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How does carbon emissions trading scheme affect emission reduction decisions of coal-fired power plants? An evolutionary game theoretic perspective

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ABSTRACT. Carbon emissions trading scheme (CETS) is widely regarded as a cost-effective market-based regulation for carbon abatement. In the context of CETS, this study develops an evolutionary game model that incorporates two representative coal-fired power plants and a government. Our model captures the interplay of emission reduction strategies between coal-fired power plants and endogenously incorporates government regulatory decisions. We analyze the strategic decisions of coal-fired power plants by discussing the dynamics and equilibrium of the game. Our findings demonstrate that in the absence of government implementation of CETS, coal-fired power plants refrain from investing in carbon abatement. However, with the enforcement of CETS, along with sufficient penalties for excessive carbon emissions, coal-fired power plants become inclined to invest in emission reduction. Furthermore, the willingness of coal-fired power plants to invest in carbon abatement exhibits a negative relationship with both the quota and the cost of emission reduction.

1. Introduction

In recent years, the environmental challenges arising from excessive greenhouse gas emissions have garnered significant attention. Consequently, governments worldwide have placed great importance on the implementation of effective policies aimed at promoting renewable energy consumption and curbing carbon emissions[1-2]. Given that fossil fuel-based energy production contributes substantially to global carbon emissions[3], it becomes imperative to prioritize emissions reduction within this sector as a key strategy for climate change mitigation.

Carbon Emissions Trading Scheme (CETS) is perceived as a viable market-based solution for carbon abatement. Under the CETS framework, coal-fired power plants receive an allocation of carbon emission quotas. They are compelled to purchase carbon permits from other plants if their carbon emissions exceed their quotas. Conversely, these plants have the option to sell any surplus carbon permits at their disposal[4]. At the end of a given compliance period, power plants must hold enough carbon quotas or face severe penalties. Extant research suggests that the effectiveness of the CETS hinges strongly on the design of its core policy indicators, namely the price of carbon permits, the quota allocation, and the penalty scheme[5-7]. These policy indicators may impact the production decisions of coal-fired power plants by influencing their production costs, consequently leading to a reduction in carbon emissions. Therefore, it is crucial to examine how these policy indicators may influence the efficacy of the CETS.

This study aims to investigate how CETS affects the carbon reduction decisions of coal-fired power plants, considering both the strategic decisions of the government and the interplay between power plants. Our study is mainly related to three streams of literature on CETS: (1) the impact of CETS on the reduction of carbon emissions and its effects on social welfare; (2) the implications of CETS on manufacturers; and (3) the influence of CETS on the adoption of green technology and investments in carbon abatement.

The first stream of literature relevant to our work concerns the carbon abatement and social welfare effects of CETS. Governments have implemented a range of policies aimed at mitigating carbon emissions, each yielding diverse outcomes. Holland et al.[8] conducted a comparative analysis of renewable fuel standards, low carbon fuel standards, ethanol subsidies, and cap-and-trade systems (a form of CETS which establishes the aggregate carbon quota based on total carbon emission targets), specifically focusing on their efficacy in reducing greenhouse gas emissions from transportation fuels. They also evaluated the externalities associated with different policy approaches. Their findings suggest that cap-and-trade systems may entail lower societal costs and offer a more effective means of addressing environmental externalities. Du et al.[9] developed a Stackelberg game model for multi-stage carbon

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abatement that incorporates firms' considerations regarding quota allocation and the additional cost of abatement. They subsequently identified the optimal grandfathering scheme from a governmental perspective, aiming to maximize social welfare. In the pursuit of Pareto optimal designs for CETS, Feijoo and Das[10] devised a two-layer mathematical-statistical model incorporating the DC optimal power flow (DC-OPF) model and policy optimization. Within the cap-and-trade program context, He et al.[11] explored the optimal production decisions of a self-pricing firm and the optimal cap-setting decisions of a regulator. Their study constructed a Stackelberg game model, wherein the firm seeks to maximize profits as a follower, while the regulator acts as the leader striving to enhance social welfare. Results indicate that as emission intensity increases, the ideal total emissions and the optimal emission cap initially rise but eventually decline. Employing a game-theoretic model, Li et al.[12] analyzed the response of a firm's operational decisions regarding sustainable energy consumption and low carbon production to changes in the cap-and-trade policy. Their findings highlight the importance of policies that elevate consumer preference for low-carbon items as a crucial step towards maximizing total social welfare, particularly if technological upgrades are necessary. In summary, this stream of literature indicates that CETS has the potential to entail lower societal costs, effectively mitigate environmental externalities, and enhance social welfare. Meanwhile, the quota system stands as a fundamental component of CETS, and its reasonable formulation and allocation serve as the bedrock for the effective implementation of CETS.

