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Influence mechanism of renewable portfolio standard on energy producers

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Abstract. Renewable energy Portfolio Standard (RPS) policy plays a significant role in reducing carbon dioxide emissions and promoting the development of renewable energy. Based on bounded rationality, this paper constructed an evolutionary game model to analyze energy power production decision-making, involving both fossil and renewable power producers as participants. Through the discussion of evolutionary game equilibrium, the study revealed the following findings: (1) marketised TGC price benefits the reduction of fossil energy power production; (2) The implementation of RPS policy does not necessarily lead to an increase in total renewable energy production; (3) Under RPS policy, the higher proportion of renewable energy quota is not always advantageous for reducing fossil energy power production.

1 Introduction [a]

Governments worldwide are increasingly focused on environmental protection and sustainable development, thus enforcing strict environmental regulations[1]. According to the International Energy Agency (IEA), 42% of global CO2 emissions come from the electricity sector, with fossil power generation being a major contributor. Thus, it is crucial for China's low-carbon energy transition to reduce fossil energy production in a reasonable and scientific way. RPS policy is a mandatory requirement for the proportion of renewable energy generation in the market, implemented by a country or region through legislation[2]. TGCs are tradable certificates issued by the government, representing a corresponding amount of renewable energy generation. Fossil energy power producers can fulfill their quota obligations under the RPS policy by purchasing TGCs.

Currently, both domestic and international scholars have mainly focused on researching the impact of RPS policy on renewable energy production and the impact of related renewable energy policies on production decisions of power production producers. Nishio, K., & Asano shows that the purchase of certificates from renewable generators will enable effective implementation of the RPS[3]. Wang et al. examined the implementation effects of different policies in the Chinese electricity market and found that RPS policy is more favorable for increasing renewable energy production[4]. ZhuFan and Lin (2020) made a system dynamics model for analyzing the strategic interactions of stakeholders in a three-party evolutionary game[5]. Chen et al. developed an evolutionary game model between manufacturing producers and the government under the RPS policy to analyze their choices regarding technological innovation[6].

This study firstly establishes an evolutionary game analysis framework that considers power producers as game entities under the assumption of bounded rationality. Subsequently, through analyzing the equilibrium outcomes of the evolutionary game, we discuss the influence of market-based TGC prices on the production decisions of different types of producers under RPS policy.

2 Model Description and Construction

Based on the assumption of bounded rationality, this paper constructs an evolutionary game model that includes N fossil energy power producers and N renewable energy power producers as participating agents in the context of market-based TGC prices. The description of parameters are shown in Table 1.

2.1. Symbol description

Table 1 Description of parameters

Items	Descriptiom
α	Quota reqquirement under RPS
$q_{T/R}$	Low production of energy producers (kWh)
$kq_{T/R}$	High production of energy producers (kWh)
P_{TGC}	TGC price (yuan/kWh)
P_e	On grid electricity price (yuan/kWh)
c	Unit cost of fossil energy power producers (yuan/kWh)
Δc	Unit difference cost between renewable and fossil energy power producers

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Table 1 Description of parameters(continued)

Items	Descriptiom
N	Number of fossil or renewable energy power producers
m	Slope of TGC price function
n	Intercept of TGC price function
Q_{supply}	Total renewable energy production
Q_{demand}	Total fossil energy production

2.2 Assumptions of the model

In order to facilitate analysis and improve the rationality of the research without losing generality, this study make the following assumptions:

(1) Both fossil energy and renewable energy power producers have two pure strategies, namely high production strategy (H) and low production strategy (L). (2) If the low production strategy is chosen, the energy power producer generates electricity, while using the high production strategy, the producer generates electricity. We suppose, it is worth pointing out that the value of does not affect the conclusion of this paper. (3) The power producers are the market entities responsible for meeting the RPS obligations. (4) In the TGC trading market, there are homogeneous fossil energy power producers and homogeneous renewable energy power producers, who are bounded rational decision-making agents aiming to maximize their own interests. (5) The demand for TGCs from fossil energy power producers can be fully satisfied, and the TGCs provided by renewable energy power producers can all be sold out completely. (6) The TGC price is expressed as a linear function, which is negatively correlated with supply and positively correlated with demand. (7) The electricity generated by renewable energy power producers can be exchanged for an equivalent quantity of TGCs[7].

