

Article

Competitive Game Model and Evolutionary Strategy Analysis of Green Power and Thermal Power Generation

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Abstract: In the context of achieving carbon peak and carbon neutrality goals, the power industry has become a key and challenging place to promote the green and low-carbon transformation of the economy and society. We selected green power generation enterprises and thermal power generation enterprises in the power industry as the research objects and applied relevant theories such as game theory and low-carbon economy theory to analyze the low-carbon transformation path of electricity under the “dual carbon” goal. We quantitatively analyzed the competition and cooperation relationship between green power and thermal power. Based on mutual benefit preferences, a competitive game model was constructed, and the optimal competitive equilibrium electricity quantity and price of both parties were discussed in different scenarios. The master–slave game problem was transformed into a double-layer game model and solved using the GA algorithm. We draw the following conclusions: (1) When green power enterprises and thermal power enterprises compete to achieve equilibrium, a high degree of altruistic willingness is a necessary condition for both parties to maximize their own utility. (2) A high-level mutually beneficial relationship is a key factor in effectively improving overall profits. (3) In the long-term mutually beneficial competitive relationship between green power and thermal power, by quantitatively adjusting the internal and external factors that affect system evolution, the quantitative adjustment of the feasible domain boundaries of the evolution of the mutually beneficial competitive relationship can be achieved, thereby influencing the existing transformation of the competitive relationship to evolve toward the desired direction.

Keywords: competitive strategy; low-carbon transformation; mutual benefit preference; green electricity and thermal power



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1. Introduction

China’s energy sector is facing severe challenges. With the gradual depletion of resources and decreasing environmental capacity, the traditional extensive development model is no longer applicable. Therefore, China is actively promoting an energy structure adjustment and diversified development to adapt to major challenges such as climate change, reduce emissions, and ensure energy security. The comprehensive development of various clean energy forms such as wind power, photovoltaic power generation, and biomass energy can reduce greenhouse gas emissions, reduce dependence on imported energy, and meet the growing energy demand. The Chinese government has adopted a series of policy measures aimed at extending the sustainable utilization period of fossil fuels, reducing dependence on fossil fuels, reducing greenhouse gas emissions, and promoting the development of energy and electricity toward low-carbon, green, and sustainable directions. The goal of this transformation is to achieve the efficient utilization of resources, promote innovation and the application of clean energy technologies, and achieve sustainable economic and social development goals.

In the current context of the economic, social, and energy power transformation and development, the power production structure is showing a diversified development trend. The core of this trend is to promote the development of renewable energy power technology, optimize the power structure, and promote the market-oriented reform of electricity to promote resource conservation and environmental protection. Renewable energy power technology is flourishing, with rapid growth in installed capacity. However, the efficiency of electricity production still needs to be improved, and further optimization of technology is needed to improve the electricity utilization rate of renewable energy and achieve more efficient energy conversion. According to the latest data, the proportion of clean and renewable energy sources such as hydropower, nuclear power, grid-connected wind power, and solar power in China's electricity production has reached 30.3%. This indicates the gradual increase in clean energy in China's power structure. However, despite the increasing proportion of clean energy, coal-fired power still dominates, accounting for over 65% of China's electricity generation [1]. This highlights the importance of coal-fired power in China's electricity production, while also highlighting the urgent need to reduce dependence on carbon energy. With the continuous deepening of electricity marketization reform and the continuous maturity of renewable energy technologies, it is foreseeable that clean energy will play a more important role in China's electricity production in the future. Our research will provide more possibilities for China's energy structure transformation and promote economic and social development toward a more environmentally friendly and sustainable direction.

The green and low-carbon transformation of the power system marks the rise of renewable energy in the power structure, but the challenges of transformation still exist. To achieve a significant proportion of renewable energy in the power structure, it is necessary to address the issues of its economy and competitiveness. In the process of power transformation, the installed capacity of renewable energy has rapidly increased, but its economic comparison with traditional energy is still unclear. Thermal power units, especially coal-fired power units, not only ensure the safety and stability of the power supply but also play an important role in emergency peak shaving and heating. Therefore, in the process of transformation, considering the complexity of the power system, more effective policy measures need to be formulated to gradually achieve the transformation of the power structure toward green, low-carbon, and diversified directions. A diversified power structure is an inevitable trend of development, which will be a complex and long-term process that requires joint efforts and continuous investment from all parties.

In recent years, China's power industry has made certain achievements, with improved thermal power efficiency and significant reductions in carbon emissions. However, there are still challenges in the coordinated development of the power structure [2]. The low matching between power sources and the power grid, uneven technological development, and difficulties in peak shaving have constrained the consumption of renewable energy. In addition, the electricity market mechanism is not perfect, relevant policy measures have significant limitations, and there is a lack of clear development paths and task goals. The transformation of electricity faces multiple challenges. The transformation of electricity not only requires technological progress but also the establishment of clean and low-carbon management and market mechanisms. To achieve the goal of power transformation, it is necessary to optimize the power structure, promote technological innovation, and establish scientific decision-making and analysis tools to promote the revolution of production and consumption, in order to support clean and low-carbon development. The scientific analysis tools and decision support systems in this paper will provide effective support for green and low-carbon development, promoting the development of the power system toward safety, efficiency, cleanliness, low-carbon strategies, and sustainability.

2. Literature Evaluation

Many studies have discussed the production, consumption, and use of green electricity and thermal power enterprises under the green certificate system as well as their impact

on the economy and environment. Here, we focus on studying the transformation paths and emission reduction effects of green power and thermal power enterprises, which are closely related to this article.

2.1. The Connotation and Related Research of the Green Certificate System

The green certificate trading system adopts a quota system, requiring quota holders to purchase a certain proportion of renewable energy electricity as part of their sales. Green power providers can obtain corresponding green certificates based on the amount of electricity integrated into the grid per unit, and the number of green certificates purchased by quota holders represents the amount of renewable energy electricity they purchase [3]. Therefore, the profits of green power suppliers come from two aspects: the sales of electricity in the electricity market and the sales of green certificates. This revenue model helps to improve the economic feasibility of renewable energy generation.

At present, most research in China focuses on the macro level of green certificate policies, but there is still a lack of in-depth research on how the transformation of evaluation subjects affects the strategic behavior of power generation companies in the electricity market and green certificate market. Some experts believe that evaluating renewable energy policies solely from the perspective of efficiency or economic output is one-sided. They suggest using cost-benefit analysis to evaluate the effectiveness of policies. Liu Xinjian and others analyzed the impact of carbon pricing, renewable energy subsidies, and their combination policies with different intensities on China's energy consumption and electricity production structure based on a dynamic computable general equilibrium model. Wang H.W. et al. analyzed the development of China's photovoltaic industry and evaluated the impact of electricity price subsidy policies on the photovoltaic industry chain [4]. Nie H. et al. developed a comprehensive average electricity price-cost model and evaluated the impact of renewable energy electricity incentive policies based on the policy background [5]. Tu Q. et al. evaluated the effectiveness of China's renewable energy policy from three perspectives: policy effectiveness, policy cost, and technological development [6].

Although China's stable network electricity pricing policy has played a certain role in promoting green electricity consumption, it has also brought financial burdens. Zhu B. C. et al. believe that the green certificate trading system plays an important role in promoting the development of the renewable energy industry and can alleviate the subsidy pressure in the process of energy industry development [7]. Zhang N. et al. constructed an "Energy Environment Economy" recursive dynamic CGE model and pointed out that mandatory green certificate trading can replace electricity price subsidy policies and promote the development of the new energy power industry [8]. The fixed grid electricity price policy and the green certificate trading system each have their own advantages, and their effectiveness depends on whether the development goals of renewable energy can be achieved. Zhao X.Q. et al. found through research that, in the early stages of the development of the renewable energy power industry, a fixed grid electricity price policy is relatively advantageous. However, when the market size expands and technology becomes more advanced, the advantage of quota-based policies in the form of green electricity certificate trading is more significant [9]. Yu Z.L. et al. believe that, as the energy system is the driving force of current economic development, energy transformation will inevitably drive the transformation of energy consumption, thereby promoting the development of the digital economy [10].

