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Transition towards a hybrid energy system: Combined effects of renewable portfolio standards and carbon emission trading

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ABSTRACT

A hybrid energy system (HES) utilizing complementary energy sources allows for high-quality development of renewables. It is a viable pathway in achieving the low-carbon transition of the power sector. Both Renewable Portfolio Standards (RPS) and Carbon Emission Trading (CET) regulate the low-carbon behavior of conventional power enterprises. This highlights the importance of investigating how the policy mix can drive the transition towards hybrid power generation. This paper develops an evolutionary game between local governments and power enterprises to explore the influence of policy-related parameters on the transition to a hybrid energy system. We find that implementing the policy mix is imperative to the transition when the technology cost of a hybrid energy system is not competitive. Power enterprises can control investment costs through the structure of multi-energy power generation, but are also limited by the lack of renewable absorption capacity. We also find an additive effect between RPS and CET, albeit with differences. Raising the price of tradeable green power certificates (TGC) can effectively facilitate the transition under either a single RPS policy or the policy mix. Reducing initial carbon permits makes sense only under the policy mix. Moreover, the coordinated implementation of multiple policies can contribute to the transition more efficiently, but it deserves attention to avoiding policy redundancy.

1. Introduction

Developing such variable renewable energy (VRE) as wind and solar power in the power sector has turned into a promising strategy to reduce carbon emissions (Creutzig et al., 2017; Cherp et al. 2021; Zhou et al., 2022). However, the power output from VRE is not flexible enough as it varies with weather conditions (Fleten et al., 2018; Helm and Mier, 2021). Coupled with limited grid transmission capacity, blind incremental development of VRE can create a supply-demand mismatch and the curtailment of large-scale renewable energy sources (Burke and O'Malley, 2011).

A hybrid energy system (HES) that utilizes clean renewable energy sources in tandem with flexible conventional energy can effectively address this problem (Upadhyay and Sharma, 2014; Llobet and Padilla, 2018). The synergy of multiple energy sources with complementary characteristics contributes to the efficiency and the dispatchability of the power generation system, and provides capital cost savings (Powell et al., 2017). Local renewable energy endowments can be fully maximized, and electricity curtailment can be reduced (Mu et al., 2020; Jiang et al., 2020). Constructing a hybrid energy system by investing in renewable energy projects on existing coal-fired power generation facilities creates significant avenues for a low-carbon transition in the power sector. However, already-constructed energy facilities normally create a strong lock-in effect in the power sector (Seto et al., 2016). Especially in China, there are significant amounts of inexpensive coal and many massive coal-fired power plants (Cui et al., 2021; Zhao et al., 2023). The uncompetitive capital investments incurred by engaging with renewables may hamper the transition to a hybrid energy system (Huang and Zou, 2020; Yang et al., 2022).

To encourage the deployment of renewable power generation and decrease carbon emission, the governments of many nations have widely adopted Renewable Portfolio Standards (RPS) and Carbon Emission Trading (CET). RPS mandates that power enterprises generate a portion of electricity from renewables (Carley et al., 2018; Feldman and Levinson, 2023), accompanied by tradable green power certificates (TGC). Power enterprises have the option of investing in renewables or

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purchasing TGC to comply with the RPS regulation. It has been demonstrated that RPS policy effectively promotes the diffusion of renewables (Bento et al., 2018; Joshi, 2021; Deschenes et al., 2023). CET limits free carbon emission permits for power enterprises (Zhou and Wang, 2016; Jarke-Neuert and Perino, 2020). As such, power enterprises invest in clean energy technology such as renewables or carbon capture technology to lower carbon emissions, or must purchase extra carbon allowances. CET mechanism can increase the power output from clean energy technologies such as renewable energy (Meng et al., 2018; Morris et al., 2019; Roach and Meeus, 2023). However, some researchers also pointed out that the CET mechanism cannot support investment in renewables independently (Mo et al., 2016; Yan et al., 2022). When investing in clean energy, power enterprises may have excess TGC or carbon quotas to sell for more profit. Therefore, the RPS policy and CET mechanism can be regarded as both policy regulations and incentives for jointly facilitating power enterprises to transition to a hybrid energy system.

Many studies have investigated how policy impacts the transition investment decisions made by the power sector using the real option method (Boomsma et al., 2012), goal programming (Kök et al., 2016), and simulation method (Peng et al., 2020). However, these methods lack a consideration of the interactions between different agents. Strategies implemented by power enterprises and governments may interact (Hopkin, 2004). Power enterprises make trade-offs about whether to engage in the transition to hybrid energy system based on the cost-benefit of the technology and policy intensity. The main purpose of RPS and CET is to promote the diffusion of low-carbon energy facilities and to control carbon emissions (Tsao et al., 2011). Governments also regulate and optimize RPS and CET implementation based on the enforcement effect (Ding et al., 2020). Effectively establishing and coordinating these policies is critical because of the intersection between implementation measures. Policy redundancy can cause market failure and should be avoided (Delarue and Van den Bergh, 2016; del Río, 2017).

Evolutionary game theory (EGT) performs as a good theoretical paradigm for studying interactions in social and business decision-making process (Cai and Kock, 2009; Esmaeili et al., 2016). EGT researches strategic trends of groups based on individual behaviors, enabling an analysis of the dynamic behaviors and long-term strategic interaction effects between different agents (Xiao and Yu, 2006; Yi and Yang, 2017; Johari and Hosseini-Motlagh, 2022). It is suitable for exploring the strategic interaction of power enterprises and governments in the long-term, as well as gradual low-carbon transition processes. Some researches applied EGT to explore feasible pathways and policy effects of low-carbon technology substitution (Encarnação et al., 2018; Tang et al., 2021), including the impacts of RPS (Fang et al., 2018) and CET (Mirzaee et al., 2022). All of these studies, however, did not explore a hybrid energy system accounting for the complementarity of conventional and renewable energy. Only the impact of a single policy was seized. An obvious research gap exists in the effect of multiple policies on the investment in a hybrid energy system.

To facilitate the high-quality development of renewables and improve policy implementation, it is important to answer the following questions: (1) Will conventional fossil energy power enterprises make the transition decision to hybrid energy system under the dual polices of RPS and CET? (2) How should governments optimize RPS and CET implementation to promote the transition of conventional power enterprises? (3) Can the simultaneous implementation of RPS and CET be coordinated with each other? Are there policy redundancies? The objective of this research is to elucidate more effective policies, by understanding their underlying mechanisms, and to devise tactics for enhancing the transition to hybrid energy system by power enterprises.

This study contributes to the literature in the following three folds. First, it improves the research perspective by discussing the transition decision towards a hybrid energy system and involving the joint effect of RPS and CET. Second, given the interaction between the transition behavior and dual policies, we constructed an evolutionary game model between power enterprises and local governments. Third, the synergistic effect and conflict relation of the policy mix are obtained through an in-depth exploration of the impact of various policy parameters. It provides policy enlightenment for promoting the transition to a hybrid energy system.

The remainder of this paper is structured as follows. Section 2 constructs the evolutionary game model and Section 3 conducts analysis on the evolutionarily stable strategies (ESS). In Section 4, we investigate the effects of key parameters on the evolution results. Ultimately, Section 5 presents conclusions and policy recommendations.

2. Model

To promote the low-carbon transition, RPS and CET are deployed at the national level or regional level, and then implemented and supervised by local governments. The transition of conventional power enterprises to a hybrid energy system can satisfy policy regulatory requirements. This section constructs an evolutionary game model to expose the behavioral interactions between power enterprises and local governments. In addition to the complementary flexibility between renewable and traditional energy, photovoltaic and wind power are also complementary at a temporal scale (Costoya et al., 2023). Moreover, the low-carbon retrofitting of conventional power plants is likely to be more economical than building new renewable power generation facilities to meet carbon regulations (Talati et al., 2016). Thus, the hybrid energy system mentioned in this study is a stable combination of clean fossil power generation and renewable power generation, including photovoltaic and wind power. Existing conventional facilities are partially retrofitted with clean production technology and are partially replaced with renewable energy sources. Relevant study parameters are defined in Table 1.

2.1. Assumptions

To conduct the theoretical analysis, the following basic assumptions

Table 1
Parameter definitions of the evolutionary game model`.

Notation	Descriptions
n	Index of renewable energy sources, $n \in \{Photovoltaic, Wind\}$.
p_e^{TE}, p_e^n	Per unit on-grid price of traditional energy generation and renewable energy generation, respectively, where $p_e^{TE}, p_e^n > 0$.
c_{TE}, b_{TE}, c_n	Per unit cost of traditional energy generation, cleaner transformation of traditional energy generation, and renewable energy generation, respectively, where $c_{TE}, b_{TE}, c_n > 0$.
Q	Annual power generation of power enterprises, $Q > 0$.
$\varphi_{CO_2}^{TE}, \varphi_{CO_2}^{TEC}, \varphi_{CO_2}^{n}$	Carbon emission factors of traditional energy generation, traditional energy generation with cleaner transformation, and renewable energy generation, respectively, where $\varphi_{CO_2}^{TE}, \varphi_{CO_2}^{TEC}, \varphi_{CO_2}^{n} > 0$.
E_g	Annual volume of initial free carbon emission permits for power enterprises, $E_g > 0$.
p_{CO_2}	Unit carbon emission price, $p_{CO_2} > 0$.
p_{TGC}	Unit TGC price, $p_{TGC} > 0$.
μ	Minimum proportion of renewable energy generation to total energy generation for power enterprises, $\mu > 0$.
π	Tax rate, $0 \le \pi \le 1$.
W	Renewable power waste from the limited absorption capacity, $W > 0$.
α_n, β	Capacity ratio of power generation from renewable energy sources and clean traditional energy, respectively, where $0 \le \alpha_n, \beta \le 1, \sum \alpha_n + \beta = 1$.
x	Proportion of local governments implementing the policy mix concerning RPS and CET, $0 \le x \le 1$.
y	Proportion of power enterprises investing in a hybrid energy system, $0 \le y \le 1$.
$G_i (i = 1, 2, 3, 4)$	Revenue of local governments under different strategies.
$P_j (j = 1, 2, 3, 4)$	Revenue of power enterprises under different strategies.

are made.

Assumption 1. Players and strategies. Local governments and power enterprises are two players in the evolutionary game. Both exhibit bounded rationality and possess asymmetric information. Local governments can choose to implement and supervise the policy mix (RPS + CET) or take no actions (NO). Power enterprises can choose to transform to a hybrid energy system (HES) or maintain traditional energy generation (TG).

Assumption 2. Learning process. It is difficult for local governments and power enterprises to confirm the most profitable incipient option. Both participants can improve strategies by learning and correcting mistakes, and finally reach an evolutionary equilibrium (Hosseini-Motlagh et al., 2022).

Assumption 3. Stable power generation capacity of power enterprises. It is assumed that the transition does not cause changes in the overall power generation capacity Q. The model only considers changes in the generation structure. If investing in HES, partial fossil energy equipment ($\sum \alpha_n Q$) is eliminated by excluding residual values.

