 - R_g + R_t$	Indeterminate
	$\lambda_{33} = T - F_1 + \alpha * R_s$	Indeterminate
E4(0, 0, 1)	$\lambda_{41} = C_g - B_g + E - S - \gamma * E$	Indeterminate
	$\lambda_{42} = R_g - C_3 - R_t$	Indeterminate
	$\lambda_{43} = F_2 - \alpha R_s$	Indeterminate
E5(1, 1, 0)	$\lambda_{51} = B_g - B_m - C_g + L * z$	Indeterminate
	$\lambda_{52} = C_3 - C_4 - R_g + R_t - L * z$	Indeterminate
	$\lambda_{53} = B_m + C_1 - F_1 + R_1 + S + T + \alpha * R_s$	Indeterminate
E6(1, 0, 1)	$\lambda_{61} = B_g - C_g - E + S + \gamma * E$	Indeterminate
	$\lambda_{62} = C_4 - C_3 + R_g - R_t + L * z$	Indeterminate
	$\lambda_{63} = F_2 - C_1 - B_m - R_t - S - \alpha * R_s$	Indeterminate
E7(0, 1, 1)	$\lambda_{71} = C_g - B_g + E - S - L * z - \gamma * E$	Indeterminate
	$\lambda_{72} = C_3 - R_g + R_t$	Indeterminate
	$\lambda_{73} = F_1 - T - \alpha * R_s$	Indeterminate
E8(1, 1, 1)	$\lambda_{81} = B_g - C_g - E + S + L * z + \gamma * E$	Indeterminate
	$\lambda_{82} = C_3 - C_4 - R_g + R_t - L * z$	Indeterminate
	$\lambda_{83} = F_1 - C_1 - B_m - R_1 - S - T - \alpha * R_s$	Indeterminate

2.5 Enumerical Case Study

To visually demonstrate the impact of initial willingness levels and parameter variations on stakeholder strategy selection, this section assigns parameter values based on scholarly research and real-world data. Sensitivity analysis is conducted by setting reasonable initial values and adjusting key parameters during simulations. Specific parameter assignments are detailed in Table 4.

As pioneering Chinese steel enterprises undertaking CCUS retrofitting, BaoSteel serves as the benchmark. Revenue from conventional products R_s is set at 25,135,200RMB (source: BaoSteel 2024 Annual Report). Following Xu Wanyue et al. (2024), post-retrofitting product sales growth rate $\alpha = 0.3$, yielding green product revenue $(1+\alpha)*R_s$.

CO_2 emissions without retrofitting Q ,Net capture rate $\eta = 85\%$ (Wei Ning et al., 2021). CO_2 intensity β=2.04 t-CO2/t-crude steel (average from BaoSteel 2024 Sustainability Report), with crude steel output Q_s=4993 million tons. Thus:

$$Q = \beta * Q_s \quad (14)$$

CO_2 emissions with retrofitting Q_0 . Comprises uncaptured emissions Q_{unc} and leakage during transport/storage Q_{es}. Leakage rate $\mu = 5\%$ (industry range: 1–5%):

$$Q_0 = Q_{unc} + Q_{es} \quad (15)$$

$$Q_{unc} = (1 - \eta)Q \quad (16)$$

$$Q_{es} = \mu * Q \quad (17)$$

Free carbon allowance Q_{es} . Based on industry benchmarking:

$$Q_e = 0.95 * \beta * Q_s \quad (18)$$

Carbon trading parameters. Carbon price Pe=91.8 RMB/t (2024 CEA average, IFIND data). Revenue from allowance sales $R_1$and purchase cost C_1:

$$R_1 = P_e * (Q_e - Q_0) \quad (19)$$

$$C_1 = P_e(Q - Q_e) = 5\%\beta * Q_s * P_e \quad (20)$$

Retrofitting costs With green credit F_1 : Direct cost c=420 RMB/t-CO2 (converted from $65/t at 2021 exchange rate, RENL study). Green credit interest rate r_g=2.1% (Green Bond Catalogue, 2021):

$$F_1 = C + C_{gr} \quad (21)$$

$$C_{gr} = r_g * c * Q \quad (22)$$

$$C = c * Q \quad (23)$$

Without green credit F_2 : Traditional loan rate rt=3.6% (5Y+ LPR, April 2025):

$$F_2 = C + C_t \quad (24)$$

$$C_t = r_t * c * Q \quad (25)$$

Alternative financing cost T: Rate rT=4.0%, where

$$T = r_T * L \quad (26)$$

Carbon social cost Coefficient λ_g =50 RMB/t-CO2 (midpoint of 20–80 RMB/t, Tsinghua Zhang Xiliang Team, 2021):

$$C_g = \lambda_g * (Q - Q_0) \quad (27)$$

Environmental benefits. Active governance benefit E. Passive governance benefit γEwith γ=0.5 (Jiao Jianling et al., 2017).