2.2. Research on Carbon Reduction in Power Enterprises under the Background of Carbon Reduction

In the study of CO₂ emission reduction potential in the power industry, many scholars have combined national and regional low-carbon goals, energy structure adjustment policies, and power planning factors to construct different development scenarios such as the comprehensive economic growth rate, power supply and demand, power structure, and low-carbon power technology. They have also studied the relationship between carbon

emission reduction and economic development. Song Peng et al. established a general equilibrium analysis framework for the national carbon market, examined the emission reduction effects of renewable energy subsidies in the power industry and the parallel operation of the national carbon market, and proposed corresponding policy coordination paths [11]. Yu B. et al. analyzed the carbon emissions of Ningxia's power industry using the five-factor generalized Dirichlet index model and the Tapio decoupling model. The results showed that the overall carbon emissions and electricity output of Ningxia's power industry have not yet achieved decoupling, but there is a trend toward decoupling. Yu Q.T. used the LMDI model to explore the key factors affecting carbon emissions in the power sector and, based on this, constructed a system dynamics model. By studying the trend evolution of carbon decoupling in the power industry, strategic suggestions were proposed, such as promoting new clean power sources, a reasonable layout, and implementing precision policies for the combination [12].

At present, research on the pricing game strategies of green power and thermal power generation enterprises mainly focuses on the trading strategies of power generation enterprises, especially in the context of a single policy. Most studies aim to maximize the profits of individual enterprises or regional total profits to explore the best strategies for power generation enterprises [13]. In terms of carbon emission trading, some studies have adopted a dynamic game model-based approach to explore the impact of initial quota allocation on enterprises [14]. Other studies have constructed double-layer optimization models to analyze the strategic behavior of electricity market participants in the context of carbon trading [15]. The research on the green electricity certificate market considers the impact of transmission congestion on the market and analyzes the bidding strategies in the electricity market and the green certificate market. Other scholars have constructed a multi-oligopoly non-cooperative game model and studied the strategic behavior of renewable energy enterprises participating in transactions. Overall, although there have been studies on the analysis of power enterprise transactions, there is still relatively little research on the transformation path of power generation enterprises.

As a major electricity consumer in China, in order to achieve a balance between energy, the environment, and economic development, it is necessary to change the traditional method of relying on coal combustion for power generation, adjust the power supply structure, and actively promote the clean power industry, with clean energy as the main focus. Based on this, in the process of studying the optimization and substitution of China's power supply, it is necessary to focus on the potential and development progress of "green electricity" replacing "thermal power", explore the best alternative solutions for thermal power in the context of the coordinated development of energy and environment, and explore the role that the government should play in different stages of "green electricity" development. In China, the development level and level of various electric energy sources have their own characteristics and are also accompanied by various differentiated issues. Therefore, a detailed study of the pace of promoting electricity resources is needed, and its potential value should be evaluated, in order to effectively summarize the growth stages and challenges encountered by each type of electricity energy, clarify the responsibilities to be undertaken at each stage, and identify the problems that need to be addressed, providing decision support for decision-makers [16]. Based on this, decision-makers can formulate promotion measures or policies that are suitable for different stages of development, stimulate social investment in the clean and efficient power industry, and accelerate the pace of replacing coal-fired power with "green electricity". This article starts from the perspective of the low-carbon transformation of power enterprises, constructs a master-slave competitive game model based on mutual benefit for green electricity and thermal power in the electricity market, quantitatively studies the optimal competitive equilibrium electricity quantity and price under certain mutually beneficial competitive conditions, and discusses the impact of changes in other factors on the profits and other equilibrium variables of both parties under the competitive game model, in order to analyze these impacts. Based on the quantitative research conclusions of the model, this paper

discusses the long-term competitive evolution and stable strategies of both parties in different feasible domains of altruistic factors, combined with case studies and scenarios. Furthermore, it analyzes the low-carbon transformation model and path analysis of power enterprises under carbon emission reduction constraints and seeks quantitative adjustment methods for the evolution direction of low-carbon transformation.

3. Model

3.1. Model Setting

Table 1 summarizes the symbols used in the paper.

Table 1. Notations.

Notation	Description
a, B	Electricity cost coefficient
R	Maximum selling price
S	Electricity price change rate
TGC	Tradable green certificate
π_c	The Altruistic Effect of Thermal Power Enterprises
π_g	The Altruistic Effect of Green Power Enterprises
U_c	The fit of thermal power enterprises
U_g	The fit of green power enterprises
ε	The Altruistic Factors of Green Power Enterprises for Thermal Power Enterprises
δ	Altruistic factors of thermal power enterprises toward green power enterprises
u_{ci}	When green power enterprises are altruistic, the average rate of change in profit increases for thermal power enterprises
u_{gi}	When thermal power enterprises are altruistic, the average rate of change in profit increase for green power enterprises
v_{ci}	When thermal power enterprises are altruistic, the average rate of change in their own profit loss
v_{gi}	The average rate of change in profit loss for green power enterprises when seeking altruism
F_c	Risk loss limit for thermal power enterprises deviating from mutual benefit
F_g	Risk loss limit for green power enterprises deviating from mutual benefit
M_c	Additional value-added profits for thermal power enterprises when mutually beneficial
M_g	Additional value-added profits for green power enterprises when mutually beneficial
E_{ci}	The demands on green power and thermal power of electricity consumers in the market
E_{gi}	Green electricity and expected profits of thermal power enterprises

With the context of the electricity industry in China taken into consideration, the assessments used in the model are as follows:

In order to improve energy efficiency, reduce carbon emissions, comply with the actual situation of market trading operations, and facilitate model derivation and theoretical analysis, the following basic assumptions will be made:

Assumption 1. Both green power and thermal power have their own pending strategies and profit functions, and they have full authority to act independently to maximize their own profits. The profit depends not only on one's own strategy but also on the mutually beneficial competitive behavior of both parties.

Assumption 2. There is an uncertain factor in the transformation model, which is fuzzy in the institutional strategy of green power enterprises and displayed in the institutional strategy of

thermal power enterprises. The uncertainty parameters simultaneously affect the profits of green power and thermal power.

Assumption 3. Uncertain factors depend on decision-making but are completely unknown. Power companies can limit the range of uncertain factors through active control. In the process of low-carbon transformation, power companies need to balance between expected profits and CvaR (conditional value at risk), consider the potential risks brought by uncertain factors, and improve the practicality of the model.

Assumption 4. The market inverse demand functions faced by power companies are all linear functions, which are specifically set according to the different types of bilateral transaction channels.

3.2. Mutual Benefit and Competitive Transformation Model

In the balanced demand for green electricity and thermal power in the market, building a model not only requires strengthening the internal control of enterprise transformation but also requires considering the uncertainty of external risk factors. It is necessary to consider the equilibrium demand of the optimal electricity price and optimal electricity production and analyze the impact of carbon emission quotas on the equilibrium results. Based on the above model and the previous description, the decision-making model for power enterprises is expressed as follows:

$$\begin{cases} \operatorname{argmax}_{q>0} \pi_c = \operatorname{argmax}_{q>0} (U_c + \sum_{i=1}^N \delta_i U_g) \\ \operatorname{argmax}_{p>0} \pi_g = \operatorname{argmax}_{p>0} (U_g + \sum_{i=1}^N \varepsilon_i U_c) \end{cases} \quad (1)$$

Equation (1) is an optimization problem with a master–slave hierarchical structure, belonging to the category of bilevel programming problems. In the bilevel programming model, the upper level is a single-objective model, and the lower level is a multi-objective model. The objective functions are all nonlinear functions. The lower-level objective function is a concave function, and to solve the maximum value problem, the solution determined by the corresponding KKT (Karush Kuhn Tucker) condition of the lower-level programming is the optimal solution of the lower-level programming. We replace the lower-level programming with the KKT optimality condition of the objective function of the lower-level model. At the same time, the optimal solution of the lower-level programming serves as a constraint condition for the upper-level programming, transforming the bilevel multi-objective programming problem into a single-level single-objective programming problem for solution. Using the KKT (Karush Kuhn Tucker) condition, the double-layer problem is transformed into a single-layer problem. First, the problem of minimizing transformation costs, i.e., maximizing profits, is solved. Then, the external risk problem is determined, and these two problems can be solved sequentially.