Assumption 4. Quota limit for renewable energy power generation. It is assumed that the ratio of renewable energy generation in HES is higher than the quota responsibility limit ($\sum \alpha_n > \mu$). If a power enterprise generates less renewable power than the quota responsibility, it is obliged to buy Tradable Green Certificates (TGC) from the market to meet the quota regulation. If a power enterprise's actual renewable power exceeds the regulated quota, it sells the surplus in the TGC market (Boomsma et al., 2012). The TGC market has sufficient capacity to allow for transaction bargaining. Power enterprises trade with participants in the TGC market, such as grid companies or individual consumers. Governments only set quota targets and supervise the market, and do not trade with power enterprises.

Assumption 5. Carbon emission permit and trading. The volume of initial free carbon emission permits E_g for power enterprises lies between the actual emissions of the TG ($\varphi_{CO_2}^{TE}Q$) and the HES ($\sum \alpha_n \varphi_{CO_2}^{n} Q + \beta \varphi_{CO_2}^{TEC} Q$). If a power enterprise emits more carbon dioxide (CO_2) than the permit allows, it is compelled to buy extra allowances from the trading market. If the emission level is lower than the permit allows, the enterprise may sell the excessive allowances (Wen et al., 2018). Power enterprises sell or buy allowances within the CET market, but do not trade with local governments.

2.2. Payoff matrix

The primary benefit of power enterprises is the revenue from selling electricity. When adhering to TG, the net profit from electricity sales after conducting taxes and costs is $\left[(1-\pi)p_e^{TE} - c_{TE}\right]Q$. If local governments implement the RPS policy, power enterprises should purchase a specified amount of TGCs μQ to meet the regulation requirement, of which the expenditure is $\mu p_{TGC} Q$. Meanwhile, if local governments implement the CET mechanism, power enterprises have to purchase carbon permits in excess of the initial free carbon permit E_g. The carbon emission generated by TG is$\varphi_{CO_2}^{TE}Q$, and then the expenditure on carbon allowances is $\left(\varphi_{CO_2}^{TE}Q - E_g\right)p_{CO_2}$.

The payoff of local governments comes mainly in the form of taxation and carbon control expenditures. With maintaining TG by power enterprises, local governments receive a tax on electricity sales of $\pi p_e^{TE} Q$. The carbon control expenditure is determined by government actions. In the absence of policy action, local governments pay for the actual carbon emission from power enterprises, i.e. $\varphi_{CO_2}^{TE} p_{CO_2} Q$. When adopting the CET mechanism, local governments pay for the cost to control pre-allocated carbon emissions, i.e. $E_g p_{CO_2}$.

When transitioning to HES, power enterprises put in new costs of renewable power generation and clean power generation from traditional energy. By setting the proportion of renewable energy and traditional energy as α_n and β, the net profit after tax is expressed as the sum of electricity sold from renewable and traditional power $\sum \alpha_n \left[(1-\pi)p_e^n - c_n\right]Q + \beta\left[(1-\pi)p_e^{TE} - c_{TE} - b_{TE}\right]Q$. Further, power enterprises may sell the surplus quota $\left(\sum \alpha_n - \mu\right)Q$ and obtain the after-tax TGC income $(1-\pi)\left(\sum \alpha_n - \mu\right)p_{TGC}Q$ under the RPS policy. Excess free carbon permits may likewise be the income of power enterprises under the CET mechanism. The carbon emission generated by HES is $\sum \alpha_n \varphi_{CO_2}^{n} Q + \beta \varphi_{CO_2}^{TEC} Q$, and then the after-tax carbon revenue is $(1-\pi)\left(E_g - \sum \alpha_n \varphi_{CO_2}^{n} Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2}$. The revenue generated by selling TGCs and carbon permits is equivalent to subsidy incentives from the market.

Correspondingly, local governments receive a tax on electricity sales of $\pi\left(\sum \alpha_n p_e^n + \beta p_e^{TE}\right)Q$. The policy action affects the carbon control costs. Additionally, it also determines whether local governments levy taxes on TGC sales $\pi\left(\sum \alpha_n - \mu\right)p_{TGC}Q$ and carbon sales$\pi\left(E_g - \sum \alpha_n \varphi_{CO_2}^{n} Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2}$. The HES can reduce the amount of renewable power wasted when the absorption capacity is limited. This potential benefit Wcan also be captured by local governments.

In summary, Table 2 shows the payoff matrix of local governments and power enterprises. The payments under different strategies in the table are presented in Eqs. (1)–(8).

2.3. Replicator dynamics equation

In the long-term evolutionary process, agents learn and adjust in response to the benefits of adopting different behavioral strategies. The replicator dynamics effectively characterize the variation and selection mechanism, providing a powerful analytical tool for describing the learning behaviors of game participants (Cressman and Tao, 2014). Each participant represents a specific population having the same attribute, who adopt pure strategy s for a long time. The term $\theta(t)$ is the proportion of populations adopting strategy s. The growth rate $\frac{d\theta(t)}{dt}$ is a strictly increasing function of the difference between the utility of strategy s and the average utility of the population.

Table 2
Payoff matrix.

$$G_1 = \pi\left(\sum \alpha_n p_e^n + \beta p_e^{TE}\right)Q + \pi\left(\sum \alpha_n - \mu\right)p_{TGC}Q + \pi\left(E_g - \sum \alpha_n \varphi_{CO_2}^{n} Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2} - p_{CO_2}E_g + W \tag{1}$$

$$P_1 = \sum \alpha_n\left[(1-\pi)p_e^n - c_n\right]Q + \beta\left[(1-\pi)p_e^{TE} - c_{TE} - b_{TE}\right]Q + (1-\pi)\left(\sum \alpha_n - \mu\right)p_{TGC}Q + (1-\pi)\left(E_g - \sum \alpha_n \varphi_{CO_2}^{n} Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2} \tag{2}$$

$$G_2 = \pi p_e^{TE} Q - p_{CO_2}E_g \tag{3}$$

$$P_2 = \left[(1-\pi)p_e^{TE} - c_{TE} - \mu p_{TGC}\right]Q - \left(\varphi_{CO_2}^{TE}Q - E_g\right)p_{CO_2} \tag{4}$$

$$G_3 = \pi\left(\sum \alpha_n p_e^n + \beta p_e^{TE}\right)Q - \left(\sum \alpha_n \varphi_{CO_2}^{n} + \beta \varphi_{CO_2}^{TEC}\right)p_{CO_2}Q + W \tag{5}$$

$$P_3 = \sum \alpha_n\left[(1-\pi)p_e^n - c_n\right]Q + \beta\left[(1-\pi)p_e^{TE} - c_{TE} - b_{TE}\right]Q \tag{6}$$

$$G_4 = \pi p_e^{TE} Q - \varphi_{CO_2}^{TE} p_{CO_2} Q \tag{7}$$

$$P_4 = \left[(1-\pi)p_e^{TE} - c_{TE}\right]Q \tag{8}$$

Government	Power Enterprise	
	HES (y)	**TG ($1-y$)**
RPS + CET (x)	(G_1, P_1)	(G_2, P_2)
NO ($1-x$)	(G_3, P_3)	(G_4, P_4)

$$\frac{d\theta(t)}{dt} = \theta(t)\cdot[u_t(s) - \overline{u_t}] \tag{9}$$

The payoff matrix is used to calculate the replicator dynamic equations associated with local governments and power enterprises. The expected utility of local governments choosing RPS + CET and NO ACTION strategies are denoted by E_{RPS} and E_{NO}, respectively. The term E_G represents the average expected utility of local governments. These are calculated as follows.

$$\begin{cases} E_{RPS} = yG_1 + (1-y)G_2 \\ E_{NO} = yG_3 + (1-y)G_4 \\ E_G = xE_{RPS} + (1-x)E_{NO} \end{cases} \tag{10}$$

Similarly, the terms E_{HES} and E_{TG} signify the expected utility when power enterprises choose HES and TG strategies, respectively. The average utility for power enterprises is E_{PE}. These are calculated as follows.

$$\begin{cases} E_{HES} = xP_1 + (1-x)P_3 \\ E_{TG} = xP_2 + (1-x)P_4 \\ E_{PE} = yE_{MG} + (1-y)E_{TG} \end{cases} \tag{11}$$

The terms $F(x)$ and $F(y)$ are replicator dynamic equations of local governments and power enterprises, respectively, as shown in Eq. (12) and (13).

$$F(x) = \frac{dx}{dt} = x(E_{RPS} - E_G) \tag{12}$$

$$F(y) = \frac{dy}{dt} = y(E_{HES} - E_{PE}) \tag{13}$$

A two-dimensional dynamic system D is formed by the above differential equations, expressed in Eq. (14).

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x(1-x)\{G_2 - G_4 + y[(G_1 - G_3) - (G_2 - G_4)]\} \\ F(y) = \dfrac{dy}{dt} = y(1-y)\{P_3 - P_4 + x[(P_1 - P_2) - (P_3 - P_4)]\} \end{cases} \tag{14}$$

3. Evolutionary equilibrium analysis

3.1. Equilibrium points

Dynamic changes in the strategic choices of local governments and power enterprises as well as the evolutionary paths of the agents' behaviors are analyzed through the dynamic system D. The property of dynamic system D is obtained by letting $x^* = \frac{P_3 - P_4}{(P_3 - P_4) - (P_1 - P_2)}$ and $y^* = \frac{G_2 - G_4}{(G_2 - G_4) - (G_1 - G_3)}$(see proof in Appendix A.1).

Proposition 1. The local equilibrium points (LEP) of dynamic system D are $E_1(0,0)$, $E_2(0,1)$,$E_3(1,0)$,$E_4(1,1)$. When it is satisfied that $0 \le \frac{P_3 - P_4}{(P_3 - P_4) - (P_1 - P_2)} \le 1$ and $0 \le \frac{G_2 - G_4}{(G_2 - G_4) - (G_1 - G_3)} \le 1$, the point$E_5(x^*, y^*)$ is also an equilibrium point.

3.2. Equilibrium stability

The LEP obtained above is insufficient to achieve an evolutionarily stable strategy (ESS). A Jacobian matrix J is defined to analyze the local stability of the dynamic system (Friedman, 1991).

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)\{G_2 - G_4 + y[(G_1 - G_3) - (G_2 - G_4)]\} & x(1-x)[(G_1 - G_3) - (G_2 - G_4)] \\ y(1-y)[(P_1 - P_2) - (P_3 - P_4)] & (1-2y)\{P_3 - P_4 + x[(P_1 - P_2) - (P_3 - P_4)]\} \end{bmatrix} \tag{15}$$

The stability then can be determined by the sign of the determinant $detJ = \frac{\partial F(x)}{\partial x}\cdot\frac{\partial F(y)}{\partial y} - \frac{\partial F(y)}{\partial x}\cdot\frac{\partial F(x)}{\partial y}$ and trace $trJ = \sum_{i=1}^{n} a_{ij}$ of the Jacobian matrix. If $detJ > 0$ and $trJ < 0$, the equilibrium point is the local asymptotically stable fixed point, corresponding to the ESS. If $detJ < 0$, the equilibrium point denotes the saddle point. We substitute the five local equilibrium points in the Jacobian matrix, as shown in Table 3.