The second stream of relevant work studies the effects of CETS on manufacturers. Using Stackelberg game theory, Xu et al.[13] and Xu et al.[14] investigated the operational decisions of a multi-product manufacturer under cap-and-trade and carbon tax policies. They compared the effects of these policies on total carbon emissions, the manufacturer's profit, and social welfare. Considering cap-and-trade and consumers' low-carbon preference, Ding et al.[15] developed a Stackelberg game to analyze the equilibrium decisions under different conditions. They found that the carbon price and quota have an impact on the manufacturer and retailer's profit when the manufacturer adopts encroachment decisions. According to Curtis and Lee [16], the NOx Budget Trading Program (NBP), which was put into place in 19 states across the country in 2004, received a heterogeneous response from manufacturing firms of all ages and sizes. Huang et al. [17] utilized a duopoly model to explore the behavior of competing manufacturers under CETS. Their results demonstrate that CETS can promote cooperation among manufacturers and may not necessarily have a negative impact on their profits. Furthermore, the cost advantage and high product substitution can accelerate the low-carbon transition for low-cost manufacturers. Chai et al. [18] studied how to make a monopolistic manufacturer, involved in manufacturing and remanufacturing operations, profitable under a carbon cap-and-trade mechanism in a single period. Their findings indicated that cap-and-trade favors remanufacturing in both the ordinary and green markets, with the carbon trading price playing a more important role in carbon emissions and manufacturer profitability than the carbon cap. Based on a closed-loop supply chain model, Hu et al.[19] analyzed the trade-off between the carbon tax and cap-and-trade system through numerical studies. Their findings reveal that the cap-and-trade system is better suited for the Chinese remanufacturing industry, as it outperforms the carbon tax system in terms of manufacturer profits, social welfare, and consumer surplus. This stream of literature highlights the impact of CETS on manufacturers' market power, profits, and their efforts for low-carbon transition. However, the existing literature lacks emphasis on the participants within the wholesale power market, specifically the coal-fired power plants.

The third stream of literature focuses on the impact of CETS on green technology adoption and carbon reduction investments. Zheng et al.[20] analyzed the decision-making of duopoly manufacturers under a cap-and-trade system. The result shows that the optimal production quantity of duopoly manufacturers and the initial carbon quota are both related to the level of green technology. Liu et al.[21] developed a dual-objective non-linear programming model that considers cap-and-trade and carbon abatement technology investment. This model shows that under a cap-and-trade system, investing in carbon abatement technology not only enables manufacturers to generate profits but also reduces greenhouse gas emissions. Given the significance of promoting the willingness of green technology adoption, Yang et al.[22] studied the difference between the effects of grandfathering and benchmarking on enterprises' green technology investment and product pricing. The findings indicate that grandfathering leads to a greater reduction in carbon emissions, while benchmarking is more effective in encouraging green technology investment. Drawing upon evolutionary game theory, Zhang et al.[23] investigated the influence of government policy on manufacturers' decision-making in the presence of cap-and-trade, demonstrating that imposing a high penalty can encourage manufacturers to adopt green technology. Pan et al.[24] proposed a two-party game model involving a greener and a dirtier manufacturer, highlighting the significant impact of carbon price and green technology costs on the implementation of green technology. Chen et al.[25] investigated firms' decisions and profits under peak-valley price policy and cap-and-trade within the electric power industry via a Stackelberg game. The findings indicate that the peak-valley policy helps enhance firms' willingness to invest in low-carbon technology. Overall, this body of literature suggests that corporate investment in emission reduction, such as the adoption of abatement technologies, may necessitate incentives provided by CETS. Furthermore, corporate willingness to reduce emissions is influenced by the design of policy indicators.

Despite the extensive literature on the impact of CETS, there is a lack of studies specifically investigating how CETS influence the emission reduction decisions of coal-fired power plants, which play a pivotal role in the electricity market. Wholesale electricity markets typically exhibit an oligopolistic structure, characterized by a small number of dominant power plants that share similar production costs and engage in interdependent decision-making[26-27]. Therefore, it is imperative to consider the interaction among these plants when analyzing abatement decisions. Additionally, most current studies neglect to explore the implications of strategic government decisions on the effectiveness of CETS. In fact, the government's choice to regulate or not is also influenced by cost-benefit considerations. Hence, as a decision-making entity, the government should not be treated as exogenous to the model.