2.3 Model establishment

The trading mechanism between fossil energy and renewable energy power producers is illustrated in Figure 1. Power producers sell electricity in the power market to gain revenue. Simultaneously, in the TGC market, fossil energy and renewable energy power producers serve as the demand side and supply side of TGCs, respectively.

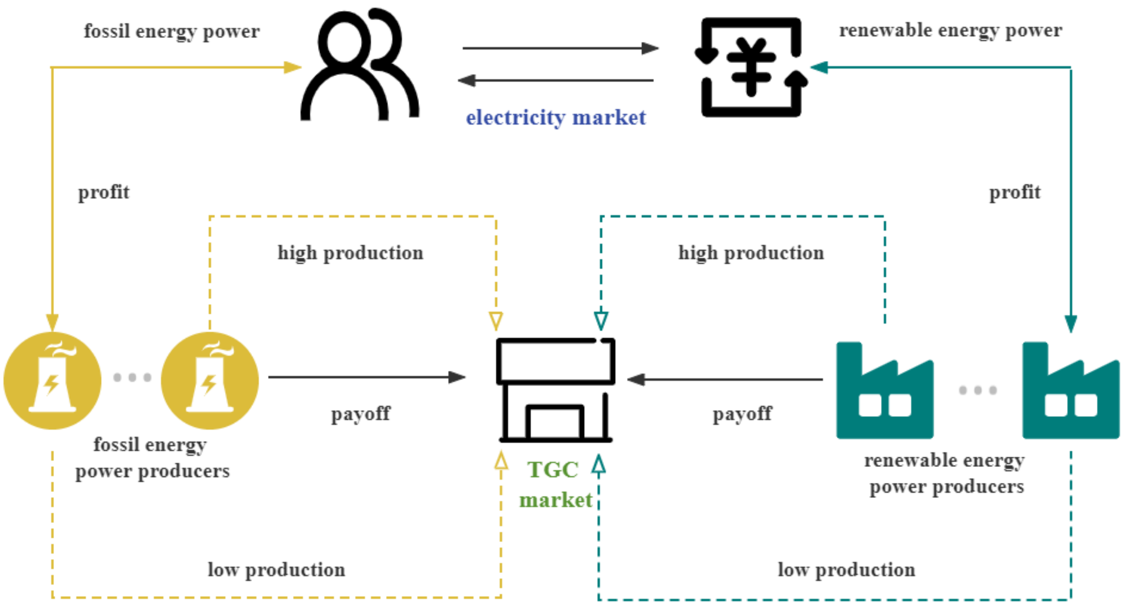

Fig. 1. Market transaction framework.

Under the RPS policy, the government sets a quota α, All power producers are required to fulfill the corresponding quota. Specifically, renewable energy power producers can only sell $(1-\alpha)$ portion of their electricity generation exchanged as TGC to generate revenue, while fossil energy power producers need to purchase α portion of TGC based on their own electricity production. Let $x(0 \le x \le 1)$ be the proportion of renewable energy power producers choosing the low production strategy, and then $(1-x)$ denotes the proportion of renewable energy power producers choosing the high production strategy. Similarly, let $y(0 \le y \le 1)$ be the proportion of fossil energy power producers choosing the low production strategy, and then $(1-y)$ denotes the proportion of fossil energy power producers choosing the high production strategy. Each player has two pure strategies to choose from: the low production strategy (L)($q_{T/R}$) and the high production strategy (H)($kq_{T/R}$, $k>1$). The strategy selection for power generation output will affect the price of TGC and the participants' revenue, each player can make choice which best favor its interest. The payoff matrix for the four different strategy combinations of power production decisions by the two players is shown in Figure 2.

