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Optimization Analysis of Multi-Party Benefit Maximization Paths in Market Transactions Based on Evolutionary Game Models

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Abstract This paper introduces an evolutionary game model for path optimization research based on the possibility of maximizing the interests of multiple participants. Through Nash equilibrium and replicated dynamics equations, it explores the evolutionary stabilization strategy of multi-party satisfaction. Taking the electricity market transaction as an example, the assumption conditions and payment functions are set to analyze the strategy evolution under the mutual game of thermal power enterprises, green power enterprises and power grid companies. Combined with simulation experiments, the evolutionary effect of the constructed evolutionary game model is verified. The results show that during the evolutionary game, the equilibrium return is stabilized at 8.758*105 yuan after 140 iterations for the grid company, 3.39*105 yuan after 68 iterations for the green power enterprise, and 4.44*105 yuan after 49 iterations for the thermal power enterprise. The carbon price is increased from 50 yuan/t to 90 yuan/t, and the market clearing tariff is correspondingly increased from 0.12 yuan/kWh to 0.91 yuan/kWh. Corresponding changes in the probability of selection of the 2 types of firms by the grid company. By adjusting the 2 parameters of thermal power price sensitivity coefficient and green power price sensitivity coefficient, the decision-making evolution of the 3 market transaction participants possesses stability.

Index Terms evolutionary game model, Nash equilibrium, replication dynamics equation, payment function, market transaction

I. Introduction

Transaction information is an important link to ensure that the stakeholders in the trading market obtain information in a timely and accurate manner, and plays an important role in maintaining the attractiveness of the market, ensuring the fairness and impartiality of the market, as well as meeting the needs of investors for transaction information [1]-[3]. However, in the process of trading information dissemination, it is impossible to avoid the emergence of diversified forms of conflict of interest [4]. The fundamental reason for this is that each interest subject for the purpose of maintaining their own interests, around the transaction information to produce a plurality of interests [5], [6]. Whether intelligent models can be used to design an interest balancing mechanism that takes into account the demands of different interest subjects, so as to maximize the benefits of market transaction information, has become an important issue of concern in the field of market transaction information research [7], [8].

Considering the limited rationality of multiple participants in market transactions, evolutionary game theory has emerged as a theoretical framework that combines elements of traditional game theory and biological evolution theory [9]. Based on limited rationality and information constraints, evolutionary game theory takes groups as the object of study and applies a dynamic approach to analyze the game process within groups and the evolution of their stabilization strategies [10]-[12]. Compared with traditional game theory, evolutionary game theory is characterized by its realism, dynamics, group orientation and explanatory power, so the conclusions are closer to reality and more persuasive, and it has become a well-established method to study human social behavior and related economic problems [13]-[16].

Maximizing the interests of multiple participants can promote the prosperity of the market. In this paper, the evolutionary game model is constructed with the ultimate goal of maximizing the interests of multiple participants in market transactions. By analyzing the basic features and basic elements of the model, we analyze the decision-making mode among the game subjects by combining the Nash equilibrium and replication dynamics equations. Thermal power enterprises, green power enterprises and power grid companies are selected as multi-participants, and relevant assumptions and payment functions are set to study the game situation in the power trading market. The model evolution sensitivity and stability are judged through simulation experiments.

II. Analysis of multi-party benefit maximization techniques for market transactions based on game evolution

This chapter analyzes the theory of evolutionary games and the techniques related to model construction, and at the same time takes the electricity market as an example to study the multi-participant's interest maximization evolutionary game strategy.

II. A.Fundamentals and core elements of multi-participant benefit maximization

II. A. 1) Basic principles

1) Reference point dependence: In the decision-making process, decision makers often set reference points to measure possible return outcomes based on their own circumstances. Reference points are influenced by individual risk preferences. Thus, even when faced with the same event, different people may have different perceptions of its potential return.

2) Loss aversion: As an example, the sense of pain caused by a person losing a hundred dollars is much greater than the sense of pleasure caused by finding a hundred dollars, so the decision maker is inclined to a small probability of profit and averse to a potentially small loss.

3) Deterministic gain propensity: faced with two choices of deterministic gain and only probabilistic gain, the decision maker will give preference to deterministic gain and be reluctant to take risks.