To address the aforementioned issues, we propose an analytical framework within the context of CETS, which comprises two representative coal-fired power plants and a government. Given that wholesale power markets are often oligopolistic, it is reasonable to consider the interactions between these two representative coal-fired power plants. The investment decision of one plant regarding emission reduction will impact the availability of carbon permits in the market, thereby influencing the cost-benefit tradeoff and emission reduction decision of the other plant. Moreover, we incorporate the government as a decision maker into the model, endogenizing its regulatory decision-making process. Then, based on the assumption of bounded rationality, we use evolutionary game theory to model the dynamics of participants in our proposed framework. We obtain evolutionary stable strategies (ESSs) under different scenarios and draw some important conclusions by analyzing these ESSs. Finally, numerical analysis is carried out to validate our findings.

The main contributions of this study can be summarized as follows: (1) We develop an evolutionary game theoretic framework to analyze the influence of CETS on the carbon abatement decisions of coal-fired power plants. Our model incorporates both interacting representative coal-fired power plants and a government, thereby providing an avenue to investigate how government regulatory decisions and the carbon abatement choices made by other power plants influence the investment decisions of a focal power plant in carbon abatement; (2) We analyze the impact of CETS on coal-fired power plants by discussing ESSs under different scenarios. Our findings reveal that without the implementation of CETS by the government, coal-fired power plants will not spontaneously invest in emissions reductions. It is only when the government enforces CETS and imposes sufficient penalties for excessive carbon emission that coal-fired power plants will choose to invest in emission reduction. We also find that the effectiveness of CETS (i.e., its ability to stimulate power plants to invest in carbon abatement) is negatively related to both the quota and carbon abatement cost. These findings provide a solid theoretical basis for policymakers to design reasonable policy indicators for CETS.

The rest of this paper proceeds as follows. In the next section, we introduce the structures and assumptions of our evolutionary game model. In Section 3, we analyze the stability of equilibrium points and some corollaries are proposed. In Section 4, numerical simulations are presented. Section 5 concludes.

2. Model structures and assumptions

2.1. Problem description and symbol definition

In this research, we assume that the governments and coal-fired power plants are players with bounded rationality. After recognizing each other's strategies, they constantly learn and adjust their behavior according to the payoffs of their participants.

There are three ways for coal-fired power plants to fulfill their carbon abatement obligations: (1) invest in carbon abatement equipment; (2) purchase permits from other power plants; (3) pay for the penalty. If a coal-fired power plant chooses to invest in carbon abatement equipment, it will have a surplus of carbon emissions permits, which also brings tremendous carbon abatement costs. Otherwise, they need to buy the permits or pay for the penalty for its excessive carbon emission.

The coal-fired power plant T_1 and T_2 can choose not to invest in carbon abatement (N) or to invest in carbon abatement (R), and the corresponding probabilities are x (or y) and $1-x$ (or $1-y$), respectively. The government can choose not to supervise (implement CETS) or to supervise carbon emissions of coal-fired power plants, with probabilities of z and $1-z$ respectively. Their interactions are shown in Fig. 1.

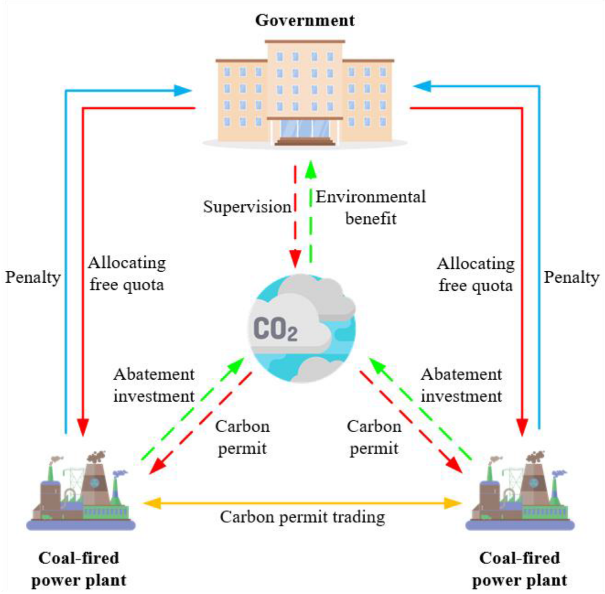

Fig. 1. An illustration of the interactions between coal-fired power plants and the government

The definitions and descriptions of symbols in this paper are shown in Table 1.

Table 1 Explanation of symbols

Symbols	Definition and description
P_e	The price (yuan / kWh) per unit of electricity
P_f	The penalty per unit of carbon emissions

	(kg) that exceed the quotas
P_{CET}	The price of carbon permits needed to offset a unit of carbon emissions (kg)
Q_h	The electricity (kWh) produced by coal-fired power plant in a cycle
Q_r	Carbon emission reduction of coal-fired power plants after carbon abatement investment
C_r	The costs that plants need to pay for carbon abatement
C_e	The reputation loss caused by government inaction
C_p	The costs of government supervision
β	The quotas allocated by the government to coal-fired power plants
ε	Carbon emissions (kg) per unit of electricity (kw) produced
γ	Net loss of social welfare resulting from unit carbon emissions (kg)

2.2. Model assumptions

Assumption 1: The government and coal-fired power plants are boundedly rational participants.