$$E = \lambda_g * (Q - Q_0) \quad (28)$$

Subsidies & penalties. Enterprise retrofit subsidy S, λs=30 RMB/t-CO2. Regulatory cost B_g , λ_b =5%, (Ma Caichen et al., 2017). Non-compliance penalty B_m (a =7.5, midpoint of 5–10× penalty per Carbon Emissions Trading Management Regulations).

$$S = \lambda_s * (Q - Q_0) \quad (29)$$

$$B_g = \lambda_b * L \quad (30)$$

$$B_m = a * P_e \quad (31)$$

Green credit parameters. Loan amount L . Management cost C_3 , b =1.2%, Green Finance in Emerging Markets, World Bank 2019). Subsidy coefficient z=1.5% (Hong Xiangjun et al., 2023). Green performance penalty C_4, λ4=2%.

$$L = (F_1 + F_2)/2 \quad (32)$$

$$C_3 = b * L \quad (33)$$

$$C_4 = \lambda 4 * L \quad (34)$$

traditional credit revenues is $R_t = r_t * L$, green credit revenues as $R_t = r_t * L$.

$$R_t = r_t * L \quad (35)$$

$$R_g = r_t * L \quad (36)$$

Initial parameter values are comprehensively summarized in Table 4.

Table 4. Initial Values of Parameters

Parameter Symbols	Values	Sources
λ_b	5%	Cai Chen et al., 2017
α	0.3	Xuan Wanyue et al., 2024
R_s	25135200 billion yuan	Annual Report of Baosteel Co., Ltd. 2023
Q_e	9676.415 million tons of CO_2	Industry practice
z	1.5%	Hong Xiangjun et al., 2023
P_e	91.8 yuan/ton of carbon dioxide	2024 National Carbon Market Emission Allowance Trading Data
C_4	8.64 yuan/ton of carbon dioxide	
γ	0.5	Jiao Jianling et al., 2017
λg	50 yuan/ton of carbon dioxide	Zhang Xiliang's Team, Tsinghua University
b	1.2%	World Bank, Green Finance in Emerging Markets
r_t	3.6%	5-year LPR (Loan Prime Rate) of the People's Bank of China
r_g	2.1%	Catalogue of Green Bond-Supported Projects (2021 Edition)
rT	4.0%	
C	420 yuan/ton of carbon dioxide	(Ren L et al., 2021)
Qs	4993 million tons	Annual Report of Baosteel Co., Ltd. 2022
η	85%	(Wei Ning et al., 2021)
μ	5%	
λs	30 yuan/ton of carbon dioxide	
λ4	2%	
a	7.5	Interim Regulations on the Administration of Carbon Emission Trading
β	2.04 tons of carbon dioxide per ton of crude steel	Sustainability Report of Baosteel Co., Ltd. 2024

To facilitate simulation analysis, the article divides the variable values obtained from the above parameter values by the adjustment coefficient 10^7, and the standard values of each variable are as follows: $B_g = 220.01112$, a=0.0075,$C_g = 422.70$, E=422.70655,

S=253.62393, L=4400.2224, z=0.01, γ=0.5, P_e=30, R_g=92.4046704, C_3=52.8026688, R_t=158.4080064, C_4=88.004448, R_s=25135.20, α=0.3, F_2=4430.7795, Q=8.14856, F_1=4390.0367, Q_e =7.639275, T=176.008896.

Analysis based on Lyapunov stability theory shows that the stability characteristics of the system's equilibrium points can be determined by the signs of the eigenvalues of the Jacobian matrix. Specifically: when all eigenvalues of the Jacobian matrix are negative real numbers, the corresponding equilibrium point has asymptotic stability; if all eigenvalues are positive, the equilibrium point is in an unstable state; when the eigenvalues have different signs, the system exhibits saddle point characteristics. According to the numerical analysis results in the table, the equilibrium point E_8(1,1,1) is the only equilibrium solution that satisfies the stability conditions in the tripartite evolutionary game system among the government, steel enterprises, and banks, meaning the government chooses active action, steel enterprises choose CCUS technological transformation, and banks choose to issue green credit.