Calculating the $detJ$ and trJ of LEP gives the results for the equilibrium stability in **Proposition 2** (see Appendix A.2 for the proof).

Proposition 2. (1) *When $P_1 < P_2$, Point $E_3(1,0)$ is the ESS. In this case, local governments implement RPS + CET, while power enterprises continue generating only traditional energy.*

(2) *When $\begin{cases} P_1 > P_2 \\ P_3 < P_4 \\ G_1 < G_3 \end{cases}$, the dynamic systemD fluctuates periodically around $E_5(x^*, y^*)$. There is no deterministic pure strategy.*

(3) *When $\begin{cases} P_1 > P_2 \\ P_3 < P_4 \\ G_1 > G_3 \end{cases}$, Point $E_4(1,1)$ is the ESS. This means local governments implement RPS + CET while power enterprises choose a hybrid energy system.*

(4) *When $\begin{cases} P_1 > P_2 \\ P_3 > P_4 \\ G_1 > G_3 \end{cases}$, Point $E_4(1,1)$ is the ESS. This means local governments implement RPS + CET while power enterprises choose a hybrid energy system.*

(5) *When $\begin{cases} P_1 > P_2 \\ P_3 > P_4 \\ G_1 < G_3 \end{cases}$, Point $E_2(0,1)$ is the ESS. This means local governments adopt NO ACTION while power enterprises invest in a hybrid energy system.*

Proposition 2 indicates there are several different evolutionary

Table 3
The results of $detJ$ and trJ for local equilibrium points (LEP).

LEP	$detJ$	trJ
$E_1(0,0)$	$(G_2 - G_4)(P_3 - P_4)$	$(G_2 - G_4) + (P_3 - P_4)$
$E_2(0,1)$	$-(G_1 - G_3)(P_3 - P_4)$	$(G_1 - G_3) - (P_3 - P_4)$
$E_3(1,0)$	$-(G_2 - G_4)(P_1 - P_2)$	$-(G_2 - G_4) + (P_1 - P_2)$
$E_4(1,1)$	$(G_1 - G_3)(P_1 - P_2)$	$-(G_1 - G_3) - (P_1 - P_2)$
$E_5(x^*, y^*)$	$\frac{-(G_1 - G_3)(G_2 - G_4)(P_1 - P_2)(P_3 - P_4)}{[(G_2 - G_4) - (G_1 - G_3)][(P_3 - P_4) - (P_1 - P_2)]}$	0

stability points.

The high comprehensive cost of investing in a hybrid energy system, which cannot compete with the low costs of traditional coal-fired power, deters power enterprises from deciding to transition. If the CET and TGC markets offer few incentives under RPS and CET implementation, the extra carbon revenue and TGC revenue are insufficient to offset new technology expenditures. Along with the weak regulation intensity, power enterprises would rather pay for carbon emissions and purchases TGC to achieve a higher return, i.e., $E_3(1,0)$. This reflects the technology lock-in effect and path dependence caused by established generation infrastructure, institutional mechanisms, and behavioral habits (Schmidt et al., 2016; Trencher et al., 2020).

As the regulatory intensity or incentive effects improve, or as comprehensive technology costs decrease but remain uncompetitive, the advantages of transitioning to HES become more significant under RPS and CET. However, the transition strategy of choosing HES becomes unstable if local governments can generate more revenue by taking no action, when power enterprises adopt HES. Similarly, it is more profitable for power enterprises to stay with conventional power generation without RPS and CET. Once power enterprises adopt TG, local governments gain more benefits by implementing the policy mix. Both agents constantly adjust their strategies based on the opponent's state, entering a cyclical state around the mixed strategy $E_5(x^*,y^*)$. Fig. 1 shows the evolutionary phase diagram, which is divided into four regions by x^* and y^*.

The evolutionary trend of the system depends on which region each agent is located in to create the initial state. When the initial state is in Region ①, the game converges to point $E_3(1,0)$. When the initial state is in Region ②, the game converges to point $E_1(0,0)$. When the initial state is in Region ③, the game evolves to point $E_2(0,1)$. When the initial state is in Region ④, the game converges to point $E_4(1,1)$. The larger the Region IV is, the more the system tends towards $E_4(1,1)$. All the points are the saddle point.

Improvements in regulatory intensity or incentive effect raise the tax revenue of local governments, by increasing the carbon benefits and TGC benefits from power enterprises. Reductions in comprehensive technology cost increases the tax revenue of local governments, by increasing the electricity sales of power enterprises. When these changes make it more profitable for power enterprises to choose HES, and for local governments to implement and supervise the policy mix, a stable evolutionary path is created, i.e.,$E_4(1,1)$.

Once the technical bottleneck is broken, and the comprehensive technical cost can effectively compete with coal-fired power generation, the lock-in effect may be removed. The decision about whether or not to implement the policy mix does not affect the transition decision made by power enterprises. However, if implementing and supervising the policy mix produces more benefits for local governments, the system stabilizes at $E_4(1,1)$. Otherwise, the evolutionary stable state is $E_2(0,1)$.

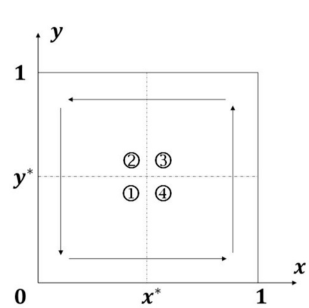

Fig. 1. Evolutionary phase diagram for the periodic solution case.

4. Results and discussions

The equilibrium stability analysis above indicates that joint implementation of RPS and CET is necessary to drive the transition of power enterprises when the comprehensive cost of HES is not yet competitive ($P_3 < P_4$). There are two undesirable evolutionary states. The first is when power enterprises adhere to TG under the policy mix, i.e., $E_3(1,0)$. The second occurs when there is uncertainty about whether to invest in HES, i.e., the periodic solution around$E_5(x^*,y^*)$.

This section investigates how the key parameters related to the comprehensive cost, the regulation intensity and the incentive level can be changed to drive power enterprises to invest in HES, i.e., $E_4(1,1)$. There is no need to discuss the scenario in which the comprehensive cost of HES can compete with traditional power generation ($P_3 > P_4$). That is when power enterprises eventually invest in HES.

4.1. Impacts from ratio of renewables in HES

Technology costs differ between photovoltaic, wind power, and clean fossil energy generation. As such, the comprehensive cost-benefit of HES varies with the proportion of each energy source. We first examine the influence from the ratio of renewable energy in HES (α_n) on the evolutionary equilibrium, demonstrated in the following proposition (see proof in Appendix A.3).

Proposition 3. *Given the uncompetitive comprehensive cost of HES* ($P_3 < P_4$), *power enterprises invest in HES under RPS + CET* (i.e., $E_4(1,1)$) *only when the ratio of renewables in HES* (α_n) *satisfies*:

$$\begin{cases} \sum \alpha_n \left\{ \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE} + b_{TE}\right] + (1-\pi)\left(p_{TGC} - \varphi_{CO_2}^{n} p_{CO_2} + \varphi_{CO_2}^{TEC} p_{CO_2}\right) \right\} Q > \Omega \\ \sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE} + b_{TE}\right] < b_{TE} \\ \sum \alpha_n \left[\pi p_{TGC} - (1-\pi)\left(\varphi_{CO_2}^{TEC} - \varphi_{CO_2}^{n}\right) p_{CO_2}\right] Q > \pi \mu p_{TGC} Q + (1-\pi)\left(E_g - \varphi_{CO_2}^{TEC} Q\right) p_{CO_2} \end{cases} \tag{16}$$

where $\Omega = b_{TE}Q - \left(\varphi_{CO_2}^{TE} - \varphi_{CO_2}^{TEC}\right) p_{CO_2} Q + \pi\left(E_g - \varphi_{CO_2}^{TEC} Q\right) p_{CO_2} - \pi \mu p_{TGC} Q$.

Proposition 3 suggests that the proportion of renewable energy in HES helps determine whether power enterprises make the decision to transition given specific technology levels and policy incentives. The allocation of the proportions determines the benefits of HES, including both the carbon and TGC benefits. Power enterprises can control the comprehensive technology cost by the ratio of renewable energy, despite that renewable energy not being competitive with coal-fired power generation. The ratio must reach a specific condition to lead power enterprises to make the transition investment. This considers emission factors, costs, and tariffs for different generation technologies, along with policy regulation and market incentive parameters.

There are realistically limitations in both the power demand and grid transmission capacity. This makes it difficult to ensure a high proportion of renewable power generation can be fully connected to the grid. Moreover, high proportion of renewable power generation may weaken the peak shaving ability of the power supply system due to the constraints of natural conditions. Even if it is economically more profitable to invest in HES with a high proportion of renewable energy, power enterprises still risk incurring economic losses from renewables that cannot be connected to the grid and poor peaking capacity. Furthermore, local governments should not blindly develop renewable energy by fully acquiring renewable energy power. The large-scale integration of renewable energy into the grid may pose a shock to the grid (Ergun et al., 2012). As a result, power enterprises should make prudent decisions about the effective ratio of renewable energy in its HES, based on the region's ability to absorb the renewable energy (known as its absorption capacity).

The ratio of renewable energy in the HES determined by considering the absorption capacity may not meet the conditions in **Proposition 3**. This means that investing in HES may not have significant benefits, and power enterprises may not decide to transition. However, changes in market incentives and policy regulation intensity can accelerate the transition investment, as discussed in the next subsection.

4.2. *Impacts from regulation intensity*

There are limitations in how much renewable energy can be absorbed. As such, stipulating too high a quota for renewable energy may lead to social risks, such as power curtailments. This section only discusses the impact of changing the volume of initial carbon emission permits.

This paper mainly aims to explore the combined effect of implementing RPS and CET simultaneously. For a better comparison, we investigate the effect of initial carbon emission permits under a single CET mechanism and the policy mix, respectively.

(1) Under a single CET mechanism

The evolution state is first calculated under a single CET mechanism when the comprehensive cost of HES is not yet competitive. The results indicate that there are only two undesirable evolutionary states and no ideal state, i.e., $E_4(1,1)$.Thus, we present the following proposition about the effect of initial carbon emission permits under a single CET mechanism (see proof in Appendix A.4.).

Proposition 4. Given the uncompetitive comprehensive cost of HES, as the initial carbon emission permit decreases, power enterprises evolve from only pursing TG under the single CET mechanism to uncertainty about investing in HES.

(2) Under the policy mix

The impact of initial carbon emission permits under the policy mix is presented in the following proposition (see proof in Appendix A.5).