Assumption 2: T_1 and T_2 are two representative coal-fired power plants in power market. Both T_1 and T_2 have the same production capacity.

Assumption 3: The initial carbon emission of coal-fired power plants is greater than the quotas allocated by the government.

Assumption 4: P_{CET} is lower than P_f .

Assumption 5: Quotas are allocated to coal-fired power plants by the government for free.

2.3. Payoff matrix

(1) If the government does not supervise carbon emissions and both T_1 and T_2 do not invest in carbon abatement, then coal-fired power plants don't have to pay for carbon abatement, their payoffs can be expressed as:

$$R_{n1} = P_e \times Q_h \tag{1}$$

The government has to pay for environmental costs and reputation loss, its payoff can be expressed as:

$$R_{g1} = -2 \times \gamma \times \varepsilon \times Q_h - C_e \tag{2}$$

(2) If the government choose to supervise and T_1 (or T_2) choose to invest in carbon abatement, then T_1 (or T_2) has to pay for carbon abatement, its payoff can be expressed as:

$$R_{r1} = P_e \times Q_h - C_r \tag{3}$$

T_2 (or T_1) 's payoff can be expressed as Eq. (1); the government's payoff can be expressed as:

$$R_{g2} = -2 \times \gamma \times \left(\varepsilon \times Q_h - Q_r \right) - C_e \tag{4}$$

(3) If the government chooses not to supervise and both T_1 and T_2 choose to invest in carbon abatement, then the payoffs of coal-fired power plants can be expressed as Eq. (3), the government's payoff can be expressed as:

$$R_{g3} = -2 \times \gamma \times \left(\varepsilon \times Q_h - 2 \times Q_r \right) - C_e \tag{5}$$

(4) If the government chooses to supervise and neither T_1 nor T_2 chooses to invests in carbon abatement, then coal-fired power plants have to pay for penalty, and their payoffs can be expressed as:

$$R_{n2} = P_e \times Q_h - P_f \times \left(\varepsilon \times Q_h - \beta \right) \tag{6}$$

The government has to pay for environmental costs and supervision costs, its payoff can be expressed as:

$$R_{g4} = -2 \times \gamma \times \varepsilon \times Q_h - C_P \tag{7}$$

(5) If the government chooses to supervise and T_1 (or T_2) chooses to invest in carbon abatement, then T_1 (or T_2) can get additional income by selling permits, its payoff can be expressed as:

$$R_{r2} = P_e \times Q_h - C_r + P_{CET} \times \left(\varepsilon \times Q_h - \beta \right) \tag{8}$$

T_2 (or T_1) 's payoff can be expressed as:

$$R_{n3} = P_e \times Q_h - P_{CET} \times \left(\varepsilon \times Q_h - \beta \right) \tag{9}$$

The government's payoff can be expressed as:

$$R_{g5} = -2 \times \gamma \times \left(\varepsilon \times Q_h - Q_r \right) - C_P \tag{10}$$

(6) If the government chooses to supervise and both T_1 and T_2 choose to invest in carbon abatement, then the payoffs of coal-fired power plants can be expressed as Eq. (3), the government's payoff can be expressed as:

$$R_{g6} = -2 \times \gamma \times \left(\varepsilon \times Q_h - 2 \times Q_r \right) - C_P \tag{11}$$

The revenue matrix of tripartite game model are shown in Table 2.

Table 2 Revenue Matrix of Tripartite Game Model

Government	Coal-fired power plants T_1	Coal-fired power plants T_2: N	Coal-fired power plants T_2: R
Non-supervision	N	$\left(R_{g1}, R_{n1}, R_{n1}\right)$	$\left(R_{g2}, R_{n1}, R_{r1}\right)$
	R	$\left(R_{g2}, R_{r1}, R_{n1}\right)$	$\left(R_{g3}, R_{r1}, R_{r1}\right)$
Supervision	N	$\left(R_{g4}, R_{n2}, R_{n2}\right)$	$\left(R_{g5}, R_{n3}, R_{r2}\right)$
	R	$\left(R_{g5}, R_{r2}, R_{n3}\right)$	$\left(R_{g6}, R_{r1}, R_{r1}\right)$

3. Model analysis

3.1. Replicator dynamic equation

The expected revenue of T_1 who chooses not to invest in carbon abatement can be calculated as follows:

$$U_X = yzR_{n1} + y(1-z)R_{n2} + (1-y)zR_{n1} + (1-y)(1-z)R_{n3}$$

(12)