4) Diminishing Margin of Gain or Loss: The nonlinear nature of the decision weighting function leads to the decision maker's tendency to magnify the importance of low-probability events while relatively underestimating high-frequency occurrences.

II. A. 2) Core content

Figure 1 shows the value function and the decision function. According to prospect theory, the perceived value U is jointly determined by two key functions: a value function $V(\Delta\pi)$ and a weighting function $\omega(p)$.

$$U=\sum_{i}\omega(p)v(\Delta\pi) \tag{1}$$

1) Value function $V(\Delta\pi)$: it is expressed as follows:

$$\begin{cases}V(\Delta\pi)=\Delta\pi^{\alpha},\Delta\pi\geq 0\\ V(\Delta\pi)=-\lambda(-\Delta\pi)^{\beta},\Delta\pi<0\end{cases} \tag{2}$$

where $\Delta\pi\geq 0$ represents the relative gain and $\Delta\pi<0$ represents the relative loss, both the loss and the gain are determined by the reference point π_0. The parameters α and β, as measures in the value function, reflect the marginal decreasing nature of gains and losses, respectively, and the larger the value, the more pronounced this decreasing trend becomes. The λ parameter measures the decision maker's risk aversion tendency, generally set to λ is greater than 1. From the figure we can see that the shape of the image appears S-shaped, indicating that the degree of loss aversion is more significant relative to the sensitivity of the gain.

2) Decision weight function $\omega(p)$: it is expressed as follows:

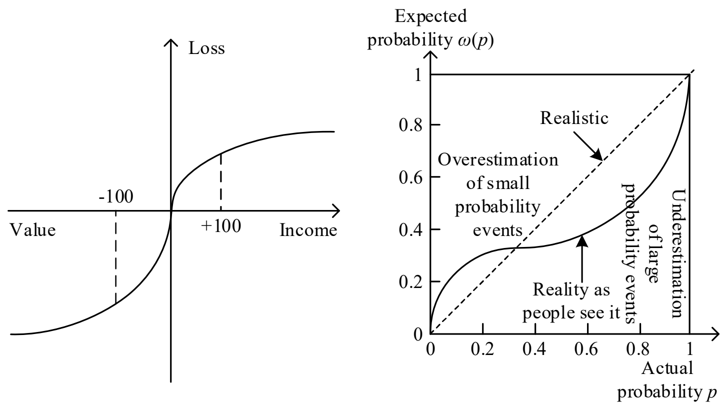
$$\omega(p)=\frac{p^{\gamma}}{(p^{\gamma}+(1-p)^{\gamma})^{\frac{1}{\gamma}}} \tag{3}$$

where the weight function $\omega(p)$ is a monotonically increasing function used to evaluate the probability that an event may occur. Where p represents the objective probability of event i occurring. There is a common cognitive bias in humans that leads to an overestimation of the probability of low probability events and an underestimation of medium and high probability events by assigning a weight of 0 to very low probability events and a weight of 1 to very high probability events. So there is $\omega(0)=0$ and $\omega(1)=1$; when p is small, there is $\omega(p)>p$; and when p is large, there is $\omega(p)<p$.

II. B.Evolutionary game theory

II. B. 1) Basic features of evolutionary game theory

Modern game theory first used Brouwer's immovable point theorem to map the continuum of games to tightly convex sets, and then provided expected utility theories that could deal with the decision-making behavior of multi-strategy players under uncertainty, which became the standard approach in game theory and economics later. Game theory was thus systematically certified at the mathematical and logical levels, but due to limitations, it was initially only applicable to a special limited set of conditions. Game theory has been continuously improved and optimized. The mathematical principles of game theory were established, and the principle concept of Nash equilibrium was introduced, where each decision maker's strategy choice is the optimal response to the choices of other subjects in the game process, and the strategy choices of this group of decision makers are called Nash equilibrium. It is used to study the competitive relationship between competitors with different interests.