The decision model includes expected returns and balances existing risks. Higher returns mean taking on higher risks. In contrast, conservative enterprises tend to avoid risks. Using the reverse induction method to solve this problem, the maximization of the altruistic utility function of the power enterprise corresponds to the following optimization problem:

$$\max \pi = \max \left[\left(p - \frac{1}{2} a q^* - b \right) q^* + \varepsilon (r - s q^* - p) q^* \right] \quad (2)$$

The decision variable q is the market demand for electricity, p is the retail electricity price, r and s are the upper selling electricity price and the electricity price change rate, respectively. The cost function is a quadratic function, $\frac{1}{2} a q^2 + b q$, where $0 < a < b \leq r$ are the cost coefficients.

The first-order optimal response equation is as follows:

$$\frac{\partial \pi}{\partial p} = (1 - \varepsilon)q^* + (p - aq^* - b) \frac{\partial q^*}{\partial p} - p + \varepsilon \left[(r - sq^* - w) \frac{\partial q^*}{\partial p} - sq^* \frac{\partial q^*}{\partial p} \right] = 0 \quad (3)$$

Among them, $\frac{\partial q^*}{\partial p} = \frac{\delta - 1}{2s + a\delta}$, and combining (3) and $q_i^* = \frac{r - p + \delta(p - b)}{2s + a\delta}$ can obtain the optimal electricity generation and price, which are as follows:

$$\begin{cases} q^* = \frac{(r - b)(1 - \varepsilon\delta)}{4s(1 - \varepsilon) + [1 - (2\varepsilon - 1)\delta]a + 2s\varepsilon(1 - \delta)} \\ p^* = \frac{r - \delta b - q^*(2s + a\delta)}{2s + a\delta} \end{cases} \quad (4)$$

Proposition 1. An increase in altruism (ε) among green power enterprises will increase the optimal electricity production (q^*) and reduce the optimal electricity prices (p^*), according to the altruistic degree of green power enterprises (ε). The increase in electricity will reduce the optimal electricity production (q^*) and increase the optimal electricity price (p^*).

Proof. According to Equation (4) above, we can obtain the following relations:

$$\begin{aligned} \frac{\partial q^*}{\partial \varepsilon} &= \frac{(2s + a\delta)(1 - \delta)(r - b)}{\{a + 4s + a\delta - 2\varepsilon[(a + s)\delta + s]\}^2} > 0, \quad \frac{\partial p^*}{\partial \varepsilon} = -s \frac{\partial q^*}{\partial \varepsilon} < 0 \\ \frac{\partial p^*}{\partial \varepsilon} &= \frac{\partial p^*}{\partial q^*} \frac{\partial q^*}{\partial \varepsilon} = -\left(\frac{2s + a\delta}{1 - \delta}\right) \frac{(2s + a\delta)(1 - \delta)(r - b)}{\{a + 4s + a\delta - 2\varepsilon[(a + s)\delta + s]\}^2} < 0 \\ \frac{\partial q^*}{\partial \delta} &= \frac{(a + 2s\varepsilon)(1 - \varepsilon)(r - b)}{\{a + 4s - 2s\varepsilon - \varepsilon[2s\varepsilon(a + s)\delta - a]\}^2} < 0, \quad \frac{\partial p^*}{\partial \delta} = -s \frac{\partial q^*}{\partial \delta} > 0 \\ \frac{\partial p^*}{\partial \delta} &= \frac{\partial p^*}{\partial q^*} \frac{\partial q^*}{\partial \delta} = \left(\frac{2s + a\delta}{1 - \delta}\right) \frac{(a + 2s\varepsilon)(1 - \varepsilon)(r - b)}{\{a + 4s - 2s\varepsilon - 2\delta[(a + s) - a]\}^2} > 0 \end{aligned}$$

The proposition is proven. $\square$

Proposition 2. The increase in the altruism (ε) of green power enterprises will not only increase the profits of thermal power enterprises (U_c) but also reduce their own profits (U_g). The increase in the altruism (δ) of thermal power enterprises will not only increase the profits of green power enterprises (U_g) but also reduce their own profits (U_c).

Proof. Both green power and thermal power achieve profit maximization in the game relationship, and according to Equation (3) above, there is the following formula:

$$\begin{cases} \frac{\partial U_c}{\partial q} = r - 2sq^* - p^* = 0 \\ \frac{\partial U_g}{\partial p} = q^* + (p - aq^* - b) \frac{\partial q^*}{\partial p} = \frac{p^* - (2s + a)q^* - b}{2s + a\delta} = 0 \end{cases} \quad (5)$$

Based on the above equation combined with the proof process of Proposition 1, it can be inferred that the rate of change in the mutually beneficial equilibrium profit for the altruistic factor is as follows:

$$\frac{\partial U_c}{\partial \varepsilon} = \frac{\partial U_c}{\partial q^*} \frac{\partial q^*}{\partial \varepsilon} + \frac{\partial U_c}{\partial p^*} \frac{\partial p^*}{\partial \varepsilon} = r - 2sq^* - p^* + q^* \frac{2s + a\delta}{1 - \delta} \frac{\partial q^*}{\partial \varepsilon} > 0$$

From (5), it is obtained that $r - 2sq^* - p^* + q^* \frac{2s + a\delta}{1 - \delta} > r - 2sq^* - p^* > 0$

$$\frac{\partial U_g}{\partial \varepsilon} = \frac{\partial U_g}{\partial q^*} \frac{\partial q^*}{\partial \varepsilon} + \frac{\partial U_g}{\partial p^*} \frac{\partial p^*}{\partial \varepsilon} = \left[p^* - q^* \left(a + \frac{2s + a\delta}{1 - \delta} \right) - b \right] \frac{\partial q^*}{\partial \varepsilon} < 0$$

From (5), it is obtained that $p^* - q^* \left(a + \frac{2s+a\delta}{1-\delta} \right) - b < p^* - q^* (a + 2s) - b = 0$

Similarly, $\frac{\partial U_c}{\partial \delta} = \frac{\partial U_c}{\partial q^*} \frac{\partial q^*}{\partial \delta} + \frac{\partial U_c}{\partial p^*} \frac{\partial p^*}{\partial \delta} = r - 2sq^* - p^* + q^* \frac{2s+a\delta}{1-\delta} \frac{\partial q^*}{\partial \delta} < 0$

$$\frac{\partial U_g}{\partial \delta} = \frac{\partial U_g}{\partial q^*} \frac{\partial q^*}{\partial \delta} + \frac{\partial U_g}{\partial p^*} \frac{\partial p^*}{\partial \delta} = \left[p^* - q^* \left(a + \frac{2s+a\delta}{1-\delta} \right) - b \right] \frac{\partial q^*}{\partial \delta} > 0$$

The proposition is proven. $\square$

Proposition 3. *The increase in altruism between green power and thermal power enterprises will increase the total profit U of both parties.*

Proof. According to Equation (5) above, it can be inferred that the rate of change in the total profit of the mutual benefit equilibrium for the altruistic factor is as follows:

$$\frac{\partial U}{\partial \varepsilon} = \frac{\partial U_c}{\partial \varepsilon} \uparrow + \frac{\partial U_g}{\partial \varepsilon} \uparrow = \left[r - (a + 2s)q^* - b \right] \frac{\partial q^*}{\partial \varepsilon} > 0$$

among

$$\frac{\partial U}{\partial \delta} = \frac{\partial U_c}{\partial \delta} \uparrow + \frac{\partial U_g}{\partial \delta} \uparrow = \left[r - (a + 2s)q^* - b \right] \frac{\partial q^*}{\partial \delta} > 0$$

The proposition is proven. $\square$

3.3. Evolutionary Dynamic Models

In the long-term dynamic game process of the electricity market, power companies with bounded rationality will choose and adjust their competitive strategies based on internal and external actual situations at any time. Through continuous improvement, stable strategy information will be transmitted to subsequent games to achieve low-carbon transformation and the development of power companies under carbon emission reduction constraints. According to the principle of replication dynamics, this dynamic process can be represented by a differential equation composed of the objective function.