Proposition 5. Given the uncompetitive comprehensive cost of HES, as the volume of initial carbon permits E_G decreases, the following occurs:

(i) *Power enterprises evolve from only pursuing TG under RPS + CET to investing in HES* (i.e.,$E_4(1,1)$) *only when* p_{TGC} *satisfies the following condition:*

$$p_{TGC} \geq \frac{\beta b_{TE} - \sum\alpha_n\left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right] - \left(\varphi_{CO_2}^{TE} - \sum\alpha_n\varphi_{CO_2}^n - \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{(1-\pi)\left(\sum\alpha_n - \mu\right) + \mu} \quad (17)$$

(ii) *Power enterprises necessarily evolve from uncertainty about investing in HES to investing in HES* (i.e.,$E_4(1,1)$).

The graphical illustration is provided based on the establishment conditions associated with ESSs under the policy mix. A linear relationship between the initial carbon permit E_g and the TGC price $p_{TGC}$is constructed in Eq. (17). The coefficient is affected by the carbon pricep_{CO_2}.

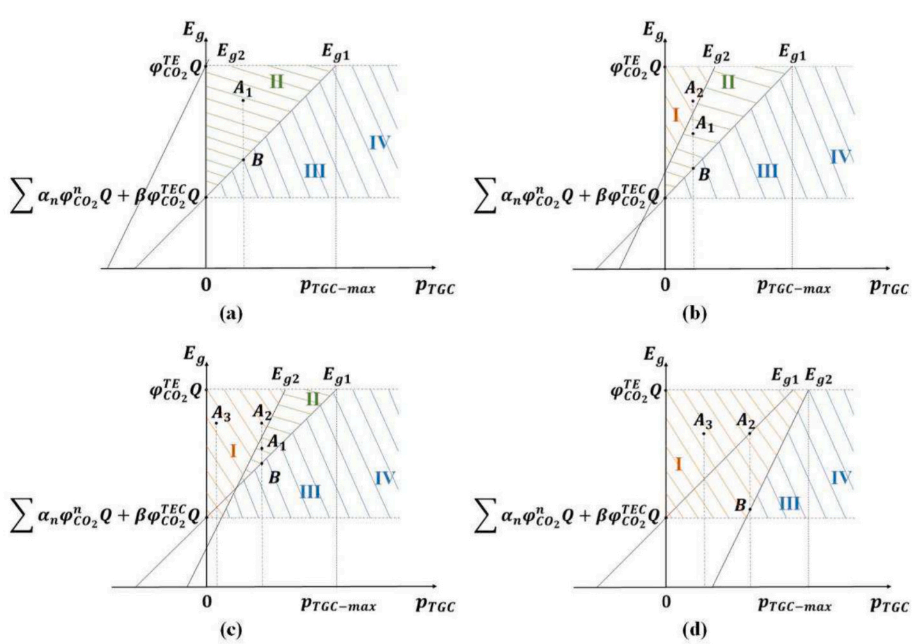

Fig. 2. Impact of changes in the volume of initial carbon permits on evolutionary game results under the policy mix (cases where the slope of E_{g1} is greater than E_{g2}).

$$\begin{cases} E_{g1}=\dfrac{\pi(\sum\alpha_n-\mu)Q}{(1-\pi)p_{CO_2}}p_{TGC}+\sum\alpha_n\varphi^n_{CO_2}Q+\beta\varphi^{TEC}_{CO_2}Q \\ E_{g2}=\dfrac{[(1-\pi)(\sum\alpha_n-\mu)+\mu]Q}{\pi p_{CO_2}}p_{TGC}+\dfrac{\left[\varphi^{TE}_{CO_2}-(1-\pi)\left(\sum\alpha_n\varphi^n_{CO_2}+\beta\varphi^{TEC}_{CO_2}\right)\right]Q}{\pi} \\ \qquad +\dfrac{\sum\alpha_n\left[(1-\pi)\left(p^n_e-p^{TE}_e\right)-c_n+c_{TE}\right]Q-\beta b_{TE}Q}{\pi p_{CO_2}} \end{cases} \tag{18}$$

Considering the slope and intercept of E_{g1} and E_{g2}, there are eight cases when $P_3<P_4$. To be more concise, we present cases where the slope of E_{g1} is greater than $E_{g2}$to illustrate the key insights. These are shown in Fig. 2. The remaining cases yield consistently uniform observations and are presented in Appendix A.11.

AreaIrepresents the value space of each policy parameter when $E_3(1,0)$ is established. When the policy parameter values fall into area II, it indicates the achievement of a periodic solution. Area III and IV represent the range of policy parameters when$E_4(1,1)$ is established. Point A_1 is an arbitrary point in area II, while points A_2 and A_3 are arbitrary points in area I.

Given p_{CO_2} and p_{TGC}, a decrease in E_g can drive point A_1 in area II to the boundary point B of area III. This is a critical condition of $E_4(1,1)$. The decline of E_g may drive point A_2 in area Ito the boundary point B of area III. However, the single action of only lowering E_g does not drive the point A_3 to any location at the boundary of area III. Only points where the abscissa falls within the p_{TGC} threshold corresponding to area III can be pushed to reach the critical boundary of $E_4(1,1)$ by decreasing E_g.

The above propositions elucidate that implementing the policy mix enlarges the effect of the initial carbon emission permit. Under a single CET mechanism, the decreases in initial emission permits may increase the carbon cost of insisting on TG, and decrease the carbon benefit of investing in HES. Compared with the high technology cost, power enterprises can hardly make a definite transition decision to HES. Under the policy mix, the RPS policy also catalyzes potential TGC revenue. Power enterprises compare the offsetting effects of both TGC and carbon benefits to the technological cost. This finding is consistent with Mo et al. (2016), which claimed that other policy measures complementing ETS are still needed.

However, the effectiveness of reducing the initial carbon permit is subject to the compensation level of TGC benefits to comprehensive technology costs. If the TGC price is low relative to technology cost and the compensation effect is limited, lowering the volume of initial carbon permits only decreases the carbon profit associated with HES. This leads power enterprises to be reluctant to make large expenditures on new technology. Instead, they still prefer to pay regulation costs by choosing TG.

If the TGC price is high compared to the technology cost and can mitigate part of the technology cost, lowering the initial carbon permit can effectively drive power enterprises to invest in HES. The evolutionary state of both agents fixed in a strategy loop is also consistent with this situation. A higher TGC price and lower volume of initial carbon permits simultaneously increase the carbon burden and the TGC cost associated with TG. Power enterprises would rather convert this high expense into new technology investments. A lower volume of initial carbon permits means that power enterprises can generate more carbon revenue incentives by choosing HES, which also increases the tax revenue for local governments.

4.3. Impacts from market incentives

4.3.1. CO_2 price

We also investigate the effect of CO_2 price under a single CET mechanism and the policy mix, respectively.

(1) Under a single CET mechanism

We present the following proposition about the effect of carbon price under a single CET mechanism (see proof in Appendix A.6.).

Proposition 6. Given the uncompetitive comprehensive cost of HES, as the CO_2 price increases, power enterprises evolve from only pursuing TG under the single CET mechanism to uncertainty about investing in HES.

(2) Under the policy mix

The following proposition reveals the impact of changing the CO_2 price on the evolutionary result under the policy mix (see proof in Appendix A.7).

Proposition 7. *Given the uncompetitive comprehensive cost of HES, power enterprises evolve from only pursuing TG and uncertainty about investing in HES under RPS + CET to investing in HES* (i.e.,$E_4(1,1)$), *only if the CO_2 price satisfies the following conditions and changes in the following interval.*

$$\frac{\beta b_{TE}Q-\sum\alpha_n\left[(1-\pi)\left(p^n_e-p^{TE}_e\right)-c_n+c_{TE}\right]Q-(1-\pi)\left(\varphi^{TE}_{CO_2}-\sum\alpha_n\varphi^n_{CO_2}-\beta\varphi^{TEC}_{CO_2}\right)p_{TGC}Q}{\left(\varphi^{TE}_{CO_2}-\sum\alpha_n\varphi^n_{CO_2}-\beta\varphi^{TEC}_{CO_2}\right)Q-\pi\left(E_g-\sum\alpha_n\varphi^n_{CO_2}Q-\beta\varphi^{TEC}_{CO_2}Q\right)} < p_{CO_2} < \frac{\pi(\sum\alpha_n-\mu)p_{TGC}Q}{(1-\pi)\left(E_g-\sum\alpha_n\varphi^n_{CO_2}Q-\beta\varphi^{TEC}_{CO_2}Q\right)} \tag{19}$$

The above propositions indicate that implementing the policy mix may change the effect of the carbon price. A single CET mechanism cannot make power enterprises transition to HES definitely. The increase in carbon price may raise the carbon cost of insisting on TG. However, there is no significant market incentive to compensate for the high technology cost. It can only drive power enterprises to waver on upgrading the generation structure. The policy mix offers a possible optimization band for carbon prices to motivate power enterprises to transition. However, the effectiveness of changing the carbon price is limited by the relationship between the regulation intensity, TGC incentives, and comprehensive technology cost. It only makes sense to adjust the carbon price to facilitate the transition by power enterprises when certain conditions are met. This finding is different from previous studies by Szolgayova et al. (2008) and Roach and Meeus (2023), who presented that rising carbon prices are conducive to the adoption of carbon reduction technologies.

4.3.2. TGC price

Similarly, we investigate the effect of TGC price under a single RPS policy and the policy mix, respectively.

(1) Under a single RPS policy

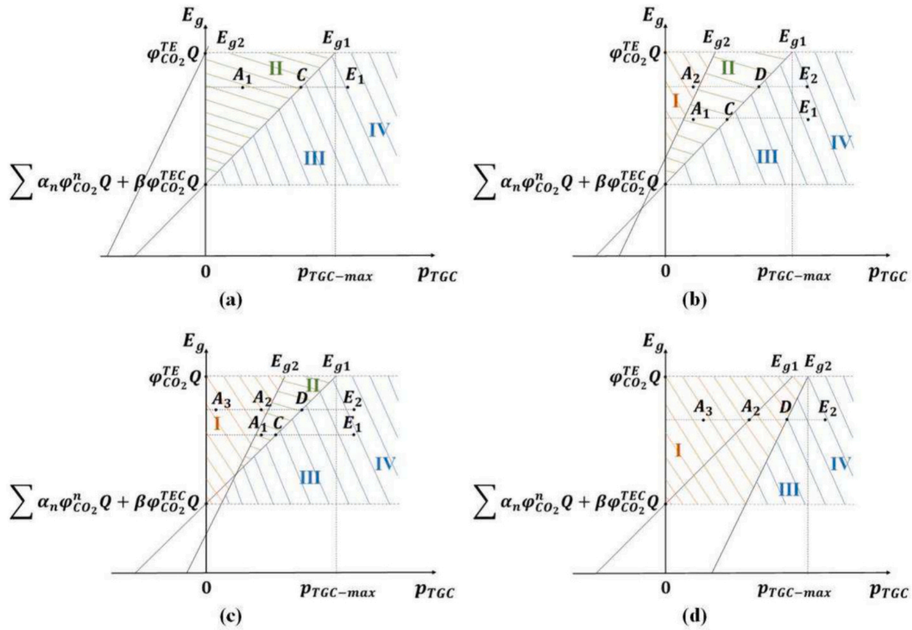

Fig. 3. Impact of changes in the TGC price on evolutionary game results under the policy mix (cases where the slope of E_{g1} is greater than E_{g2}).