Table 5. Stability of Each Equilibrium Point

Equilibrium Point	Positive/Negative Eigenvalues	Stability
E1(0,0,0)	(+, -, +)	Saddle point
E2(1,0,0)	(-, +, +)	Saddle point
E3(0,1,0)	(+, +, +)	Unstable point
E4(0,0,1)	(+, -, -)	Saddle point
E5(1,1,0)	(-, -, +)	Saddle point
E6(1,0,1)	(-, +, -)	Saddle point
E7(0,1,1)	(+, +, -)	Saddle point
E8(1,1,1)	(-, -, -)	Stable point

2.6 Influence of Initial Strategies on Evolution Resuls

By setting the initial values of x, y, and z as (0.1, 0.1, 0.1), (0.5, 0.5, 0.5), (0.9, 0.9, 0.9), and (0.1, 0.5, 0.9), the tripartite evolution results are obtained as shown in Figure 14. The probability of the government choosing active action tends to 1, the probability of banks choosing to issue green credit tends to 1, and the probability of steel enterprises choosing to invest in CCUS tends to 1. This indicates that different initial strategy proportions have little impact on the simulation results, which is consistent with the stability analysis findings.

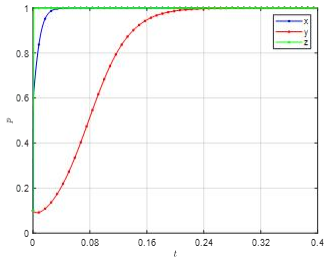

Fig. 1. Evolution results under initial values (0.1, 0.1, 0.1)

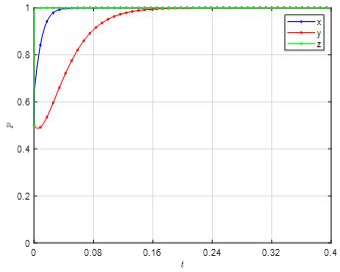

Fig. 2. Evolution results under initial values (0.5, 0.5, 0.5)

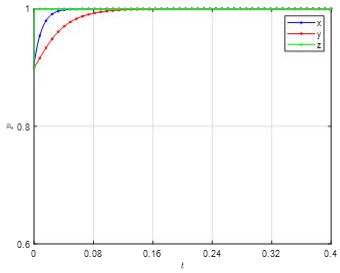

Fig. 3. Evolution results under initial values (0.9, 0.9, 0.9)

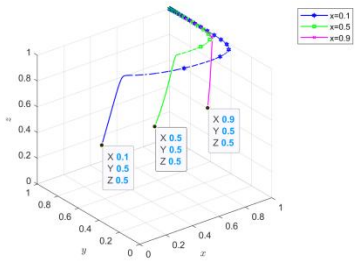

Fig. 4. Evolution results under initial values (0.1, 0.5, 0.9)

2.7 Sensitivity Analysis

Based on the tripartite game model, this study further conducts sensitivity analysis on key parameters, aiming to reveal the influence mechanisms of variables such as subsidy intensity, carbon price, and information cost on the strategic choices of the government, banks, and steel enterprises, providing a quantitative basis for policy optimization in CCUS technology promotion. The following discusses the specific parameter settings and analysis results.

2.7.1 Government Subsidy Coefficien

The enterprise subsidy coefficient λ_s directly reflects the government's fiscal support intensity for

CCUS transformation of steel enterprises. Its variation affects decisions by reducing enterprise transformation costs, influencing the evolutionary behaviors of each subject. When λ_S takes values of 10, 30, and 90 respectively, λ_S results indicate that the probability of steel enterprises implementing retrofitting significantly increases with higher \lambda_s, demonstrating the strong incentivizing effect of subsidies. Conversely, banks' willingness to provide green credit progressively decreases. This occurs because substantial subsidies substantially lower enterprise retrofitting costs, making the additional costs of traditional financing insufficient to compensate for the diminished revenue gap from green credit, thus disincentivizing banks.Government active intervention probability remains relatively low under weak subsidies, exhibits a moderate increase at intermediate subsidy levels, but declines and stabilizes at low levels under high subsidies due to fiscal pressure.