The expected revenue of T_1 who chooses to invest in carbon abatement can be calculated as follows:

$$U_{1-X} = yzR_{r1} + y(1-z)R_{r2} + (1-y)zR_{r1} + (1-y)(1-z)R_{r1} \tag{13}$$

The expected revenue of T_1 can be calculated as follows:

$$\overline{U}_X = xU_X + (1-x)U_{1-X} \tag{14}$$

The replicator dynamic equation of T_1 can be calculated as follows:

$$F(x) = \frac{dx}{dt} = x(U_X - \overline{U}_X) \tag{15}$$

The expected revenue of T_2 who chooses not to invest in carbon abatement can be calculated as follows:

$$U_Y = xzR_{n1} + x(1-z)R_{n2} + (1-x)zR_{n1} + (1-x)(1-z)R_{n3} \tag{16}$$

The expected revenue of T_2 who chooses to invest in carbon abatement can be calculated as follows:

$$U_{1-Y} = xzR_{r1} + x(1-z)R_{r2} + (1-x)zR_{r1} + (1-x)(1-z)R_{r1} \tag{17}$$

The expected revenue of T_2 can be calculated as follows:

$$\overline{U}_Y = yU_Y + (1-y)U_{1-Y} \tag{18}$$

The replicator dynamic equation of T_2 can be calculated as follows:

$$F(y) = \frac{dy}{dt} = y(U_Y - \overline{U}_Y) \tag{19}$$

The expected revenue of government who chooses not to supervise carbon emissions can be calculated as follows:

$$U_Z = xyR_{g1} + x(1-y)R_{g2} + (1-x)yR_{g2} + (1-x)(1-y)R_{g3} \tag{20}$$

The expected revenue of government who chooses to supervise carbon emissions can be calculated as follows:

$$U_{1-Z} = xyR_{g4} + x(1-y)R_{g5} + (1-x)yR_{g5} + (1-x)(1-y)R_{g6} \tag{21}$$

The expected revenue of government can be calculated as follows:

$$\overline{U}_Z = zU_Z + (1-z)U_{1-Z} \tag{22}$$

The replicator dynamic equation of government can be calculated as follows:

$$F(z) = \frac{dz}{dt} = z(U_Z - \overline{U}_Z) \tag{23}$$

The Jacobian matrix of replicator dynamic equations is as follows:

$$J = \begin{bmatrix} (1-2x)(U_X - U_{1-X}) & x(1-x)(z \times P_f \times Q_C - P_f \times Q_C) & x(1-x)(y \times P_f \times Q_C + P_{CET} \times Q_C) \\ y(1-y)(z \times P_f \times Q_C - P_f \times Q_C) & (1-2y)(U_Y - U_{1-Y}) & y(1-y)(x \times P_f \times Q_C + P_{CET} \times Q_C) \\ 0 & 0 & (1-2z) \times (C_P - C_e) \end{bmatrix} \tag{24}$$

where:

$$Q_C = \varepsilon \times Q_h - \beta \tag{25}$$

3.2. Evolutionary stable strategy (ESS)

Proposition 1: The equilibrium points (x, y, z) of replicator dynamic equations are: $(0, 0, 0)$, $(0, 0, 1)$, $(0, 1, 0)$, $(1, 0, 0)$, $(0, 1, 1)$, $(1, 0, 1)$, $(1, 1, 0)$, $(1, 1, 1)$ and $(x_0, y_0, 0)$, where

$$x_0 = y_0 = \frac{C_r - P_{CET} \times Q_C}{P_f \times Q_C} \tag{26}$$

The conditions for each ESS are shown in Table 3.

Table 3 Corresponding conditions of ESSs

ESS	Condition
$(0, 0, 0)$	$C_r - P_{CET} \times Q_C < 0$, $C_P - C_e < 0$
$(0, 1, 0)$	$C_r - P_{CET} \times Q_C > 0$,
$(1, 0, 0)$	$C_r - P_f \times Q_C - P_{CET} \times Q_C < 0$, $C_P - C_e < 0$
$(1, 1, 0)$	$C_r - P_f \times Q_C - P_{CET} \times Q_C > 0$, $C_P - C_e < 0$
$(1, 1, 1)$	$C_P - C_e > 0$

Proof: Let $F(x) = 0$, $F(y) = 0$, $F(z) = 0$, then the equilibrium points $(0, 0, 0)$, $(0, 0, 1)$, $(0, 1, 0)$, $(1, 0, 0)$, $(0, 1, 1)$, $(1, 0, 1)$, $(1, 1, 0)$, $(1, 1, 1)$ can be obtained. When $x_0, y_0 \in [0, 1]$, the equilibrium point $(x_0, y_0, 0)$ can be obtained. According to the Lyapunov stability principle, if the eigenvalues corresponding to the equilibrium point have real negative parts, the equilibrium point is an evolutionary equilibrium point. The eigenvalues corresponding to the equilibrium point are shown in Table 4.