The evolution state is first calculated under a single RPS policy when the comprehensive cost of HES is not yet competitive. The results show that there is a critical state evolving towards an undesirable equilibrium outcome and a desirable state, i.e., $E_4(1,1)$. Thus, we draw the following proposition to reveal the impact of changing the TGC price on the evolution result under a single RPS policy (see proof in Appendix A.8.).

Proposition 8. Given the uncompetitive comprehensive cost of HES, as the TGC price increases, power enterprises evolve from the undesirable critical state under a single RPS policy to investing in HES (i.e., $E_4(1,1)$).

(2) Under the policy mix

The following proposition reveals the impact of changing the TGC price on the evolution result under the policy mix (see proof in Appendix A.9.).

Proposition 9. Given the uncompetitive comprehensive cost of HES, as the TGC price increases, power enterprises evolve from only pursuing TG and uncertainty about investing in HES under RPS + CET to investing in HES (i.e.,$E_4(1,1)$).

Fig. 3 provides a graphical interpretation of this, where the slope of E_{g1} is greater than E_{g2}. The remaining cases with identical viewpoints are listed in Appendix A.11. Increasing p_{TGC} can drive point A_1 to point C with a given E_g and p_{CO_2}. Such an increase can also drive points A_2 and A_3 to point D. Both points C and D are located at the boundary of area III, which is the critical condition of $E_4(1,1)$.

The above propositions indicate that raising the TGC price may

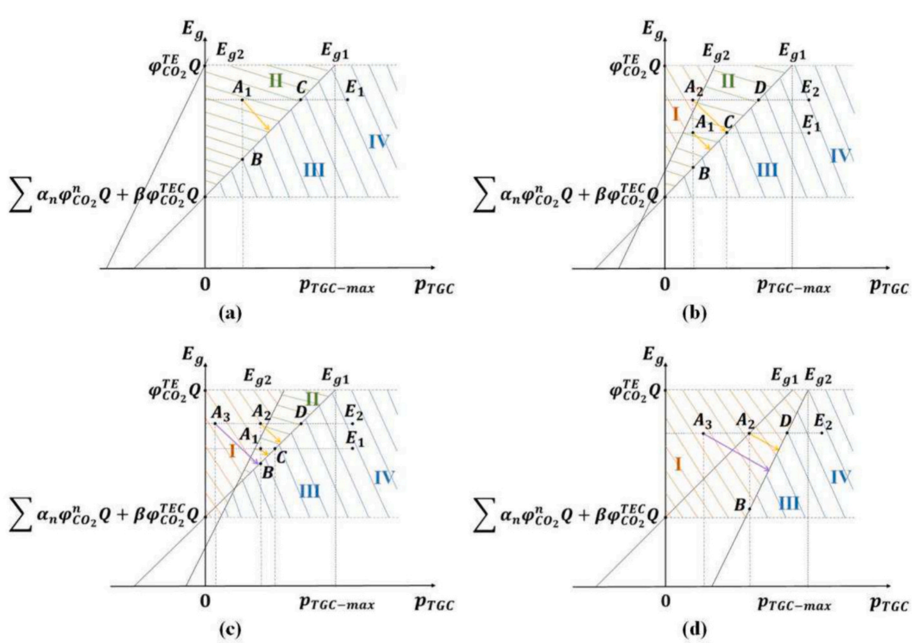

Fig. 4. Impact of changes in the dual parameters on evolutionary game results under the policy mix (cases where the slope of E_{g1} is greater than E_{g2}).

incentivize power enterprises to invest in HES, either under a single RPS policy or the policy mix. Regardless of whether the CET mechanism is implemented, increasing the TGC price may increase the incentive effect and promote the transition. This finding aligns with Deschenes et al. (2023). The TGC price belongs to the key elements of RPS policy, and serves as the equivalent of a renewable energy subsidy under the market mechanism. As the TGC price incrementally increases, the increase in TGC revenue provides a higher compensation effect to mitigate the technology cost. Power enterprises tend to invest in the transition when the TGC price is higher. The TGC revenue generated by power enterprises also offer more tax revenue. Local governments tend to guide and supervise the policy implementation and the corresponding market.

There is also a difference in the floor TGC price that effectively promotes the transition. The condition of the TGC price that makes the reduction of the initial carbon permits effective, as presented in **Proposition 5**, also represents the minimum TGC price under the policy mix, denoted as p_{TGC}^{MIX}. The minimum TGC price under a single RPS policy is p_{TGC}^{R} (detailed in Appendix in A.6). It is clear that $p_{TGC}^{MIX} < p_{TGC}^{R}$. The floor TGC price under the policy mix is lower than that under a single RPS policy.

$$p_{TGC} \leq max\left\{\frac{(1-\pi)\left(\varphi_{CO_2}^{TE} - \sum\alpha_n\varphi_{CO_2}^{n} - \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{\pi(\sum\alpha_n - \mu)},\right.$$
$$\left.\frac{\beta b_{TE} - \sum\alpha_n\left[(1-\pi)(p_e^n - p_e^{TE}) - c_n + c_{TE}\right] - (1-\pi)\left(\varphi_{CO_2}^{TE} - \sum\alpha_n\varphi_{CO_2}^{n} - \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{(1-\pi)(\sum\alpha_n - \mu) + \mu}\right\} \tag{20}$$

4.4. Policy coordination

The above analysis reveals that while these two policies create different effects, they still have an overlap effect. First, the synergistic implementation of CET and RPS can enable decreasing initial carbon permits to be an effective facilitator of the transition. Second, the synergistic implementation can reduce the demand for market incentives by lowering the floor TGC price which effectively promotes the transition. It means that the CET mechanism provides some compensation against the comprehensive technology cost.

Furthermore, we propose the following corollary, together with presenting Fig. 4, to illustrate the policy optimization initiatives that effectively facilitate the transition by power enterprises under the policy mix.

Corollary 1. *(i) Raising the TGC price definitely promotes the transition to HES, while lowering the volume of the initial carbon permit may not necessarily work.*

(ii) Simultaneously increasing the TGC price and lowering the volume of the initial carbon permit can certainly promote the transition to HES by power enterprises, and improve the efficiency of evolution to the transition to HES.

Corollary 1 suggests that coordinated dual policy implementation provides a higher level of policy efficiency than a single policy measure. To be specific, when a single increase in carbon regulation intensity does not effectively promote the transition, supplemental TGC incentives become critical. As illustrated in Fig. 4, point A_3 can reach area III along the purple arrow, corresponding to a simultaneous decrease in E_g and increase in p_{TGC}. Further, when the single measure of reducing the volume of initial carbon permits does work, a parallel increase in TGC incentives can induce power enterprises to transition faster. Points A_1 and A_2 can reach area III by concurrently reducing E_g and increasing p_{TGC}. The amplitude of simultaneous changes is shown by the yellow arrow. For point A_1, the line segments A_1C and A_1B represent the minimum variation of E_g and p_{TGC}, respectively, needed to drive point A_1 to the critical condition of area III. The length of any arrow inside the triangle ΔA_1BC starting from the point A_1 is shorter than the line segments A_1C and A_1B. That means the point A_1 along the yellow arrow reaches area III faster. The same is true for point A_2. Simultaneously reducing the initial carbon permit and increasing the TGC price is more efficient than using one of the two changes alone to drive the transition.

Additionally, we propose another corollary about the efficient variation interval with respect to the TGC price under the policy mix (see proof in Appendix A.10.).

Corollary 2. *To avoid the policy redundancy, the TGC price should be within a reasonable interval, expressed as*:

Corollary 2 is proposed to shed light on the coordination interval between the RPS policy and the CET mechanism. A higher TGC price furnishes power enterprises with attractive TGC benefits to offset expenditures on the new technology, similar to early feed-in tariffs in China (Li et al., 2019). In Fig. 4, the arbitrary points E_1 and E_2 inside area IV represent this circumstance, which can realize the evolutionary stable equilibrium of $E_4(1,1)$ independent of the E_g value. The presence of carbon benefits does not affect the decision of power enterprises to transition to HES. If more initial carbon permits are allocated compared to the actual emissions from the HES, the excess allocated permits provide a net profit to the power enterprises. However, local governments have to spend unnecessary carbon expenditures, reflecting a policy redundancy. This finding is consistent with Yi et al. (2019), which believed that one policy may become ineffective if another is more stringent. As illustrated by Feng et al. (2018) and Yan et al. (2022), guaranteeing the effective coordination of policy combinations is extremely important.

Further, regulators usually need to guide and supervise that the TGC price fluctuates within a reasonable range. An extravagant TGC can discourage consumers, resulting in an oversupply and market disorder. The synergistic implantation of the RPS policy and CET mechanism provides a binding effect on the ceiling TGC price. It can be controlled based on the relevant factors in the carbon emission market, rather than blindly compensating for the cost-effectiveness of new power technologies.

5. Conclusions and implications

The transition of conventional energy power enterprises to a hybrid energy system is an effective direction for encouraging the high-quality development of renewables and the low-carbon transition of the power sector. The main objective of this study is to examine how the combined mechanism of RPS and CET influences investments in a hybrid energy system. By constructing an evolutionary game between local governments and power enterprises, the study identifies the evolutionarily stable equilibrium between the policy mix and the transition to a HES. This paper further theoretically analyzes the effects of core parameters on the equilibrium outcomes and the coordinated development boundary of the policy mix.

Our results demonstrate that the evolutionarily stable strategy depends on the comprehensive technology cost of the hybrid energy system, the incentive level from the trading market, and the regulation intensity of the policy mix. When the hybrid energy system cannot economically compete with traditional power generation, external policy regulation or policy incentives provide a necessary thrust. Under the coexistence of RPS and CET, power enterprises can ideally determine whether to invest in a hybrid energy system through the structure of a multi-energy power generation pattern. In reality, however, a region's ability and capacity to absorb renewables must be considered.

In particular, it has been found that the RPS policy and CET mechanism together have an additive effect on promoting the transition to a HES, yet remain distinct. Whether under a single RPS policy or the policy mix, the role of increasing the TGC price in facilitating the transition is remarkable. Under a single CET mechanism, optimizing initial carbon permits or the carbon price can merely sway power enterprises to stick with traditional energy. In contrast, lowering initial carbon permits with fixed TGC incentives facilitates the transition effectively under the policy mix. A carbon price interval that potentially facilitates the transition emerges, constrained by the new technology cost. The policy mix also reduces the TGC incentives required to promote the transition. Moreover, simultaneous increases in TGC price and reductions in initial carbon permits contribute more efficiently to the transition than the single measure. Notably, a steep TGC price can render the CET mechanism meaningless.