Further evolutionary analysis will be conducted on how power companies can achieve a stable and balanced state of development during the transformation process. The transformation process is a long-term mutual observation, adjustment, and improvement process of power companies in the market, which is influenced by both their own conditions and external factors. Based on the aforementioned research, we set the appropriate transformation variables, analyzed the transformation stability of power enterprises, and discussed the corresponding transformation evolution path and related factors affecting it.

The dynamic equation of the proportion x of thermal power enterprises choosing altruistic strategies over time is as follows:

$$\begin{aligned} S(x) &= \frac{dx}{dt} = x(1-x)(E_{c0} - E_{c1}) \\ &= x(1-x) \{ y[(v_{c2} - v_{c1})\delta + (u_{c2} - u_{c1})\varepsilon + M_c + F_c - F_g] - \delta u_{c2} + F_g \} \end{aligned} \quad (6)$$

Similarly, the dynamic equation of the proportion y of green power enterprises choosing altruistic strategies over time can be obtained as follows:

$$\begin{aligned} S(y) &= \frac{dy}{dt} = y(1-y)(E_{g0} - E_{g1}) \\ &= y(1-y) \{ x[(v_{g2} - v_{g1})\varepsilon + (u_{g2} - u_{g1})\delta + M_g + F_g - F_c] - \varepsilon u_{g2} + F_c \} \end{aligned} \quad (7)$$

The two differential Equations (6) and (7) above together constitute the dynamic transformation and evolution system of green power and thermal power enterprises:

$$\begin{cases} S(x) = \frac{dx}{dt} = x(1-x) \{ y[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g] \\ \quad - \delta v_{c2} + F_g \} \\ S(y) = \frac{dy}{dt} = y(1-y) \{ x[(v_{g2} - v_{g1})\varepsilon + (u_{g1} - u_{g2})\delta + M_g + F_g - F_c] \\ \quad - \varepsilon v_{g2} + F_c \} \end{cases} \quad (8)$$

It can be seen that the initial altruistic strategy ratios x and y in both systems are variable, and the equilibrium state of the entire system is not robust with respect to small disturbances in x and y . It can be transformed and changed toward the desired strategy direction by adjusting relevant variables. The next step is to analyze the strategy selection ratio in evolutionary games, which no longer changes over time, and the system reaches an equilibrium state, that is, tends to be stable. According to (8),

$$\begin{cases} S(x) = \frac{dx}{dt} = 0 \\ S(y) = \frac{dy}{dt} = 0 \end{cases} \quad (9)$$

By solving this system of differential equations, five local equilibrium stagnation points can be obtained: A(0, 0), B(0, 1), C(1, 0), D(1, 1), $P(x^*, y^*)$. Among them,

$$\begin{aligned} x^* &= \frac{\varepsilon v_{g2} - F_c}{(u_{g1} - u_{g2})\delta + (v_{g2} - v_{g1})\varepsilon + M_g + F_g - F_c} \\ y^* &= \frac{\varepsilon v_{c2} - F_g}{(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g} \end{aligned} \quad (10)$$

According to the Jacobian matrix analysis method used by Friedman et al. in evolutionary games, the stability of the system equilibrium point can be obtained by analyzing the local stability of the Jacobian matrix J . The specific method is to calculate the determinant $\text{Det}(J)$ of matrix J and the trace $\text{Tr}(J)$ of matrix J , respectively, and judge the stability of the equilibrium point based on their signs: when $\text{Det}(J) > 0$ and $\text{Tr}(J) < 0$, the equilibrium point is an ESS stable strategy; when $\text{Det}(J) > 0$ and $\text{Tr}(J) > 0$, the equilibrium point is an unstable strategy; when $\text{Det}(J) < 0$ and $\text{Tr}(J) = 0$ or is uncertain, the equilibrium point is the saddle point. The Jacobian matrix corresponding to Equation (9) above is as follows:

$$J = \begin{pmatrix} \frac{\partial S(x)}{\partial x} & \frac{\partial S(x)}{\partial y} \\ \frac{\partial S(y)}{\partial x} & \frac{\partial S(y)}{\partial y} \end{pmatrix} \quad (11)$$

Among them,

$$\begin{cases} \frac{\partial S(x)}{\partial x} = (1-2x) \{ y[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g] - \delta v_{c2} + F_g \} \\ \frac{\partial S(x)}{\partial y} = x(1-x) [(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g] \\ \frac{\partial S(y)}{\partial x} = y(1-y) [(v_{g2} - v_{g1})\varepsilon + (u_{g1} - u_{g2})\delta + M_g + F_g - F_c] \\ \frac{\partial S(y)}{\partial y} = (1-2y) \{ x[(v_{g2} - v_{g1})\varepsilon + (u_{g1} - u_{g2})\delta + M_g + F_g - F_c] - v_{g2} + F_c \} \end{cases} \quad (12)$$

We can calculate $\text{Det}(J) = \frac{\partial S(x)}{\partial x} \frac{\partial S(y)}{\partial y} - \frac{\partial S(x)}{\partial y} \frac{\partial S(y)}{\partial x}$ and $\text{Tr}(J) = \frac{\partial S(x)}{\partial x} + \frac{\partial S(y)}{\partial y}$ and obtain the determinant $\text{Det}(J)$ and trace $\text{Tr}(J)$ for each equilibrium point, as shown in Table 2.

Table 2. Jacobi matrix equilibrium points $\text{Det}(J)$ and $\text{Tr}(J)$.

Equilibrium Point	$\text{Det}(J)$	$\text{Tr}(J)$
A (0, 0)	$(F_g - \delta v_{c2})(F_c - \varepsilon v_{g2})$	$F_g - \delta v_{c2} + F_c - \varepsilon v_{g2}$
B (0, 1)	$[(u_{c2} - u_{c1})\varepsilon - v_{c1}\delta + M_c + F_c](v_{c2}\delta - F_c)$	$\varepsilon(u_{c1} - u_{c2} + v_{g2}) - \delta v_{c1} + M_c$
C (1, 0)	0	$\delta(v_{c2} + u_{g1} - u_{g2}) - \varepsilon v_{g1} + M_g$
D (1, 1)	$[(u_{c2} - u_{c1})\varepsilon - v_{c1}\delta + M_c + F_c] \times [(u_{g1} - u_{g2})\delta - v_{g1}\varepsilon + M_g + F_g]$	$-[(u_{c2} - u_{c1})\varepsilon - v_{c1}\delta + M_c + F_c + (u_{g1} - u_{g2})\delta - v_{g1}\varepsilon + M_g + F_g]$
$P(x^*, y^*)$	L	0

$$L = - \frac{[(u_{g1}-u_{g2})\delta-v_{g1}\varepsilon+M_g+F_g][(u_{c1}-u_{c2})\varepsilon-v_{c1}\delta+M_c+F_c](v_{g2}-F_g)(\delta v_{c2}-F_g)}{[(u_{g1}-u_{g2})\delta+(v_{g2}-v_{g1})\varepsilon+M_g+F_g-F_c][(v_{c2}-v_{c1})\delta+(u_{c1}-u_{c2})\varepsilon+M_c+F_c-F_g]}$$

The symbols of the determinant Det (J) and trace Tr (J) for the above equilibrium points are related to the relevant assumptions and set profit and loss variables. The following will be discussed based on different scenario classifications.

3.4. Analysis of Transformation and Evolution Scenarios

3.4.1. Analysis of Transformation and Evolution Stability Scenarios

Scenario 1. Under the strong constraint of carbon emissions reduction, the net profit increment of both green power and thermal power under the mutually beneficial competition strategy will inevitably be greater than the net profit increment obtained under their deviation competition strategy, and the transformation and evolution will inevitably stabilize toward the mutually beneficial competition strategy.