It can be seen from Table 4 that there are eigenvalues with real part greater than 0 in the Jacobian matrix at equilibrium points $(0, 0, 1)$, $(0, 1, 1)$, $(1, 0, 1)$ and $(x_0, y_0, 0)$, therefore, they cannot be asymptotically stable points. According to the Lyapunov stability principle, the general conditions for $(0, 0, 0)$, $(0, 1, 0)$, $(1, 0, 0)$, $(1, 1, 0)$ and $(1, 1, 1)$ to be asymptotically stable points are obtained.

Table 4 Eigenvalues of Jacobi matrix at each equilibrium point

Equilibrium points	Eigenvalues and symbols
$(0,\ 0,\ 0)$	$C_r - P_{CET} \times Q_C, C_r - P_{CET} \times Q_C, C_P - C_e$
$(0,\ 0,\ 1)$	$C_r, C_r, C_e - C_P$
$(0,\ 1,\ 0)$	$C_r - P_{CET} \times Q_C - P_f \times Q_C, P_{CET} \times Q_C - C_r, C_P - C_e$
$(0,\ 1,\ 1)$	$C_r, -C_r, C_e - C_P$
$(1,\ 0,\ 0)$	$P_{CET} \times Q_C - C_r, C_r - P_{CET} \times Q_C - P_f \times Q_C, C_P - C_e$
$(1,\ 0,\ 1)$	$-C_r,\ C_r,\ C_e - C_P$
$(1,\ 1,\ 0)$	$P_{CET} \times Q_C + P_f \times Q_C - C_r, P_{CET} \times Q_C + P_f \times Q_C - C_r, C_P - C_e$
$(1,\ 1,\ 1)$	$-C_r, -C_r, C_e - C_P$
$(x_0,\ y_0,\ 0)$	$x_0 \times (1-x_0) \times P_f \times Q_C, -x_0 \times (1-x_0) \times P_f \times Q_C, C_P - C_e$

Corollary 1: If the government does not implement CETS, coal-fired power plants will not choose to invest in carbon abatement.

Proof: According to the stability point analysis, if the government doesn't implement regulation, only the equilibrium point $(1,\ 1,\ 1)$ is an evolutionary equilibrium point, which means that coal-fired power plants are reluctant to spend additional costs for carbon abatement.

Corollary 2: If the government implements regulation, coal-fired power plants will choose to invest in carbon abatement only if P_f is large enough.

Proof: According to inequalities $C_r - P_f \times Q_C - P_{CET} \times Q_C < 0$ and $C_r - P_f \times Q_C - P_{CET} \times Q_C > 0$, under the premise of $C_P - C_e < 0$, coal-fired power plants don't choose to invest in carbon abatement if (27) is satisfied:

$$P_f < \frac{C_r}{Q_C} - P_{CET} \tag{27}$$

Under the premise of inequality $C_P - C_e < 0$, coal-fired power plants invest in carbon abatement if (28) is satisfied:

$$P_f > \frac{C_r}{Q_C} - P_{CET} \tag{28}$$

Corollary 3: If the government implements regulation, the carbon abatement willingness of coal-fired power plants is negatively related to the quotas.

Proof: According to (25), $C_r - P_{CET} \times Q_C < 0$, $C_r - P_{CET} \times Q_C > 0$, $C_r - P_f \times Q_C - P_{CET} \times Q_C < 0$ and $C_r - P_f \times Q_C - P_{CET} \times Q_C > 0$, under the premise of $C_P - C_e < 0$, the point $(1,\ 1,\ 0)$ is an evolutionary equilibrium point if (29) is satisfied:

$$\varepsilon \times Q_h - \frac{C_r}{P_f + P_{CET}} < \beta \tag{29}$$

Under the premise of $C_P - C_e < 0$, the points $(0,\ 1,\ 0)$ and $(1,\ 0,\ 0)$ are evolutionary equilibrium points if (30) is satisfied:

$$\varepsilon \times Q_h - \frac{C_r}{P_{CET}} < \beta < \varepsilon \times Q_h - \frac{C_r}{P_f + P_{CET}} \tag{30}$$

Under the premise of $C_P - C_e < 0$, the point $(0,\ 0,\ 0)$ is an evolutionary equilibrium point if (31) is satisfied:

$$\beta < \varepsilon \times Q_h - \frac{C_r}{P_{CET}} \tag{31}$$

It can be seen from the above that with continuous reduction of quotas, coal-fired power plants gradually tend to invest in carbon abatement, that is, the fewer quotas are, the better the effectiveness of CETS is.

Corollary 4: If the government implements regulation, the carbon abatement willingness of coal-fired power plants is negatively related to the cost of carbon abatement.