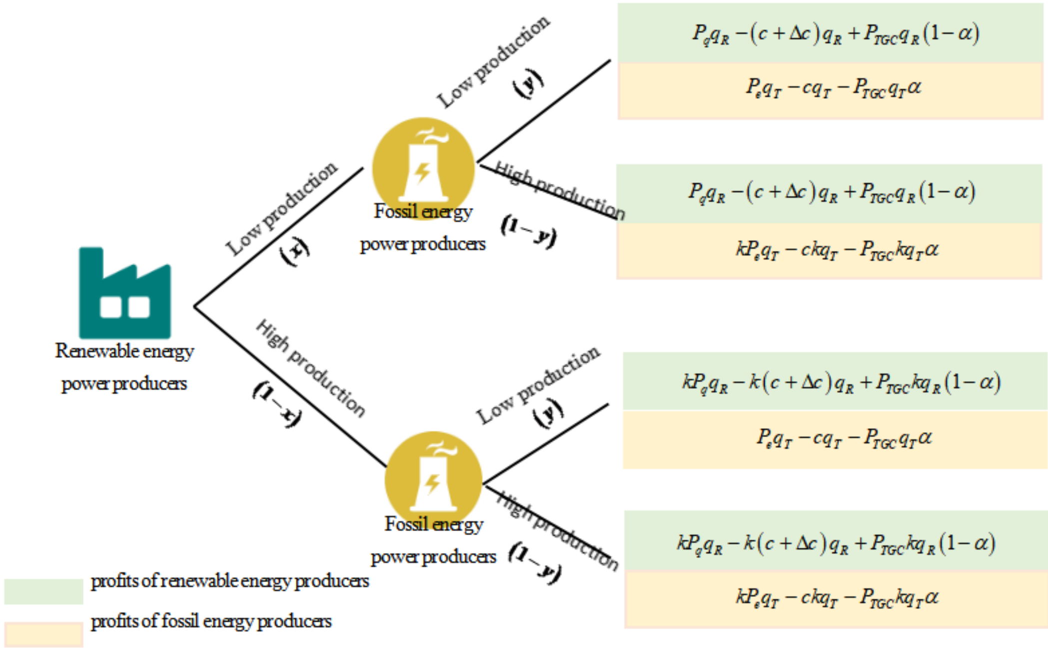

Fig. 2. Game tree and revenue of two kinds of power generation producers.

For analytical convenience, the price of TGC is set as a linear function, that is, the supply and demand of TGCs are vertically related to the energy output of all power generation enterprises [8], that is, $Q_{supply} - Q_{demand} = xNq_R + (1-x)Nkq_R - (1-y)Nkq_T - yNq_T$. Thus, the price of TGC can be expressed as :

$$P_{TGC} = m - n(xNq_R + (1-x)Nkq_R - (1-y)Nkq_T - yNq_T) \quad (1)$$

Where, m and n are the slope and intercept of the TGC price function, respectively.

3 Equilibrium Analysis

Based on the assumptions of bounded rationality and evolutionary stability strategy theory, and represent the rates of change over time in the proportions of power producers choosing the low production strategy for renewable and fossil energy respectively. The replicator dynamic equations for the behaviour of the replicators [10] are given by Equations (2) and (3).

$$F(x) = \frac{dx}{dt} = x(Eg_L - Eg)$$
$$= (1-x)xq_R(c + \Delta c - P_e + (\alpha - 1)[m + (x-2)nNq_R + (2-y)nNq_T)] \quad (2)$$

$$F(y) = \frac{dy}{dt} = y(Eb_L - Eb)$$
$$= (y-1)yq_T(P_e - c + \alpha[-m + (2-x)nNq_R + (y-2)nNq_T)] \quad (3)$$