Proof. At this point, the net increase in profit after deducting the risk loss amount from the direct profit increase in both green power and thermal power is as follows:

$$\varepsilon u_{c2} - F_c < 0, \delta u_{g2} - F_g < 0$$

Then there must be $\varepsilon u_{c2} - F_c < 0 < \varepsilon u_{c1} - \delta v_{c1} + M_c$ and $\delta u_{g2} - F_g < 0 < \delta u_{g1} - \varepsilon v_{g1} + M_g$ constant holds. If the equilibrium point $P(x^*, y^*)$ ($\varepsilon u_{c2} - F_c < 0 < \varepsilon u_{c1} - \delta v_{c1} + M_c$) does not meet its corresponding existence conditions, the stability calculation results of the evolution of the remaining four equilibrium points in the transformation evolution system are shown in Table 3, which is verified. $\square$

Table 3. Each equilibrium point Det (J) and Tr (J) in Scenario 1.

Equilibrium Point	Det (J) Symbol	Tr (J) Symbol	Stability
A(0, 0)	+	+	Unstable
B(0, 1)	−	−	Saddle point
C(1, 0)	−	−	Saddle point
D(1, 1)	+	−	ESS

At this point, the evolutionary system has an unstable point A(0, 0), two saddle points B(0, 1) and C(1, 0), and a unique evolutionary stable point D(1, 1), indicating that both the green power and thermal power adopt a mutually beneficial competitive strategy as the ESS stable strategy. The system evolution path is shown in Figure 1.

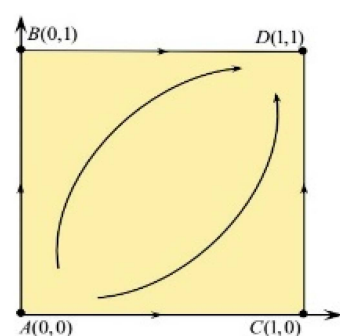


Figure 1. Convergence domain of evolution for Scenario 1.

As can be seen from the figure, in Scenario 1, due to the speculative behavior of both the green power and thermal power, they will face high-risk losses. Therefore, regardless of any initial conditions, the green power and thermal power will eventually converge steadily to the D(1, 1) mutually beneficial competitive transformation and development strategy.

3.4.2. Analysis of Uncertain Situations in Transformation and Evolution

Scenario 2. *In general, due to information asymmetry, feedback, and lagging effects in decision-making, there is an increase in uncertainty factors in organizational transformation and development. If under weak constraints of carbon reduction, the transformation and evolution of green power and thermal power are slow, and the risk of unilateral deviation from the transformation and development of green power and thermal power increases, tending toward a strategy of perfect competition. Based on the above formula, the following proof process can be obtained.*

Proof. (a) If both green power and thermal power are weakly constrained by carbon reduction, the net increase in competitive profits is smaller than the net increase in profits obtained through speculation. At this point, $\varepsilon u_{c1} - \delta v_{c1} + M_c < \varepsilon u_{c2} - F_c$ and $\delta u_{g1} - \varepsilon v_{g1} + M_g < \delta u_{g2} - F_g$.

According to the above, if the equilibrium point $P(x^*, y^*)$ [$x^* \notin (0, 1)$, $y^* \notin (0, 1)$] does not satisfy its corresponding existence conditions in this scenario, the evolutionary stability calculation results of the remaining four equilibrium points of the evolutionary dynamical system are shown in Table 4.

Table 4. Each equilibrium point Det (J) and Tr (J) in Scenario 2 (a).

Equilibrium Point	Det (J) Symbol	Tr (J) Symbol	Stability
A(0, 0)	+	−	ESS
B(0, 1)	−	Unstable	Saddle point
C(1, 0)	−	Unstable	Saddle point
D(1, 1)	+	+	Unstable

At this point, the system has an unstable point D(1, 1), two saddle points B(0, 1) and C(1, 0), and a unique evolutionary stable point A(0, 0), indicating that the green power and thermal power are deviating from the transformation and development under weak constraints of carbon reduction, and both adopt their own economic benefit maximization strategy, which is ESS stability. The transformation and evolution path is shown in Figure 2a.

(b) If the thermal power is weakly constrained by carbon emissions reduction, the net increase in competitive profits is smaller than the net increase in profits obtained through speculation. At this point, $\varepsilon u_{c1} - \delta v_{c1} + M_c < \varepsilon u_{c2} - F_c$ and $\delta u_{g1} - \varepsilon v_{g1} + M_g > \delta u_{g2} - F_g$. According to the above, if the equilibrium point $P(x^*, y^*)$ does not exist, the evolutionary stability calculation results of the other four equilibrium points in the evolutionary dynamics system are shown in Table 5.

Table 5. Each equilibrium point Det (J) and Tr (J) in Scenario 2 (b).

Equilibrium Point	Det (J) Symbol	Tr (J) Symbol	Stability
A(0, 0)	+	−	ESS
B(0, 1)	−	+	Unstable
C(1, 0)	−	Unstable	Saddle point
D(1, 1)	+	Unstable	Saddle point

At this point, the system has an unstable point $B(0, 1)$, two saddle points $C(1, 0)$ and $D(1, 1)$, and a unique evolutionary stable point $A(0, 0)$, indicating that, under the weak constraint of carbon reduction, both the green power and thermal power adopt the ESS stability strategy of maximizing their own economic benefits. The system evolution path is shown in Figure 2b.

(c) If green power is weakly constrained by carbon emissions reduction, the net increase in competitive profits is smaller than the net increase in profits obtained through speculation. At this point, $\varepsilon u_{c1} - \delta v_{c1} + M_c > \varepsilon u_{c2} - F_c$ and $\delta u_{g1} - \varepsilon v_{g1} + M_g < \delta u_{g2} - F_g$. According to the above, if the equilibrium point $P(x^*, y^*)$ also does not exist, the evolutionary stability calculation results of the other four equilibrium points in the evolutionary dynamics system are shown in Table 6.

Table 6. Each equilibrium point Det (J) and Tr (J) in Scenario 2 (c).

Equilibrium Point	Det (J) Symbol	Tr (J) Symbol	Stability
$A(0, 0)$	+	−	ESS
$B(0, 1)$	−	Unstable	Saddle point
$C(1, 0)$	+	+	Unstable
$D(1, 1)$	−	Unstable	Saddle point

At this point, the system has an unstable point $C(1, 0)$, two saddle points $B(0, 1)$ and $D(1, 1)$, and a unique evolutionary stable point $A(0, 0)$, indicating that under the weak constraint of carbon reduction, both the green power and thermal power adopt the strategy of maximizing economic self-interest as the ESS stability strategy. The evolutionary path of its system is shown in Figure 2c, which has been verified. $\square$

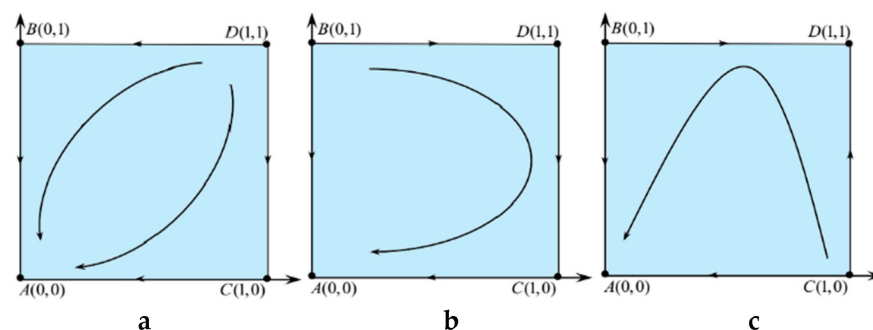


Figure 2. Evolution convergence domain of Scenario 2.