The results above point to important policy implications and recommendations.

First, a scientific and rational policy mix concerning RPS and CET can give full play to the synergistic effect and more efficiently foster the development of a hybrid energy system. Under the premise of regional absorption ability for renewables, the governments should sensibly control the carbon regulation intensity. It is necessary to consider reducing free carbon permits appropriately or adopting a billed allocation method for initial carbon permits to facilitate the transition of conventional power enterprises.

Second, local governments should perform their regulatory functions and control the TGC price within a certain range. It is a critical condition to maximize the efficiency of the policy mix and achieve the stable operation of the market mechanism. If market factors are completely freely allocated, inefficiency and market failure may occur. The incentive effect cannot be realized when the TGC price is too low. The orderly operation of the market economy is damaged when the TGC price is too high. It will also lead to needless implementation of the CET mechanism, implying policy redundancy.

Third, technological innovation measures should be consistently strengthened to drive decreases in clean energy technology cost, and to enhance the capacity of the grid infrastructure to absorb renewables. A low technical cost can encourage power enterprises to invest in generating clean energy power. Ideally, transition investments no longer depend on incentives or regulation measures. While achieving technological progress, it's also conducive to reducing financial expenditures by local governments. Power enterprises should invest in as much renewable energy as possible in the long run, but are subjected to grid capacity. Upgrading the grid-connection technology, strengthening grid resilience, and improving the grid reliability are ways to fundamentally improve the absorption capacity of the power grid and achieve a high percentage of renewable energy supply.

This paper does have some limitations. For example, the research does not explore supply and demand within the electricity market, CET market, and TGC market. The electricity price, carbon price, and TGC price are all modeled as deterministic parameters. Incorporating uncertainty deserves further research. Besides, this study assumes there is no expansion in power generation capacity. Capacity expansion investment to address growing electricity demand may lead to additional interesting conclusions. These extensions highlight future research opportunities.

CRediT authorship contribution statement

Q. Su: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **P. Zhou:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **H. Ding:** Writing – review & editing, Validation, Supervision. **G. Xydis:** Supervision, Resources.

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Appendix A. Appendix

A.1. Proof of Proposition 1

The equilibrium points of the evolutionary game are determined by setting the replicator dynamic equations equal to 0.

$$\begin{cases} F(x) = x(1-x)\{G_2 - G_4 + y[(G_1 - G_3) - (G_2 - G_4)]\} = 0 \\ F(y) = y(1-y)\{P_3 - P_4 + x[(P_1 - P_2) - (P_3 - P_4)]\} = 0 \end{cases} \text{Equation Section 1} \quad (A.1)$$

In the solution domain $R = \{(x, y)|0 \le x \le 1, 0 \le y \le 1\}$, there are four distinct equilibrium points, i.e. $(0,0)$, $(0,1)$, $(1,0)$ and $(1,1)$. Additionally, point (x^*, y^*) may exist in the domain, but are subjected to the following conditions.

$$\begin{cases} G_2 - G_4 + y[(G_1 - G_3) - (G_2 - G_4)] = 0 \\ P_3 - P_4 + x[(P_1 - P_2) - (P_3 - P_4)] = 0 \end{cases} \quad (A.2)$$

By solving the above equations, another solution can be yielded as follows.

$$(x^*, y^*) = \left(\frac{P_3 - P_4}{(P_3 - P_4) - (P_1 - P_2)}, \frac{G_2 - G_4}{(G_2 - G_4) - (G_1 - G_3)} \right) \quad (A.3)$$

There are five equilibrium points for the dynamic system D when both x^* and y^* fall within the range of the solution domain R. As such, **Proposition 1** is proven.

A.2. Proof of Proposition 2

Since $\sum \alpha_n > \mu$, $\sum \alpha_n \varphi^n_{CO_2} Q + \beta \varphi^{TEC}_{CO_2} Q < E_g < \varphi^{TE}_{CO_2} Q$, and $\pi \in (0,1)$, we know $G_2 - G_4 > 0$. The relationship between $P_1 - P_2$ and $P_3 - P_4$ is discussed below.

$$\begin{aligned} P_1 - P_2 = & \sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right]Q - \beta b_{TE}Q + \left[(1-\pi)\left(\sum \alpha_n - \mu\right) + \mu\right]p_{TGC}Q \\ & +(1-\pi)\left(E_g - \sum \alpha_n \varphi_{CO_2}^n Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2} - \left(E_g - \varphi_{CO_2}^{TE} Q\right)p_{CO_2} \\ = & (P_3 - P_4) + \left[(1-\pi)\left(\sum \alpha_n - \mu\right) + \mu\right]p_{TGC}Q \\ & +(1-\pi)\left(E_g - \sum \alpha_n \varphi_{CO_2}^n Q - \beta \varphi_{CO_2}^{TEC} Q\right)p_{CO_2} - \left(E_g - \varphi_{CO_2}^{TE} Q\right)p_{CO_2} \end{aligned} \tag{A.4}$$

If $P_1 < P_2$, then $P_3 < P_4$ holds. There is no case that satisfies $P_1 < P_2$ and $P_3 > P_4$. Thus, the existence conditions for ESS are discussed in six scenarios (see Table. A.1.). By summarizing the determination of *detJ* and *trJ*in each case, **Proposition 2** is proved.

Table A.1
The evolutionary stability analysis under RPS + CET in various scenarios.*

Scenario	$P_1 < P_2$				Scenario	$P_1 > P_2$								
	Points	*detJ*	*trJ*	**State**		**Points**	*detJ*	*trJ*	**State**	**(Scenarios)**	**Points**	*detJ*	*trJ*	**State**
$G_1 > G_3$					$G_1 > G_3$									
$P_3 < P_4$	$E_1(0,0)$	−	/	SP	$P_3 < P_4$	$E_1(0,0)$	−	/	SP	$P_3 > P_4$	$E_1(0,0)$	+	+	UNS
	$E_2(0,1)$	+	+	UNS		$E_2(0,1)$	+	+	UNS		$E_2(0,1)$	−	/	SP
	$E_3(1,0)$	+	−	**ESS**		$E_3(1,0)$	−	/	SP		$E_3(1,0)$	−	/	SP
	$E_4(1,1)$	−	/	SP		$E_4(1,1)$	+	−	**ESS**		$E_4(1,1)$	+	−	**ESS**
$G_1 < G_3$					$G_1 < G_3$									
$P_3 < P_4$	$E_1(0,0)$	−	/	SP	$P_3 < P_4$	$E_1(0,0)$	−	/	SP	$P_3 > P_4$	$E_1(0,0)$	+	+	UNS
	$E_2(0,1)$	−	/	SP		$E_2(0,1)$	−	/	SP		$E_2(0,1)$	+	−	**ESS**
	$E_3(1,0)$	+	−	**ESS**		$E_3(1,0)$	−	/	SP		$E_3(1,0)$	−	/	SP
	$E_4(1,1)$	+	+	UNS		$E_4(1,1)$	−	/	SP		$E_4(1,1)$	−	/	SP

* Abbreviation in the Table: Evolutionarily stable strategy (ESS), Unstable state (UNS) and Saddle point (SP).

A.3. Proof of Proposition 3

Given $P_3 < P_4$, the threshold of α_n, when $E_4(1,1)$ holds, is calculated according to the condition $\begin{cases} P_1 > P_2 \\ P_3 < P_4 \\ G_1 > G_3 \end{cases}$ by substituting $\beta = 1 - \sum \alpha_n$.

$$\begin{cases} \sum \alpha_n \left\{\left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE} + b_{TE}\right] + (1-\pi)\left(p_{TGC} - \varphi_{CO_2}^n p_{CO_2} + \varphi_{CO_2}^{TEC} p_{CO_2}\right)\right\}Q \\ \qquad > b_{TE}Q - \left(\varphi_{CO_2}^{TE} - \varphi_{CO_2}^{TEC}\right)p_{CO_2}Q + \pi\left(E_g - \varphi_{CO_2}^{TEC}Q\right)p_{CO_2} - \pi\mu p_{TGC}Q \\ \sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE} + b_{TE}\right] < b_{TE} \\ \sum \alpha_n \left[\pi p_{TGC} - (1-\pi)\left(\varphi_{CO_2}^{TEC} - \varphi_{CO_2}^n\right)p_{CO_2}\right]Q > \pi\mu p_{TGC}Q + (1-\pi)\left(E_g - \varphi_{CO_2}^{TEC}Q\right)p_{CO_2} \end{cases} \tag{A.5}$$

Accordingly, **Proposition 3** is proven.

A.4. Proof of Proposition 4

G_{iC} and P_{jC} are denoted as the revenue of both agents under the single CET mechanism. By supposing $p_{TGC} = 0$ in Section 2.2, we get the value of P_{jC} and G_{iC}. Equilibrium points and determination rules of equilibrium stability are consistent with the previous content. With $P_{3C} < P_{4C}$, the existence conditions for ESS are discussed in Table. A.3. The only evolutionarily stable strategy is $E_3(1,0)$.

Table A.3
The evolutionary stability analysis under CET in various scenarios.

Scenario	$P_{1C} < P_{2C}$				Scenario	$P_{1C} > P_{2C}$			
	Points	*detJ*	*trJ*	**State**		**Points**	*detJ*	*trJ*	**State**
$G_{1C} < G_{3C}$					$G_{1C} < G_{3C}$				
$P_{3C} < P_{4C}$	$E_1(0,0)$	−	/	SP	$P_{3C} < P_{4C}$	$E_1(0,0)$	−	/	SP
	$E_2(0,1)$	−	/	SP		$E_2(0,1)$	−	/	SP
	$E_3(1,0)$	+	−	**ESS**		$E_3(1,0)$	−	/	SP
	$E_4(1,1)$	+	+	UNS		$E_4(1,1)$	−	/	SP

The derivatives of $P_{1C} - P_{2C}$ with respect to E_g is derived as follows.

$$\frac{\partial(P_{1C} - P_{2C})}{\partial E_g} = -\pi p_{CO_2} < 0 \tag{A.6}$$

$P_{1C} - P_{2C}$ decreases with E_g. Letting $P_{1C} - P_{2C} = 0$ gives the zero-point

$$E_g^C = \frac{\left[\varphi_{CO_2}^{TE} - (1-\pi)\left(\sum \alpha_n \varphi_{CO_2}^n + \beta\varphi_{CO_2}^{TEC}\right)\right]Q}{\pi} + \frac{\sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right]Q - \beta b_{TE}Q}{\pi p_{CO_2}} \tag{A.7}$$

As $E_g$decreases and satisfies$E_g < E_g^C$, then$P_{1C} > P_{2C}$holds. It fulfills the establishment condition of the period solution.
Accordingly, **Proposition 4** is proved.