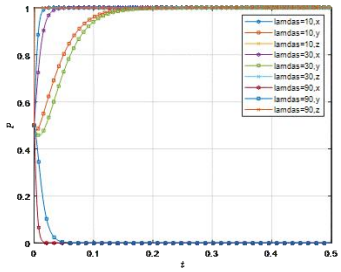

Figure. 5. Sensitivity Analysis of λ_S

2.7.2 Carbon Trading Price

The carbon trading price P_e, as the core variable of the carbon trading mechanism, affects enterprise profits by internalizing carbon emission costs, which in turn influences transformation decisions. By assigning P_e values of 30, 90, and 150 respectively, the simulation results of the evolution are shown in Figure 13. The carbon trading price P_e significantly impacts the strategic choices of steel enterprises. As the carbon trading price increases, the enthusiasm and convergence speed of steel enterprises adopting CCUS technology transformation strategies both increase, while it has no effect on the strategic probabilities of the government and banks. This implies that under the carbon price mechanism, the decision-making behaviors of the government and steel enterprises are more sensitive to carbon price changes, and their strategic choices can be guided by adjusting the carbon price, whereas bank strategies are relatively independent of carbon price fluctuations.

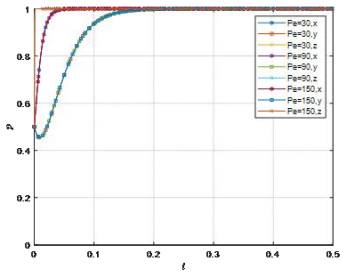

Figure. 6. Sensitivity Analysis of P_e

2.7.3 Information Cost for Green Credit

The information cost b for banks to issue green credit reflects the difficulty for financial institutions to obtain enterprise environmental data. Its level directly affects the cost-benefit ratio of green credit, thereby interfering with bank decision-making and possibly forcing the government and enterprises to adjust their strategies, influencing the evolutionary behavior of the three parties. This paper assigns three scenarios of b=1.2%, 5%, and 10%, and the simulation evolution results are shown in Figure 14. The results show that the information cost b significantly affects the strategic choices of the government and steel enterprises. The larger the b value, the faster the convergence speed of the two to take active actions and technological transformation respectively. With the increase of b value, the cost for banks to implement green credit increases, and the convergence rate of banks not issuing green credit becomes faster and faster. The b value can be adjusted to guide the government and steel enterprises to make positive decisions faster, but the negative impact on banks issuing green credit should be considered.

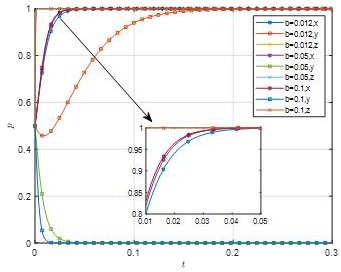

Fig. 7. Sensitivity Analysis of b

2.7.4 Subsidy Coefficient for Banks

The government's subsidy coefficient z for banks reflects the incentive intensity for financial institutions, influencing bank strategies by reducing the cost of green credit, and simultaneously indirectly affecting the government's own decisions due to changes in fiscal burden, thereby impacting the evolutionary behavior of the three parties. This paper assigns three scenarios of

z=1.5%, 2%, and 3.5%, and the simulation evolution results are shown in Figure 15. The parameter z has different impacts on the strategic choices of the government, banks, and steel enterprises. For the government, it shows a negative impact: the smaller the z value, the faster the government's strategy converges to passive inaction. For banks and steel enterprises, z has a positive effect: the larger the z value, the faster the convergence speed of banks implementing green credit strategies and steel enterprises carrying out CCUS technological transformation. In relevant decision-making contexts, adjustments to the z value have different influences on the strategic evolution of the three parties, so the selection of z needs to be comprehensively considered to guide the three parties to make decisions more in line with expectations.