Scenario 3. Under the weak constraint of carbon emissions reduction, if the net profit increase in both green power and thermal power under the mutually beneficial competition strategy is greater than the net profit increase obtained under their speculative strategy (unilateral deviation from competition), the direction of transformation and evolution convergence will have uncertainty, and the final stable strategy of the system is related to the initial conditions and saddle point position.

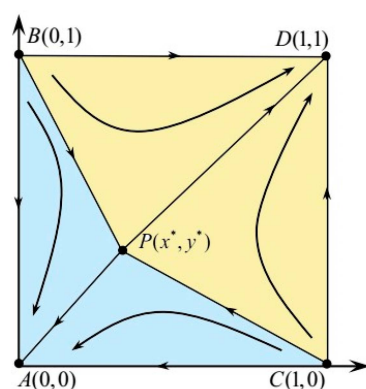
Proof. The relation $\varepsilon u_{c1} - \delta v_{c1} + M_c > \varepsilon u_{c2} - F_c$ and $\delta u_{g1} - \varepsilon v_{g1} + M_g > \delta u_{g2} - F_g$ is established at this time. The calculation results of the evolutionary stability of the five equilibrium points in the transformation evolution system are shown in Table 7.

Table 7. Each equilibrium point Det (J) and Tr (J) in Scenario 3.

Equilibrium Point	Det(J) Symbol	Tr(J) Symbol	Stability
A(0, 0)	+	−	ESS
B(0, 1)	+	+	Unstable
C(1, 0)	+	+	Unstable
D(1, 1)	+	+	ESS
$P(x^*, y^*)$	−	0	Saddle point

At this point, there are two unstable points B(0, 1) and C(1, 0) in the system, one saddle point $P(x^*, y^*)$, and two evolutionary stable points A(0, 0) and D(1, 1), respectively, indicating that under the weak constraint of carbon reduction, if the green power and thermal power undergo a mutually beneficial competition strategy, the convergence direction of their transformation and evolution will be uncertain. The strategy of maximizing their own interests is the ESS stability strategy. The system evolution path is shown in Figure 3.

As can be seen from the figure, when the initial state is within the region S_{CPBD} , the system evolution will eventually converge to the steady-state equilibrium point D(1, 1), that is, both the green power and thermal power choose the moderately cooperative and mutually beneficial competition strategy as the ESS stable strategy, while the region S_{CPBD} is the convergence domain for choosing the mutually beneficial competition strategy, and its area size represents the probability of the transformation and development evolution system ultimately evolving toward mutual benefit between both parties. When the initial state is within the region S_{ABPC} , the system evolution will eventually converge to the steady-state equilibrium point A(0, 0), that is, both the green power and thermal power are weakly constrained by carbon reduction, and the strategy to maximize their own economic benefits is the ESS stability strategy. The region S_{ABPC} is the convergence domain of the free development strategy, and its area represents the probability of the power system ultimately evolving toward competition for the interests of both parties. Obviously, the total area of the two convergence domains is 1, and the larger the convergence domain area of the stable strategy, the greater the possibility of the dynamic system ultimately evolving toward that strategy. □

**Figure 3.** Evolution convergence domain of Scenario 3.

3.4.3. Factors Influencing the Evolution of Competition and Cooperation among Power Enterprises

Under the constraint of carbon emissions reduction, the equilibrium state of the transformation and evolution of green power and thermal power may either converge to perfect competition or be mutually beneficial, and the saddle point makes the results uncertain. The transformation and evolution development strategies of green power and thermal power are always in a dynamic and gradual process, and the benefits obtained

by enterprises will directly affect the possibility of strategy selection in the next stage. Therefore, the initial conditions for the transformation and evolution of green power and thermal power, continuously adjusting the parameters of internal and external influencing factors, can change the position of the saddle point, thereby transforming the evolution path and direction, guiding the system to evolve from uncertainty to a certain direction, and achieving convergence toward mutual benefit and competition under carbon emission reduction constraints.

Based on the above analysis, it is found that there may be saddle points $P(x^*, y^*)$ and two convergence domains under carbon emission reduction constraints. The larger the area of the convergence domain S_{CPBD} , the greater the probability that the transformation evolution system converges to the optimal steady-state equilibrium point $D(1, 1)$ and the greater the possibility that the green power and thermal power ultimately choose mutual benefit and competitive cooperation as their long-term stable strategy. The area of the convergence domain S_{CPBD} depends on the position of the saddle point $P(x^*, y^*)$. According to Figure 3, the area of the convergence domain S_{CPBD} can be expressed as $S_{\Delta CPD} + S_{\Delta PBD}$, that is,

$$S_{CPBD} = S_{\Delta CPD} + S_{\Delta PBD} = \frac{1}{2} (1 - y^* + 1 - x^*) = 1 - \frac{1}{2}(x^* + y^*)$$

The rate of change in the convergence domain S_{CPBD} area for any parameter in the influencing factors can be obtained as follows:

$$\frac{\partial S}{\partial \theta} = -\frac{1}{2} \left(\frac{\partial x}{\partial \theta} + \frac{\partial y}{\partial \theta} \right) \quad (13)$$

The following will analyze the effect of changes in relevant parameters on the saddle point and obtain the influence of changes in influencing factors on the convergence domain S_{CPBD} area. According to the analytical form of saddle point $P(x^*, y^*)$, the main influencing factors on the saddle point position are the following: risk loss limit F_c, F_g , additional value-added profit M_c, M_g , and the average rate of change for profit increase $u_{c1}, u_{g1}, u_{c2}, u_{g2}$, and the average rate of change for profit loss $v_{c1}, v_{g1}, v_{c2}, v_{g2}$.

Proposition 4. When other parameters remain unchanged, increasing the risk loss limit (F_c, F_g) of both parties, when deviating from mutual benefit, is beneficial for the long-term relationship between green power and thermal power to evolve toward the mutual benefit and competition under carbon emission reduction constraints.

Proof.

$$\begin{aligned} \frac{\partial x^*}{\partial F_g} &= -\frac{\varepsilon v_{g2} - F_c}{[(u_{g1} - u_{g2})\delta + (v_{g2} - v_{g1})\varepsilon + M_g + F_g - F_c]^2} < 0 \\ \frac{\partial y^*}{\partial F_g} &= -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2} < 0 \\ \frac{\partial S}{\partial F_g} &= -\frac{1}{2} \left(\frac{\partial x^*}{\partial F_g} + \frac{\partial y^*}{\partial F_g} \right) > 0 \end{aligned}$$

Similarly, $\frac{\partial S}{\partial F_c} = -\frac{1}{2} \left(\frac{\partial x^*}{\partial F_c} + \frac{\partial y^*}{\partial F_c} \right) > 0$; proof completed. $\square$

Proposition 5. When other parameters remain unchanged, increasing the additional value-added profits of both parties will incentivize the long-term relationship between green power and thermal power to evolve toward mutual benefit and competition under carbon emission reduction constraints.

Proof.

$$\frac{\partial x^*}{\partial M_c} = 0$$

$$\frac{\partial y^*}{\partial M_c} = -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2}$$

$$\frac{\partial S}{\partial M_c} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial M_c} + \frac{\partial x^*}{\partial M_c}\right) > 0$$

Similarly, $\frac{\partial S}{\partial M_g} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial M_g} + \frac{\partial x^*}{\partial M_g}\right) > 0$; proof completed. $\square$

Proposition 6. Under the condition that other parameters remain unchanged, increasing the average rate of profit increase for both parties during mutual benefit (M_c , M_g) is beneficial for the long-term relationship between green power and thermal power to evolve toward the mutual benefit and competition under carbon emission reduction constraints. Increasing the average rate of change in profits for both parties during speculation will promote the long-term relationship between green power and thermal power to evolve toward maximizing their own interests under weak carbon emission reduction constraints.