The equations above describe the adjustment rates of the behaviour strategies for renewable energy and fossil energy power producers. The game reaches a relatively stable state only when the dynamic equations of the replicators are equal to zero. When and, eight equilibrium points can be obtained: (0,1), (1,1), (0, y_5), (1, y_6), (x_7, 0), (x_8, 1), where y_5、 y_6、 x_7、 x_8 are expressed as Equations (4), (5), (6), and (7), respectively:

$$y_5 = \frac{c - P_e + (m - 2nNq_R + 2nNq_T)\alpha}{nN\alpha q_T} \quad (4)$$

$$y_6 = \frac{c - P_e + (m - nNq_R + 2nNq_T)\alpha}{nN\alpha q_T} \quad (5)$$

$$x_7 = \frac{P_e - c - \Delta c + (m - 2nNq_R + 2nNq_T)(1-\alpha)}{nN(-1+\alpha)q_R} \quad (6)$$

$$x_8 = \frac{P_e - c - \Delta c + (m - 2nNq_R + nNq_T)(1-\alpha)}{nN(-1+\alpha)q_R} \quad (7)$$

Whereas Equations (8) and (9) represent the average payoff functions for renewable energy power producers in the low and high production strategies, respectively. Among them, $\pi_1 = \pi_2 = P_e q_R - (c+\Delta c)q_R + P_{TGC} q_R (1-\alpha)$, $\pi_3 = \pi_4 = kP_e q_R - k(c+\Delta c)q_R + P_{TGC} kq_R (1-\alpha)$.

$$Eg_L = y\pi_1 + (1-y)\pi_2 = P_e q_R - (c+\Delta c)q_R + P_{TGC} q_R (1-\alpha) \quad (8)$$

$$Eg_H = y\pi_3 + (1-y)\pi_4 = kP_e q_R - k(c+\Delta c)q_R + P_{TGC} kq_R (1-\alpha) \quad (9)$$

Similarly, Equations (10) and (11) provide the average payoff functions for fossil energy power producers in the low and high production strategies, respectively. Among them, $\Pi_1 = \Pi_3 = P_e q_T - c q_T - P_{TGC} q_T \alpha$, $\Pi_2 = \Pi_4 = kP_e q_T - ckq_T - P_{TGC} kq_T \alpha$.

$$Eb_L = x\Pi_1 + (1-x)\Pi_3 = P_e q_T - c q_T - P_{TGC} q_T \alpha \quad (10)$$

$$Eb_H = x\Pi_2 + (1-x)\Pi_4 = kP_e q_T - ckq_T - P_{TGC} kq_T \alpha \quad (11)$$

The average payoffs of renewable and fossil energy producers can be defined in the following way:

$$Eg = xEg_L + (1-x)Eg_H$$
$$= (2-x)q_R(P_e - c - \Delta c + (1-\alpha)P_{TGC}) \quad (12)$$

$$Eb = yEb_{L} + (1-y)Eb_{H} = (2-y)q_T(P_e - c - \alpha P_{TGC}) \tag{13}$$

The Jacobian matrix can be obtained by differentiating the replicator dynamic Equations (2) and (3).

$$\begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix} \tag{14}$$

$$\begin{cases} J_1 = q_R\{(-1+2x)P_e - nN(2-6x+3x^2)(-1+\alpha)q_R - (-1+2x)[c-m+m\alpha+\Delta c - nN(-2+y)(-1+\alpha)q_T]\} \\ J_2 = (1-x)xq_R(nNq_T - nN\alpha q_T) \\ J_3 = -nN(-1+y)y\alpha q_R q_T \\ J_4 = q_T[c-2cy+m\alpha-2my\alpha+(-1+2y)P_e+nN(-2+x+4y-2xy)\alpha q_R+2nN\alpha q_T-6nNy\alpha q_T+3nNy^2\alpha q_T] \end{cases} \tag{15}$$

By calculating the determinant and trace of the Jacobian matrix, and satisfying and , the equilibrium point is an evolutionarily stable strategy (ESS); when and , it is an unstable point; when , it is an saddle point[1] . By analysing and discussing the stability of the equilibrium points using the Jacobian matrix, the following theorem and corollary are obtained. The ESS under different conditions can be found in Table 2.