Proof: According to (25), $C_r - P_{CET} \times Q_C < 0$, $C_r - P_{CET} \times Q_C > 0$, $C_r - P_f \times Q_C - P_{CET} \times Q_C < 0$ and $C_r - P_f \times Q_C - P_{CET} \times Q_C > 0$, under the premise of $C_P - C_e < 0$, the point $(1,\ 1,\ 0)$ is an evolutionary equilibrium point if (32) is satisfied:

$$P_f \times Q_C + P_{CET} \times Q_C < C_r \tag{32}$$

Under the premise of $C_P - C_e < 0$, the points $(0,\ 1,\ 0)$ and $(1,\ 0,\ 0)$ are evolutionary equilibrium points if (33) is satisfied:

$$P_{CET} \times Q_C < C_r < P_f \times Q_C + P_{CET} \times Q_C \tag{33}$$

Under the premise of $C_P - C_e < 0$, the point $(0,\ 0,\ 0)$ is an evolutionary equilibrium point if (34) is satisfied:

$$C_r < P_{CET} \times Q_C \tag{34}$$

It can be seen from the above that with continuous reduction of carbon abatement costs, coal-fired power plants gradually tend to invest in carbon abatement, that is, the lower the carbon abatement cost is, the better the effectiveness of CETS is.

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4. Numerical simulations

Following Nie et al.[28], we perform numerical simulations in different scenarios to validate our conclusions. For all scenarios, we set $P_e = 0.635$, $Q_h = 97500$, $\varepsilon = 0.835$, $P_{CET} = 0.8$, $\gamma = 0.8$, $Q_r = 20000$. Table 5 presents the corresponding values for other parameters. We assign values to the parameters based on the conditions of each scenario and then conduct numerical simulations, and the results are demonstrated in Table 5 and Figure 2-4. All the ESSs and corollaries were verified through numerical analysis, ensuring the validity of our main conclusions.

Table 5 Influence of changes in relevant indicators on ESS

Corresponding corollary	P_f	β	C_r	C_e	C_P	Corresponding conditions	ESS	Result
Corollary 1 (Scenario 1)	0.9	80000	2000	50000	60000	$C_P - C_e > 0$	$(1,1,1)$	Fig. 4
Corollary 2 (Scenario 2)	0.6	80000	2000	60000	50000	$C_P - C_e < 0,\ P_f < \frac{C_r}{Q_C} - P_{CET}$	$(1,1,0)$	Fig. 4
	0.9	80000	2000	60000	50000	$C_P - C_e < 0,\ P_f > \frac{C_r}{Q_C} - P_{CET}$	$(1,0,0)$ $(0,1,0)$	Fig. 3
Corollary 3 (Scenario 3)	0.9	100000	2000	60000	50000	$C_P - C_e < 0,$ $\varepsilon \times Q_h - \frac{C_r}{P_f + P_{CET}} < \beta$	$(1,1,0)$	Fig. 4
	0.9	80000	2000	60000	50000	$C_P - C_e < 0,\ \varepsilon \times Q_h - \frac{C_r}{P_{CET}}$ $< \beta < \varepsilon \times Q_h - \frac{C_r}{P_f + P_{CET}}$	$(1,0,0)$ $(0,1,0)$	Fig. 3
	0.9	60000	2000	60000	50000	$C_P - C_e < 0,$ $\beta < \varepsilon \times Q_h - \frac{C_r}{P_{CET}}$	$(0,0,0)$	Fig. 2
Corollary 4 (Scenario 4)	0.9	80000	3000	60000	50000	$C_P - C_e < 0,\ P_f \times Q_C$ $+ P_{CET} \times Q_C < C_r$	$(1,1,0)$	Fig. 4
	0.9	80000	2000	60000	50000	$C_P - C_e < 0,\ P_{CET} \times Q_C$ $< C_r < P_f \times Q_C + P_{CET} \times Q_C$	$(1,0,0)$ $(0,1,0)$	Fig. 3
	0.9	80000	1000	60000	50000	$C_P - C_e < 0,\ C_r < P_{CET} \times Q_C$	$(0,0,0)$	Fig. 2

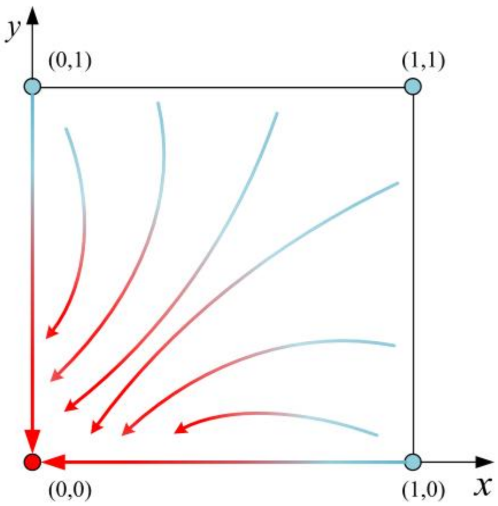

Fig. 2. The evolution trend of coal-fired power plants: (0, 0, 0) is an asymptotically stable point, that is, all coal-fired power plants invest in carbon abatement.