A.5. Proof of proposition 5

(1) When the evolutionarily stable strategy is $E_3(1,0)$.

There is $P_1 < P_2$. Whether$G_1 > G_3$ or $G_1 < G_3$ does not affect the evolution result. The derivatives of $P_1 - P_2$ and $G_1 - G_3$ with respect to E_g are derived as follows.

$$\frac{\partial(P_1 - P_2)}{\partial E_g} = -\pi p_{CO_2} < 0 \tag{A.8}$$

$$\frac{\partial(G_1 - G_3)}{\partial E_g} = (\pi - 1)p_{CO_2} < 0 \tag{A.9}$$

Both $P_1 - P_2$ and $G_1 - G_3$ decreases with E_g. Letting $P_1 - P_2 = 0$and $G_1 - G_3 = 0$ gives the zero-point, respectively.

$$E_{g-P} = \frac{[(1-\pi)(\sum \alpha_n - \mu) + \mu]Q}{\pi p_{CO_2}} p_{TGC} + \frac{\left[\varphi_{CO_2}^{TE} - (1-\pi)\left(\sum \alpha_n \varphi_{CO_2}^n + \beta\varphi_{CO_2}^{TEC}\right)\right]Q}{\pi} + \frac{\sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right]Q - \beta b_{TE}Q}{\pi p_{CO_2}} \tag{A.10}$$

$$E_{g-G} = \frac{\pi(\sum \alpha_n - \mu)Q}{(1-\pi)p_{CO_2}} p_{TGC} + \sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q \tag{A.11}$$

As$E_g$decreases and satisfies$E_g < min\{E_{g-P}, E_{g-G}\}$, both$P_1 > P_2$ and $G_1 > G_3$ holds. It fulfills the establishment condition of $E_4(1,1)$. It is worth noting that, due to $\sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q < E_g < \varphi_{CO_2}^{TE} Q$, lowering E_g to be meaningful also requires fulfilling $min\{E_{g-P}, E_{g-G}\} > \sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q$.
Since $E_{g-G} > \sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q$ distinctly holds, the following threshold of $p_{TGC}$is derived through letting $E_{g-P} > \sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q$.

$$p_{TGC} > \frac{\beta b_{TE} - \sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right] - \left(\varphi_{CO_2}^{TE} - \sum \alpha_n \varphi_{CO_2}^n - \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{(1-\pi)(\sum \alpha_n - \mu) + \mu} \tag{A.12}$$

That is, decreasing in $E_g$can effectively drive the equilibrium outcome from $E_3(1,0)$ to $E_4(1,1)$ only if p_{TGC} meets a certain range of values.

(2) When the evolution result is the periodic solution around $E_5(x^*, y^*)$.

There is $\begin{cases} P_1 > P_2 \\ P_3 < P_4 \\ G_1 < G_3 \end{cases}$. The evolutionary phase diagram is divided into four regions by x^* and y^*. The derivatives of x^* and y^* with respect to p_{TGC} are derived as follows.

$$\frac{\partial x^*}{\partial E_g} = \frac{-\left\{\sum \alpha_n \left[(1-\pi)\left(p_e^n - p_e^{TE}\right) - c_n + c_{TE}\right]Q - \beta b_{TE}Q\right\}\pi p_{CO_2}}{\left\{\left(\pi E_g - \varphi_{CO_2}^{TE} Q\right)p_{CO_2} + (1-\pi)\left(\sum \alpha_n \varphi_{CO_2}^n + \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2} Q - [(1-\pi)(\sum \alpha_n - \mu) + \mu]p_{TGC} Q\right\}^2} \tag{A.13}$$

$$\frac{\partial y^*}{\partial E_g} = \frac{-p_{CO_2}\left[(1-\pi)\left(\varphi_{CO_2}^{TE} - \sum \alpha_n \varphi_{CO_2}^n - \beta\varphi_{CO_2}^{TEC}\right)p_{CO_2} Q - \pi(\sum \alpha_n - \mu)p_{TGC} Q\right]}{\left[\left(\varphi_{CO_2}^{TE} Q - \pi E_g\right)p_{CO_2} + (\pi - 1)\left(\sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q\right)p_{CO_2} - \pi(\sum \alpha_n - \mu)p_{TGC} Q\right]^2} \tag{A.14}$$

When $P_3 < P_4$ and $G_1 < G_3$, we have $\frac{\partial x^*}{\partial E_g} > 0$ and $\frac{\partial y^*}{\partial E_g} < 0$. x^* is an increasing function with respect to E_g, while y^* is a decreasing function with respect to E_g. As E_g decreases, x^*decreases, and y^* increases. The area of Region ④IV in Fig. 1. becomes larger, and the system tends to converge to $E_4(1,1)$. However, $E_4(1,1)$ is still a saddle point.$E_{g-G} < E_g < E_{g-P}$ and $min\{E_{g-P}, E_{g-G}\} > \sum \alpha_n \varphi_{CO_2}^n Q + \beta\varphi_{CO_2}^{TEC} Q$ indeed hold when $P_1 > P_2$ and $G_1 < G_3$. Provided that $E_g$decreases to satisfy $E_g < min\{E_{g-P}, E_{g-G}\}$and enable $G_1 > G_3$, the periodic state is removed. The system evolves to $E_4(1,1)$.
As such, **Proposition 5** is proved.

A.6. Proof of Proposition 6

The derivatives of $P_{1C} - P_{2C}$ with respect to p_{CO_2} is derived as follows.

$$\frac{\partial(P_{1C} - P_{2C})}{\partial p_{CO_2}} = (1-\pi)\left(E_g - \sum \alpha_n \varphi_{CO_2}^n Q - \beta\varphi_{CO_2}^{TEC} Q\right) - \left(E_g - \varphi_{CO_2}^{TE} Q\right) > 0 \tag{A.15}$$

$P_{1C} - P_{2C}$ increases with p_{CO_2}. Letting $P_{1C} - P_{2C} = 0$ gives the zero-point.

$$p^{C}_{CO_2} = \frac{\beta b_{TE}Q - \sum \alpha_n \left[(1-\pi)\left(p^n_e - p^{TE}_e\right) - c_n + c_{TE}\right]Q}{(1-\pi)\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right) - \left(E_g - \varphi^{TE}_{CO_2} Q\right)} \tag{A.16}$$

As p_{CO_2} increases and satisfies $p_{CO_2} > p^{C}_{CO_2}$, then $P_{1C} > P_{2C}$ holds. It fulfills the establishment condition of the period solution. Accordingly, **Proposition 6** is proved.

A.7. Proof of Proposition 7

(1) When the evolutionarily stable strategy is $E_3(1,0)$.

The derivatives of $P_1 - P_2$ and $G_1 - G_3$ with respect to p_{CO_2} are derived as follows.

$$\frac{\partial(P_1 - P_2)}{\partial p_{CO_2}} = \left(\varphi^{TE}_{CO_2} - \sum \alpha_n \varphi^n_{CO_2} - \beta \varphi^{TEC}_{CO_2}\right)Q - \pi\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right) > 0 \tag{A.17}$$

$$\frac{\partial(G_1 - G_3)}{\partial p_{CO_2}} = (\pi - 1)\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right) < 0 \tag{A.18}$$

$P_1 - P_2$ increases with p_{CO_2}, while $G_1 - G_3$ decreases. Letting $P_1 - P_2 = 0$ and $G_1 - G_3 = 0$ gives the zero-point, respectively.

$$p_{CO_2-P} = \frac{\beta b_{TE}Q - \sum \alpha_n \left[(1-\pi)\left(p^n_e - p^{TE}_e\right) - c_n + c_{TE}\right]Q - \left[(1-\pi)\left(\sum \alpha_n - \mu\right) + \mu\right]p_{TGC}Q}{\left(\varphi^{TE}_{CO_2} - \sum \alpha_n \varphi^n_{CO_2} - \beta \varphi^{TEC}_{CO_2}\right)Q - \pi\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right)} \tag{A.19}$$

$$p_{CO_2-G} = \frac{\pi\left(\sum \alpha_n - \mu\right)p_{TGC}Q}{(1-\pi)\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right)} \tag{A.20}$$

When $p_{CO_2} > p_{CO_2-P}$, we have $P_1 > P_2$. When $p_{CO_2} < p_{CO_2-G}$, we have $G_1 > G_3$. There is no way to determine the magnitude relationship between p_{CO_2-P} and p_{CO_2-G}. Only when $p_{CO_2-P} < p_{CO_2-G}$, a change in p_{CO_2} may drive system D to evolve towards $E_4(1,1)$.

(2) When the evolution result is the periodic solution around $E_5(x^*, y^*)$.

The derivatives of x^* and y^* with respect to p_{CO_2} are derived as follows:

$$\frac{\partial x^*}{\partial p_{CO_2}} = -\left\{\sum \alpha_n \left[(1-\pi)\left(p^n_e - p^{TE}_e\right) - c_n + c_{TE}\right]Q - \beta b_{TE}Q\right\} \cdot \frac{\left[\pi\left(E_g - \sum \alpha_n \varphi^n_{CO_2} Q - \beta \varphi^{TEC}_{CO_2} Q\right) - \left(\varphi^{TE}_{CO_2} - \sum \alpha_n \varphi^n_{CO_2} - \beta \varphi^{TEC}_{CO_2}\right)Q\right]}{\left\{\left(\pi E_g - \varphi^{TE}_{CO_2} Q\right)p_{CO_2} + (1-\pi)\left(\sum \alpha_n \varphi^n_{CO_2} + \beta \varphi^{TEC}_{CO_2}\right)p_{CO_2}Q - \left[(1-\pi)\left(\sum \alpha_n - \mu\right) + \mu\right]p_{TGC}Q\right\}^2} \tag{A.21}$$

$$\frac{\partial y^*}{\partial p_{CO_2}} = \frac{-\left(\varphi^{TE}_{CO_2} Q - E_g\right)\pi\left(\sum \alpha_n - \mu\right)p_{TGC}Q}{\left[\left(\varphi^{TE}_{CO_2} Q - \pi E_g\right)p_{CO_2} + (\pi - 1)\left(\sum \alpha_n \varphi^n_{CO_2} Q + \beta \varphi^{TEC}_{CO_2} Q\right)p_{CO_2} - \pi\left(\sum \alpha_n - \mu\right)p_{TGC}Q\right]^2} \tag{A.22}$$

With $P_3 < P_4$, we have $\frac{\partial x^*}{\partial p_{CO_2}} < 0$ and $\frac{\partial y^*}{\partial p_{CO_2}} < 0$. Both x^* and y^* are the decreasing function with respect to p_{CO_2}. Thus, the influence of changes in p_{CO_2} on Area ④ in Fig. 1. is uncertain. Similarly, only when $p_{CO_2-P} < p_{CO_2-G}$, changes in p_{CO_2} break the periodic solution.

As such, **Proposition 7** is proven.