Table 2. ESS and corresponding conditions

Equilibrium point	det(J)	tr(J)	Local stability	conditions
(0,0)	+	-	ESS	$q_T > q_R + \frac{m}{2nN}$ and $0<\alpha<\frac{P_e-c}{m+2nN(q_T-q_R)}$
(0,1)	+	-	ESS	$q_T > 2q_R - \frac{m}{nN}$ and $\frac{c-P_e}{nN(2q_R-q_T)-m}<\alpha<1$
(1,0)	+	-	ESS	$q_R > 2q_T + \frac{m}{nN}$ and $0<\alpha<1-\frac{c+\Delta c-P_e}{nN(2q_T-q_R)+m}$ or $0<\alpha<\frac{P_e-c}{P_{TGC}}$ and P_{TGC} is fixe-d
(1,1)	+	-	ESS	$1>\alpha>\frac{P_e-c}{P_{TGC}}$ and P_{TGC} is fixed

Theorem 1: If the price of TGC is fixed and $0 < \alpha < \frac{P_e-c}{P_{TGC}}$, (0,0) is ESS; when the TGC price is fixed and $\frac{P_e-c}{P_{TGC}} < \alpha < 1$, (0,1) is ESS.

Proof: Under the conditions of $0 < \alpha < \frac{P_e-c}{P_{TGC}}$, when the TGC price is fixed, the determinant of the Jacobian matrix at point (0,0) is $k^2q_R[(P_e-c)(q_T+q_R)+P_{TGC}\alpha(q_R-q_T)+(P_{TGC}-\Delta c)q_R]<0$, and the trace is , $-k[(P_e-c)(q_T+q_R)+P_{TGC}\alpha(q_R-q_T)+(P_{TGC}-\Delta c)q_R]<0$ According to the stability criterion for equilibrium points[9], (1,0) is ESS. Similarly, (0,1) is ESS when $0 < \alpha < \frac{P_e-c}{P_{TGC}}$.

Theorem 2: In the case of $q_T > 2q_R - \frac{m}{nN}$, if the quota is met $\frac{P_e-c}{m+nN(q_T-2q_R)} < \alpha < 1$, (0,1) is ESS.

Corollary 1: Compared to a marketised TGC price, the fixed TGC price will suppress the total production of fossil energy.

Proof: In the case of a fixed TGC price, the profits of renewable and fossil energy power producers are not affected by each other's production levels. Moreover, when the TGC supply and demand can be met, the profits of energy power prodcuers are only affected by their own production decisions. In order to achieve higher profits, producers typically adopt a high production strategy. According to Theorem 1, in the fixed TGC price scenario, (0,0) or (0,1) is the ESS, and renewable energy power procducers will choose the high-production strategy. Fossil energy power producers tend to choose the high production strategy when the quota is low, but choose the low production strategy when the quota is high. Combined with Theorem 2, in a market-driven TGC pricing system, in order to achieve the current market conditions where fossil energy power production far exceeds renewable energy power production, it is preferable for fossil energy power producers to adopt the low production strategy. At this point, the quota requirement $\frac{P_e-c}{m+nN(q_T-2q_R)}$ is relatively smaller and easier than $\frac{P_e-c}{P_{GCT}}$ to meet, indicating that the marketised TGC price enables the government to suppress the increase in fossil energy power production with a lower quota requirement.

Theorem 3: Under the terms of $q_T > q_R - \frac{m}{2nN}$ and $0 < \alpha < \frac{P_e-c}{m+2nN(q_T-q_R)}$, (0,0) is ESS.