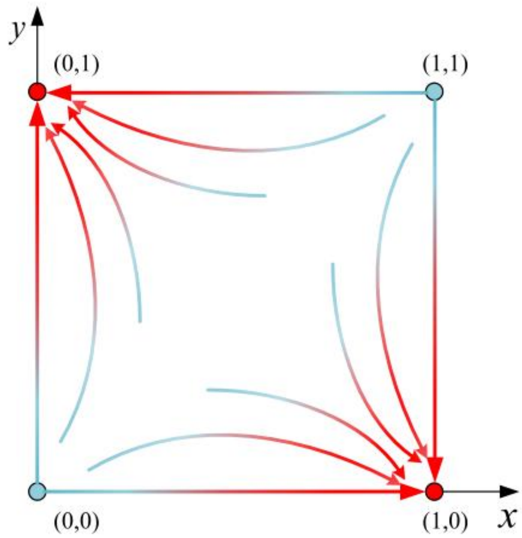

Fig. 3. The evolution trend of coal-fired power plants: (1, 0, 0) and (0, 1, 0) are asymptotically stable points, that is, one of the coal-fired power plants chooses to invest in carbon abatement.

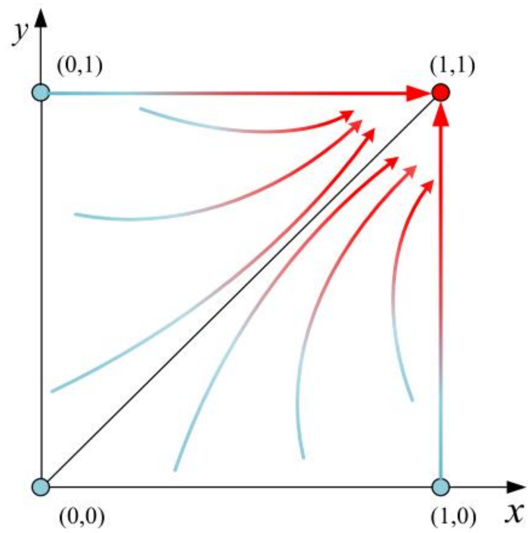

Fig. 4. The evolution trend of coal-fired power plants: (1, 1, 1) and (1, 1, 0) are asymptotically stable points, that is, coal-fired power plants don't invest in carbon abatement

5. Conclusion

In this study, we propose an analytical framework rooted in evolutionary game theory to study the impact of CETS on the strategic decisions of coal-fired power plants. Firstly, in the context of CETS, we construct a tripartite evolutionary game theoretic framework to model the dynamics of representative coal-fired power plants and the government under different scenarios. Secondly, by analyzing the ESS of each scenario, we analyze the impact of CETS on the strategic choices of coal-fired power plants. Finally, we corroborate our findings through numerical simulations.

The conclusions of this study are as follows: First, coal-fired power plants will not invest in carbon abatement if the government chooses not to implement CETS in all scenarios; Second, CETS is ineffective if the penalty for per unit carbon emission is not high enough. Coal-fired power plants will invest in carbon abatement only if the penalty exceeds a certain value; Third, the efficacy of CETS is negatively related to the carbon emission quota and the carbon abatement cost of power plants.

The findings of this paper may provide following managerial implications: Firstly, the government should implement CETS to promote the investment of carbon abatement of coal-fired power plants. Second, the government should establish a dynamical punishment mechanism to make sure that the penalty for excessive carbon emission is strictly higher than the cost of purchasing carbon emission permits; Third, the government should dynamically adjust the carbon emission quota in order to promote carbon abatement while protecting sufficient power supplies of the power market. Finally, the government should encourage innovation in carbon abatement technologies to effectively mitigate the carbon abatement cost for coal-fired power plants.

Author contributions

Bo Xu: Conceptualization, Methodology, Writing—review & editing, Supervision, Project administration. Liucheng Wu: Methodology, Investigation, Writing—original draft, Software, Visualization. Jiexin Wang: Conceptualization, Methodology, Investigation, Writing—original draft, Writing—review & editing.

Data availability

The data used in this study are available from the authors upon reasonable request.

Declarations

Ethical approval: Not applicable.

Consent to participate: All authors of this article consent to participate.

Consent for publication: All authors of the article consent to publish.

Competing interests: 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.

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