Proof.

$$\frac{\partial x^*}{\partial u_{c1}} = 0, \frac{\partial y^*}{\partial u_{c1}} = -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2} < 0$$

$$\frac{\partial S}{\partial u_{c1}} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial u_{c1}} + \frac{\partial x^*}{\partial u_{c1}}\right) > 0, \text{ similarly, } \frac{\partial S}{\partial u_{g1}} > 0$$

$$\frac{\partial x^*}{\partial u_{c2}} = 0, \frac{\partial y^*}{\partial u_{c2}} = -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2} < 0$$

$$\frac{\partial S}{\partial u_{c2}} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial u_{c2}} + \frac{\partial x^*}{\partial u_{c2}}\right) > 0, \text{ similarly, } \frac{\partial S}{\partial u_{g2}} > 0; \text{ proof completed. } \square$$

Proposition 7. The average change in profit loss for both parties (v_{c1} , v_{g1} , v_{c2} , v_{g2}) is increased while keeping other parameters constant. Whether in a state of mutually beneficial competition or speculative situations, it will always lead to the long-term relationship between green power and thermal power evolving toward maximizing their own interests under weak carbon reduction constraints.

Proof.

$$\frac{\partial x^*}{\partial v_{c1}} = 0, \frac{\partial y^*}{\partial v_{c1}} = -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2} > 0$$

$$\frac{\partial S}{\partial v_{c1}} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial v_{c1}} + \frac{\partial x^*}{\partial v_{c1}}\right) < 0, \text{ similarly, } \frac{\partial S}{\partial v_{g1}} < 0$$

$$\frac{\partial x^*}{\partial u_{c2}} = 0, \frac{\partial y^*}{\partial u_{c2}} = -\frac{\varepsilon v_{c2} - F_g}{[(v_{c2} - v_{c1})\delta + (u_{c1} - u_{c2})\varepsilon + M_c + F_c - F_g]^2} > 0$$

$$\frac{\partial S}{\partial v_{c2}} = -\frac{1}{2}\left(\frac{\partial x^*}{\partial v_{c2}} + \frac{\partial x^*}{\partial v_{c2}}\right) < 0, \text{ similarly, } \frac{\partial S}{\partial v_{g2}} < 0; \text{ proof completed. } \square$$

According to the model conclusions and evolutionary assumptions, both green power and thermal power can improve their profits under carbon emission reduction constraints. At this point, the process of achieving the mutual benefit and stable evolution of the competitive relationship between both parties is also a process of long-term profit growth for both parties. Given parameter conditions, the different convergence domains corresponding to feasible mutually beneficial competitive relationships can be analyzed by evolving constraint conditions in different scenarios, namely, the evolutionary convergence domain, to establish a quantitative relationship between the mutually beneficial relationship strategy set and the final evolutionary result.

4. Cases and Simulations

To verify the relevant conclusions regarding the evolution of the mutually beneficial and competitive relationship between the green power and thermal power transformation, and further analyze the quantitative relationship between the evolution results, Qinghai Electric Power Company-State Grid Corporation of China is selected as the research object. In the same regional market environment, independent power-selling companies face the same market reverse demand function as in the previous chapter. The coal-fired units of the company's subordinate power generation enterprises are all 660 MW (data sourced from Qinghai Electric Power Company-State Grid Corporation of China).

The calculation of the average change rate of profits for both parties in the evolutionary model is derived from the conclusion of the model's solution analysis in Section 3.3. Using the partial derivative of profit over altruistic factors, we calculate the average rate of change in profit increase (loss) for green power and thermal power enterprises. By selecting altruistic factors (ε, δ) , we calculate the rate of change in profit (loss) for both parties in the event of mutual benefit, competition, and risk losses. For the convenience of further evolutionary analysis, the relevant data were processed using normalization methods in Stata16 to obtain the normalized profit change rate and calculate its mean. Simultaneously, we set reasonable risk loss amounts and value-added profit parameters (As shown in Table 8).

Table 8. Evolution-related profit and loss variable parameters.

	The Average Rate of Change for Profit Increase		The Average Rate of Change for Profit Loss		Risk Loss Limit	Value-Added Profit
Green power enterprises	u_{c1}	u_{c2}	v_{c1}	v_{c2}	F_c	M_c
	0.64	0.86	0.30	0.65	[0.26, 0.49]	[0.10, 0.32]
Thermal power enterprises	u_{g1}	u_{g2}	v_{g1}	v_{g2}	F_g	M_g
	0.57	0.79	0.39	0.76	[0.26, 0.49]	[0.10, 0.32]

We simulate the evolution process using Matlab2023a, with a step size of 0.1 and an evolution time of [0, 100] (this time is reflected as the number of iterations in the simulation evolution program). Firstly, we verify the final evolution direction of different sets of altruistic factors under the given parameter conditions. Secondly, we will examine the changes in the value of relevant influencing factors, the changes in the altruistic factor set, and their impact on the evolution results of the transformation model.

4.1. Dynamic Simulation of Transformation and Evolution

In the evolution process of green power and thermal power transformation systems, limited by relevant assumptions and situational constraints, not all mutually beneficial competitive relationships meet the evolutionary constraint premise or can satisfy the conditions for the system to evolve in a certain direction under given parameter conditions. Different evolutionary scenarios and constraints correspond to different sets of feasible altruistic factors. Analyzing relevant constraints can obtain feasible domains of altruistic factors in different evolutionary convergence directions. The initial risk loss amount and excess appreciation profit are determined as follows. According to the formula in the previous section, the feasible domains for the evolution of altruistic factors under the above parameters are as follows:

$$\omega_1 : s.t \begin{cases} 0.5\delta < \varepsilon < 1.27\delta \\ 0 < \varepsilon < 0.38 \\ 0 < \delta < 0.30 \end{cases}$$

$$\omega_2 : s.t \begin{cases} 0.5\delta < \varepsilon < 1.27\delta \\ \delta > \min(-1.46\delta + 1.65, -0.46\delta + 0.87) \\ 0.38 < \varepsilon < 1 \\ 0.30 < \delta < 1 \end{cases}$$

$$\omega_3 : s.t \begin{cases} 0.5\delta < \varepsilon < 1.27\delta \\ \varepsilon < -1.46\delta + 1.65 \\ \varepsilon < -0.46\delta + 0.87 \\ 0.38 < \varepsilon < 1 \\ 0.30 < \delta < 1 \end{cases}$$

The three regions ω_1 , ω_2 , ω_3 , where the altruistic factor takes values in the above equation, are the constraint sets corresponding to Scenarios 1, 2, and 3 in the previous section. At this point, the transformation evolution system converges to three situations: a mutually beneficial competition strategy, a profit maximization strategy, and an uncertainty strategy. There are three feasible regions for the evolution of the factor set, as shown in Figure 4. The following validates the final evolution results of the mutually beneficial competitive relationship among the three feasible regions.

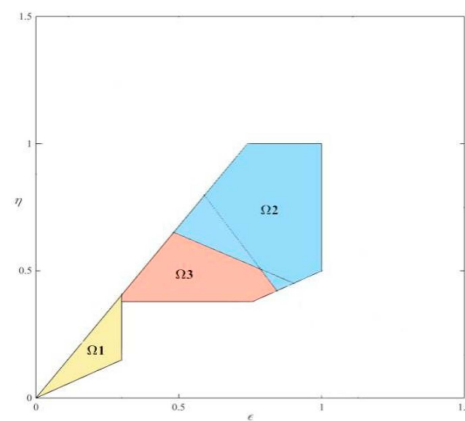


Figure 4. Feasible Domain of Altruistic Factors in the Transformation and Evolution System.

4.2. Simulation Analysis Discussion

When the set of altruistic factors is such that $((\varepsilon, \delta) \in \omega_1)$, the ESS strategy for transforming and evolving systems is mutually beneficial and competitive. Given parameter conditions, according to the constraint conditions, for the altruistic factor strategy set in this region, the risk loss amount belongs to a strong constraint condition, and its evolution process corresponds to Scenario 1. Any altruistic coefficient within the region $(\varepsilon = 0.1, \delta = 0.2) \in \omega_1$ is used for verification, and the system evolution simulation results are shown in Figure 5. Regardless of the initial proportion of the green power and thermal power choosing competitive strategies, all altruistic strategy sets with values in the feasible domain will have stable convergence to mutually beneficial competitive strategies in the long term, which is consistent with the theoretical analysis results of Scenario 1.