Corollary 2: When renewable energy production far exceeds fossil energy production $q_T > q_R - \frac{m}{2nN}$, implementing RPS policy increases renewable energy power production.

Proof: When $2q_R - \frac{m}{2nN} > q_T > q_R - \frac{m}{2nN}$, according to Theorem 3, a lower quota satisfies $0 < \alpha < \frac{P_e-c}{m+2nN(q_T-q_R)}$ makes (0,0) ESS. While $q_T > 2q_R - \frac{m}{nN}$ and a higher quota satisfies $\frac{P_e-c}{m+nN(q_T-2q_R)} < \alpha < 1$ lets (0,1) ESS, which means, N renewable energy power prodcuers will choose high production, as a result, the renewable energy production quantity will be $2Nq_R > 1.5Nq_R$. Therefore, when fossil energy power production far exceeds renewable energy power production, the RPS policy increases renewable energy production.

Theorem 4: According to the terms of $q_T < q_R - \frac{m}{2nN}$ and $\frac{P_e-c-\Delta c}{m+2nN(q_T-q_R)} + 1 < \alpha < 1$, (0,0) is ESS.

Theorem 5: Under the terms of $q_T < \frac{1}{2}q_R - \frac{m}{2nN}$ and $0 < \alpha < 1 + \frac{c+\Delta c-P_e}{nN(q_T-2q_R)-m}$, (1,0) is ESS.

Corollary 3: The ratio of requirement quota does not necessarily have to be higher to have a reduction in fossil energy production.

Proof: From theorem 5, when $q_T < \frac{1}{2}q_R - \frac{m}{2nN}$ and $0 < \alpha < 1 + \frac{c+\Delta c-P_e}{nN(q_T-2q_R)-m}$, (1,0) is ESS, this implies that N fossil energy power producers will tend to choose the high production strategy. And c ombine Theorem 2, when

$q_T > 2q_R - \frac{m}{nN}$ and $\frac{P_e - c}{m + nN(q_T - 2q_R)} < \alpha < 1$, fossil energy power producers tend to choose the low production strategy. Therefore, a lower quota is beneficial to increase fossil energy power production.

Corollary 4: The implementation of RPS policy may not necessarily lead to an overall increase in renewable energy production.

Proof: According to theorem 5, when $q_T < \frac{1}{2}q_R - \frac{m}{2nN}$ and $0 < \alpha < 1 + \frac{c + \Delta c - P_e}{nN(q_T - 2q_R) - m}$, (1,0) is ESS. This indicates that N renewable energy power producers will eventually choose the low production strategy. As a result, the amount of renewable produced Nq_R will be lower than the initial renewable energy production quantity $1.5Nq_R$. Therefore, the implementation of the RPS policy with lower quota requirements may even decrease renewable energy production.

4 Conclusions

Based on the results of this research, the main conclusions of the above analysis are as follows: Firstly, the results suggest that the marketised price of TGC negatively impacts the overall level of fossil energy production and facilitates a decrease in carbon emissions. Secondly, the implementation of RPS policy may not necessarily lead to an increase in the overall amount of renewable energy production. If the amount of renewable energy power production vastly exceeds the amount of fossil energy power production, then under low quota requirements with a lower quota, the RPS policy will result in a reduction in renewable energy production but an increase in fossil energy power production. Thirdly, under RPS policy, increased quotas are not inherently harmful to the development of fossil energy production, and the policy criteria should be adaptably regulated in accordance with the levels of energy generation.Based on the research findings, we proposed the following policy implications: First, the government ought to embrace a marketised TGC pricing strategy when implementing the RPS policy. Second, when implementing the RPS policy, the government should continuously modify the policy specifics, such as quotas, based on the real power production scenario.

However, there are some limitations to the above study that need to be improved. The study only considers the impact of energy production on the profits of power producers in the electricity and TGC markets, without taking into account factors such as penalties and subsidies. There is ample room for expansion and improvement in future studies.

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