A.8. Proof of Proposition 8

G_{iR} and P_{jR} are denoted as the revenue of both agents under the single RPS policy. By supposing $p_{CO_2} = 0$ in Section 2.2, we get the value of P_{jR}. As for G_{iR}, it is reconstructed as described in Section 2.2. Equilibrium points and determination rules of equilibrium stability are consistent with the previous content. With $P_{3R} < P_{4R}$, the existence conditions for ESS are discussed in Table. A.2.

Table A.2
The evolutionary stability analysis under RPS in various scenarios.*

Scenario	$P_{1R} < P_{2R}$				Scenario	$P_{1R} > P_{2R}$			
	Points	*detJ*	*trJ*	**State**		**Points**	*detJ*	*trJ*	**State**
$G_{1R} > G_{3R}$ $P_{3R} < P_{4R}$	$E_1(0,0)$	0	–	CP	$G_{1R} > G_{3R}$ $P_{3R} < P_{4R}$	$E_1(0,0)$	0	–	CP
	$E_2(0,1)$	+	+	UNS		$E_2(0,1)$	+	+	UNS
	$E_3(1,0)$	0	–	CP		$E_3(1,0)$	0	+	UNS
	$E_4(1,1)$	–	/	SP		$E_4(1,1)$	+	–	**ESS**

* Abbreviation in the Table: Critical point (CP). When $detJ = 0$ and $trJ < 0$, the LEP is a critical point. When $detJ = 0$ and $trJ > 0$, the LEP is unstable.

The critical point may be either a stable point or a saddle point. Since none of the critical points are ideal results, we do not expand on it. The only evolutionarily stable strategy is $E_4(1,1)$, and there is $P_{1R} > P_{2R}$. The derivatives of $P_{1R} - P_{2R}$ with respect to p_{TGC} is derived as follows.

$$\frac{\partial(P_{1R}-P_{2R})}{\partial p_{TGC}}=\left[(1-\pi)\left(\sum\alpha_n-\mu\right)+\mu\right]Q>0 \tag{A.23}$$

$P_{1R}-P_{2R}$ increases with p_{TGC}. Letting $P_{1R}-P_{2R}=0$ gives the zero-point.

$$p_{TGC}^R=\frac{\beta b_{TE}Q-\sum\alpha_n\left[(1-\pi)\left(p_e^n-p_e^{TE}\right)-c_n+c_{TE}\right]Q}{[(1-\pi)(\sum\alpha_n-\mu)+\mu]Q} \tag{A.24}$$

As p_{TGC} increases and satisfies $p_{TGC}>p_{TGC}^R$, then $P_{1R}>P_{2R}$ holds. It fulfills the establishment condition of $E_4(1,1)$.

Accordingly, **Proposition 8** is proved.

A.9. Proof of Proposition 9

(1) When the evolutionarily stable strategy is $E_3(1,0)$.

The derivatives of P_1-P_2 and G_1-G_3 with respect to p_{TGC} are derived as follows.

$$\frac{\partial(P_1-P_2)}{\partial p_{TGC}}=\left[(1-\pi)\left(\sum\alpha_n-\mu\right)+\mu\right]Q>0 \tag{A.25}$$

$$\frac{\partial(G_1-G_3)}{\partial p_{TGC}}=\pi\left(\sum\alpha_n-\mu\right)Q>0 \tag{A.26}$$

Both P_1-P_2 and G_1-G_3 increase with p_{TGC}. Letting $P_1-P_2=0$ and $G_1-G_3=0$ gives the zero-point, respectively.

$$p_{TGC-P}=\frac{\beta b_{TE}Q-\sum\alpha_n\left[(1-\pi)\left(p_e^n-p_e^{TE}\right)-c_n+c_{TE}\right]Q}{[(1-\pi)(\sum\alpha_n-\mu)+\mu]Q} \\ -\frac{(1-\pi)\left(E_g-\sum\alpha_n\varphi_{CO_2}^nQ-\beta\varphi_{CO_2}^{TEC}Q\right)p_{CO_2}-\left(E_g-\varphi_{CO_2}^{TE}Q\right)p_{CO_2}}{[(1-\pi)(\sum\alpha_n-\mu)+\mu]Q} \tag{A.27}$$

$$p_{TGC-G}=\frac{(1-\pi)\left(E_g-\sum\alpha_n\varphi_{CO_2}^nQ-\beta\varphi_{CO_2}^{TEC}Q\right)p_{CO_2}}{\pi(\sum\alpha_n-\mu)Q} \tag{A.28}$$

As p_{TGC} increases and satisfies $p_{TGC}>max\{p_{TGC-P},p_{TGC-G}\}$, both $P_1>P_2$ and $G_1>G_3$ hold. It fulfills the establishment condition of $E_4(1,1)$.

(2) When the evolution result is the periodic solution around $E_5(x^*,y^*)$.

The derivatives of x^* and y^* with respect to p_{TGC} are derived as follows:

$$\frac{\partial x^*}{\partial p_{TGC}}=\frac{\left\{\sum\alpha_n\left[(1-\pi)\left(p_e^n-p_e^{TE}\right)-c_n+c_{TE}\right]Q-\beta b_{TE}Q\right\}[(1-\pi)(\sum\alpha_n-\mu)+\mu]Q}{\left\{\left(\pi E_g-\varphi_{CO_2}^{TE}Q\right)p_{CO_2}+(1-\pi)\left(\sum\alpha_n\varphi_{CO_2}^n+\beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}Q-[(1-\pi)(\sum\alpha_n-\mu)+\mu]p_{TGC}Q\right\}^2} \tag{A.29}$$

$$\frac{\partial y^*}{\partial p_{TGC}}=\frac{p_{CO_2}\left(\varphi_{CO_2}^{TE}Q-E_g\right)\pi(\sum\alpha_n-\mu)Q}{\left[\left(\varphi_{CO_2}^{TE}Q-\pi E_g\right)p_{CO_2}+(\pi-1)\left(\sum\alpha_n\varphi_{CO_2}^n+\beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}Q-\pi(\sum\alpha_n-\mu)p_{TGC}Q\right]^2} \tag{A.30}$$

Since $\sum\alpha_n>\mu$, $\sum\alpha_n\varphi_{CO_2}^nQ+\beta\varphi_{CO_2}^{TEC}Q<E_g<\varphi_{CO_2}^{TE}Q$, $p_{TGC}>0$, and $\pi\in(0,1)$, given $P_3<P_4$, then $\frac{\partial x^*}{\partial p_{TGC}}<0$ and $\frac{\partial y^*}{\partial p_{TGC}}>0$. x^* is a decreasing function with respect to p_{TGC}, while y^* is an increasing function with respect to p_{TGC}. As p_{TGC} increases, x^* decreases, and y^* increases. The area of Region ④ in Fig. 1. becomes larger, and the system tends to converge to $E_4(1,1)$. However, we have $p_{TGC-G}>p_{TGC}>p_{TGC-P}$ when $P_1>P_2$ and $G_1<G_3$. That means $E_4(1,1)$ is still a saddle point. Only if p_{TGC} increases to satisfy $p_{TGC}>max\{p_{TGC-P},p_{TGC-G}\}$ and enable $G_1>G_3$, the periodic state is broken. The system definitely evolves to $E_4(1,1)$.

Accordingly, **Proposition 9** is proven.

A.10. Proof of Corollary 2

Since $\sum\alpha_n\varphi_{CO_2}^nQ+\beta\varphi_{CO_2}^{TEC}Q<E_g<\varphi_{CO_2}^{TE}Q$, substituting $E_g=\varphi_{CO_2}^{TE}Q$ into p_{TGC-P} and p_{TGC-G} derives the following thresholds:

$$p_{TGC-P}^{'}=\frac{\beta b_{TE}-\sum\alpha_n\left[(1-\pi)\left(p_e^n-p_e^{TE}\right)-c_n+c_{TE}\right]-(1-\pi)\left(\varphi_{CO_2}^{TE}-\sum\alpha_n\varphi_{CO_2}^n-\beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{(1-\pi)(\sum\alpha_n-\mu)+\mu} \tag{A.31}$$

$$p_{TGC-G}^{'}=\frac{(1-\pi)\left(\varphi_{CO_2}^{TE}-\sum\alpha_n\varphi_{CO_2}^n-\beta\varphi_{CO_2}^{TEC}\right)p_{CO_2}}{\pi(\sum\alpha_n-\mu)} \tag{A.32}$$

If $p_{TGC}>max\{p_{TGC-P}^{'},p_{TGC-G}^{'}\}$, the system consequentially evolves to $E_4(1,1)$ regardless of the value of E_g. To ensure the significance of E_g, it should satisfy $p_{TGC}\le max\{p_{TGC-P}^{'},p_{TGC-G}^{'}\}$.

A.11. Supplement of graphical exposition

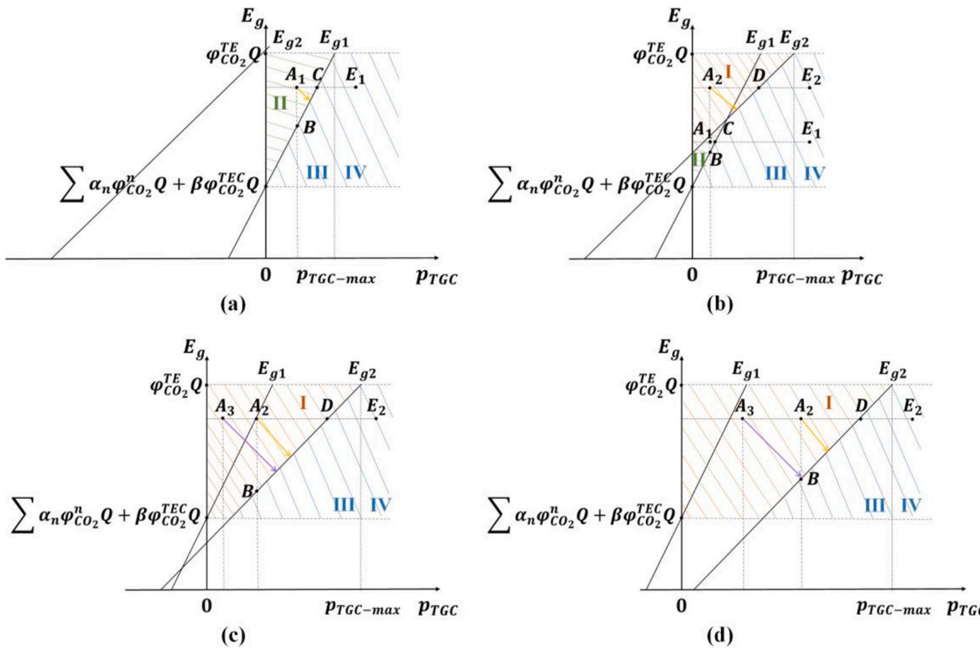

Fig. A.1. Impact of changes in the TGC price and the volume of initial carbon permits on evolutionary game results under the policy mix (cases where the slope of E_{g1} is less than E_{g2}).

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