As long as power companies establish appropriate risk loss amounts, they will significantly reduce the actual gains from speculative profits, and the stability of the long-term competitive relationship between green power and thermal power will be guaranteed. However, cooperation in this relationship is moderate and also limited, and its depth is positively correlated with the amount of risk loss.

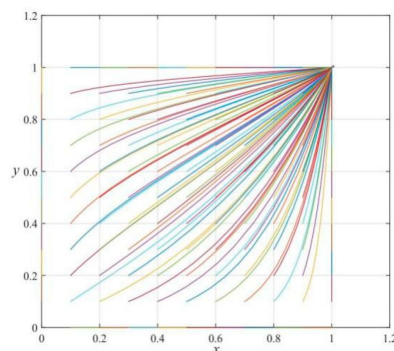


Figure 5. System Evolution Simulation for Scenario 1.

When the set of altruistic factors is such that $((\varepsilon, \delta) \in \omega_2)$, the ESS strategy for transforming and evolving systems is the strategy of maximizing benefits. Given parameter conditions, according to the constraint conditions, for the altruistic factor strategy set in this region, the risk loss amount belongs to a weak constraint condition, and its evolution process corresponds to Scenario 2. The final evolution results of the three scenarios in Scenario 2 are the same, and the simulation images are similar; the altruistic coefficient can be arbitrarily taken inside $(\varepsilon = 0.65, \delta = 0.72) \in \omega_2$ for verification. The simulation results of the transformation and evolution system are shown in Figure 6. Regardless of the initial proportion of the competitive strategy chosen by both parties, the evolution results of all altruistic factor set with values in the feasible domain will stably converge to the strategy of maximizing benefits, which is consistent with the theoretical analysis results of Scenario 2.

Analysis shows that, in a mutually beneficial competitive relationship, if the existing risk loss is relatively weak and either party (or both parties) adopts a speculative strategy with a net profit increase higher than the transformation and the mutually beneficial development of both parties, the opportunity cost of mutually beneficial cooperation is higher. Both parties will lack the willingness to build or maintain a long-term mutually beneficial relationship and will also lose the motivation to promote the transformation and development of both parties.

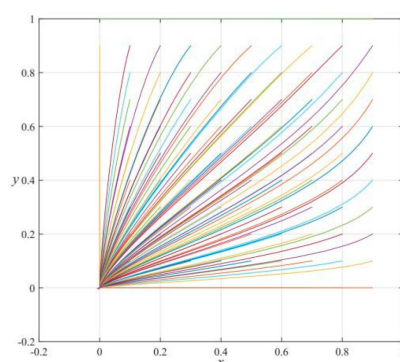


Figure 6. System Evolution Simulation for Scenario 2.

When the set of altruistic factors is such that $((\varepsilon, \delta) \in \omega_3)$, the ESS strategy of the transformation and evolution system has uncertainty. Given the parameter conditions, according to the constraint conditions, for the altruistic factor set in the region, the risk loss amount belongs to the weak constraint condition, and its evolution process corresponds to Scenario 3. If we take any altruistic coefficient within the region ($\varepsilon = 0.44$, as shown in Figure 7), the transformation and evolution results of the internal altruistic strategy set are uncertain due to the dual influence of the initial proportion of competitive strategies and the position of saddle point $P(x^*, y^*)$, which is consistent with the theoretical analysis results of Scenario 3. To further verify the evolutionary convergence results of different initial values, we calculated the saddle point $P(x^*, y^*) = (0.49, 0.41)$ and found $(x = 0.3, y = 0.4)$ and

($x = 0.5, y = 0.4$) as the initial value points in the divided evolutionary convergence domain. As shown in Figure 8, when (0.3, 0.4) is used as the initial probability for simulation, the final evolution of both parties converges to a perfect competitive strategy. When using (0.5, 0.4) as the initial probability simulation, the final evolution of both parties converges to a mutually beneficial competitive strategy.

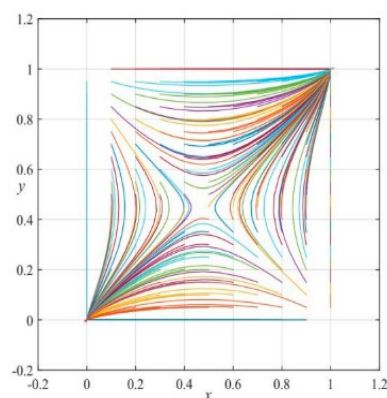


Figure 7. System Evolution Simulation for Scenario 3.

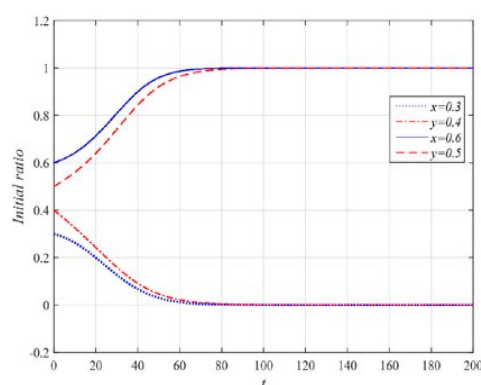


Figure 8. Simulation of system evolution with different initial values.

In the electricity market, although the net profit increase brought by mutual benefit and competition in the short term may be higher than the risk loss amount, due to the relatively weak risk loss amount and the existence of excess profits from market speculation, it will inevitably increase concerns about the risks faced by transformation and development. In an environment where it is difficult to determine the pros and cons of the power balance, green power and thermal power will be affected by various internal and external factors, and their long-term transformation and evolution will present uncertainty.

Simulation analysis shows that the increase in the average rate of profit loss during mutual benefit between green power and thermal power significantly reduces the feasible and mutually beneficial competitive relationship between the two parties, resulting in a slower transformation and development process. The increase in the average rate of change in one's own profit loss during speculation by the other party leads to a reduction in the stable and mutually beneficial competitive relationship of transformation and evolution and a decrease in the level of mutually beneficial competition in the system. Therefore, there is a negative effect on the long-term stability of the mutually beneficial competitive relationship between both parties.

5. Conclusions

Our paper quantitatively studies the cooperative and competitive relationship between green power and thermal power during the transformation process. Based on mutual benefit preferences, a long-term competitive evolutionary dynamics model was constructed.

We solved the optimal equilibrium electricity quantity (price) for both parties and analyzed the impact of changes in altruistic factors on various equilibrium variables. This paper discusses the ESS strategies of the evolutionary systems of both parties in different feasible domains of altruistic factors based on case studies, analyzes the internal and external factors that affect the competitive evolution results of both parties, and concludes that, under certain mutually beneficial conditions of green power and thermal power, the optimal electricity production and electricity price for the transformation and development mode can be solved. In the long-term mutually beneficial competitive relationship between green power and thermal power, quantifying and adjusting the internal and external factors that affect system evolution, increasing the amount of risk losses, the additional value-added profits from competition, and the average rate of change in mutually beneficial profits will promote the transformation and development of both parties. The higher the average rate of increase in speculative profits and the average rate of change in self-profit loss during competition, the more likely it is for both parties to slow down their transformation and development.

The low-carbon transformation path of the power industry can not only promote the sustainable development of green power enterprises, but it must also effectively reduce carbon emissions, improve energy utilization efficiency, reduce energy costs, and promote innovation and the application of green technologies. Therefore, the low-carbon transformation path of the power industry is considered an important policy tool that can achieve emission reduction goals while promoting sustainable development. The green certificate policy is an effective emission reduction measure that can reduce carbon emissions by promoting the development and utilization of green electricity. However, there are still some problems and challenges in the implementation process that require the joint efforts of the government, enterprises, and all sectors of society to solve. Future research can further explore the influencing factors and mechanisms of green certificate policies, providing a scientific basis for further improving and optimizing the development of green electricity.

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