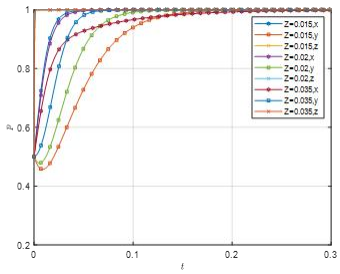

Fig. 8. Sensitivity Analysis of z

2.7.5 Social Cost of Carbon

The social cost of carbon (λg) quantifies the long-term environmental and economic damages caused by carbon emissions, and its value reflects the government's emphasis on ecological risks, thereby influencing policy enthusiasm and affecting the evolutionary behavior of the three parties. This paper assigns three scenarios of λg =10, 60, and 110, and the simulation evolution results are shown in Figure 16. The social cost of carbon significantly impacts the strategies of the three parties. When λg =10, the government's active action strategy rapidly declines and approaches 0. When λg is higher than 60, due to the excessively high socioeconomic and environmental benefit losses caused by carbon emissions, the government's convergence rate towards active action becomes faster and faster. When λg =10, the bank's green credit strategy also drops significantly to approach 0, and when λg is higher than 60, the bank's convergence rate to implement green credit becomes faster and faster. For steel enterprises, the probability of choosing transformation remains unchanged.

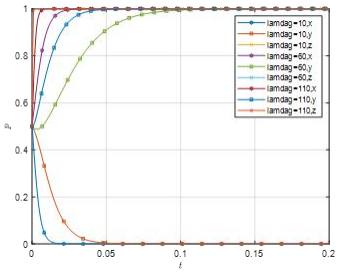

Fig. 9. Sensitivity Analysis of λg

2.7.6 Green Credit Revenue

The green credit revenue R_g reflects the commercial return for banks to carry out green finance, and its level directly determines the strategic choices of banks, while possibly indirectly affecting government fiscal pressure due to changes in financing scale. By assigning three scenarios of R_g =30, 70, and 100, this study observes the impact of revenue changes on banks' credit willingness and the sustainability of government strategies, to verify the key role of commercial sustainability in green credit. The simulation results are shown in Figure 17. Overall, different values of R_g lead to significant differences in the strategic evolution of the three parties. R_g has no impact on the probability of steel enterprises adopting CCUS technological transformation. When R_g is low, banks' strategies to implement green credit significantly decline and approach 0; when R_g is higher than 70, the probability of banks implementing green credit increases, and the convergence rate accelerates. For the government, the higher the R_g , the lower the probability of taking active actions, and the slower the convergence speed. This is because a higher R_g , possibly caused by an increase in financing scale, leads to higher government subsidies for banks' green credit, increasing fiscal burden and reducing the government's motivation to promote active strategies.

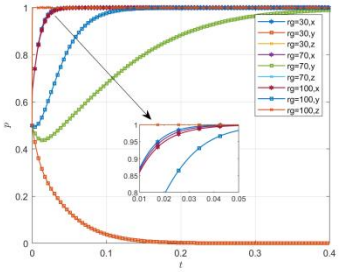

Fig. 10. Sensitivity Analysis of R_g

3. RESULTS

In static simulation analysis, varying initial strategy proportions exhibit minimal impact on outcomes. The evolutionary game model among the government, banks, and steel enterprises converges to a unique stable equilibrium where the government enforces active intervention, banks extend green credit, and steel enterprises implement CCUS retrofitting—consistent with Lyapunov stability theory.

For government incentive policies: Increasing investment subsidies intensifies corporate willingness to adopt CCUS retrofitting while progressively weakening banks' green credit provision. Beyond a subsidy threshold, governmental intervention willingness declines. Higher green credit subsidies significantly strengthen banks' lending motivation and corporate retrofitting intent, yet reduce governmental proactive engagement.

Regarding other parameters: Rising carbon prices strongly motivate corporate retrofitting but negligibly affect governmental or banking strategies. Elevated green credit operational costs suppress bank participation while amplifying governmental intervention and corporate retrofitting. Higher carbon social costs enhance governmental and banking engagement without altering corporate behavior. Increased green credit returns incentivize banks but diminish governmental intervention, leaving corporate decisions unchanged.

4. CONCLUSIONS

Moderate fiscal subsidies for steel CCUS retrofitting by establishing subsidy thresholds with dynamic adjustment mechanisms to alleviate fiscal burdens. Implement declining free carbon allowance allocations to compel high-emission enterprises to internalize carbon costs. Refine carbon pricing mechanisms through price floors or carbon taxes to ensure long-term growth and enhance corporate motivation.

Address high bank green credit costs via interest subsidies and tax relief. Adopt a phased subsidy scheme: initially elevate subsidies to stimulate lending, then gradually reduce support while transitioning to market-driven instruments to avoid fiscal dependency.

Integrate carbon social costs into governmental performance evaluations to compel stricter oversight. Mandate carbon cost assessments in bank credit reviews. Monitor green credit returns, reducing direct intervention when market mechanisms mature.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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