(a) Image of the value function (b) Image of the decision function

Figure 1: Image of value function and decision function

II. B. 2) Basic Elements of Evolutionary Game Theory

Evolutionary stable strategy (ESS) is the core of evolutionary game. Definition specifically refers to the game process to participate in all subjects tend to choose a certain strategy, eliminate the game process may occur in the case of mutation, can not produce alternative strategies, this strategy is the evolutionary stable strategy.ESS is not necessarily the optimal strategy, but the game process of each subject is the most suitable, more satisfactory strategy. If G^* exists when and only when the evolutionary stable strategy and for other strategies $G \neq G^*$, then:

1) $\pi\left(G^* \nabla G^*\right) \geq \pi\left(G \nabla G^*\right)$;

2) If $\pi\left(G^* \nabla G^*\right) = \pi\left(G \nabla G^*\right)$, then $\pi\left(G^* \nabla G\right) = \pi\left(G \nabla G\right)$.

The most widely used dynamics method in evolutionary game theory is replication dynamics. The main principle of replication dynamics (RD) is the assumption that each game participant subject will be other participants in the game in the previous round of the game process gain and their own gain comparison, if the selected subject to obtain a higher gain, their own will be taken by the selected person's strategy, strategy selection probability is proportional to the difference between the gain is the endogenous dynamics of the evolutionary game. The replication dynamic equation is the replication dynamics used to describe the game dynamic process proposed by the differential dynamic equation, the replication dynamic equation of evolutionary game theory is shown in equation (4):

$$F(k) = \frac{dx_k}{dt} = x_i\left[u_k - u_s\right], k = 1,2,3\cdots K \tag{4}$$

where k represents the strategy concentration strategy, x_i represents the proportion of strategy k chosen by the game subject at moment t, and u_k and u_s represent the expected return and average return of strategy k, respectively.

II. C. Assumptions and Payment Functions

II. C. 1) Assumptions

In order to construct an evolutionary game model with multiple participants (thermal power enterprises, green power enterprises and grid companies) under the transactional environmental regulation policy, the following assumptions are made in the context of reality:

1) Under the framework of the renewable energy quota system (RPS) system, considering the green power enterprises as the supply side of green certificates (TGCs) and the grid company as the demand side of TGCs, the study is limited to the trading behavior of green certificates between the green power enterprises and the grid company. The grid company is the subject of assessment for the RPS mandatory quota. The grid company bears

the quota obligation corresponding to its total electricity sales, and the assessed subject that fails to fulfill the quota obligation has to pay a certain amount of penalty, while it will be rewarded when it overfulfills the quota requirement.

2) The electricity market is always in an equilibrium state of clearing, i.e. electricity demand equals electricity supply. The grid company buys different types of electricity from thermal power companies and green power companies, and the prices of thermal power and green power are competitive. The scope of the electricity market is also considered to be limited to China, without considering the international market and its possible impact.

3) This paper does not take into account the differences in the unit power generation costs of different types of renewable energy, i.e., the average power generation cost of green power is utilized to uniformly represent the power generation costs of different types of renewable energy.

4) Thermal power enterprises buy or sell carbon quotas through the carbon trading market, and the carbon quotas are settled with the end of the accounting period, without considering that the carbon quotas in the current period can be superimposed to the next period.

5) Green certificates are time-sensitive and green certificates are not storable, only the green certificate spot trading market is considered. For each unit of green electricity produced by a green power enterprise, the green certificate issuing organization issues a unit of green certificate for it.

6) The unit generation cost of a thermal power company will not change due to the change of its strategy choice. If the strategy choice of a thermal power company changes, its unit cost of electricity generation does not change.

Table 1 shows the decision variables and parameters involved in this paper. There are five decision-making parameters in the model, which are thermal power wholesale price, green power wholesale price, thermal power price, green power price, and carbon emission reduction level of thermal power enterprises. There are 16 parameters involved, covering potential electricity demand, thermal power price sensitivity coefficient and so on. It is able to represent the interest-related factors of multiple participants in the market transaction in a more comprehensive way.

Table 1: Decision variables and parameters

Decision variables	
ωT	Wholesale price of thermal power
ωR	Wholesale price of green electricity
PT	Thermal power price
PR	Green electricity price
E1	Carbon reduction level of thermal power enterprises
Parameters	
α	Potential electricity demand
β	Thermal power price sensitivity coefficient
γ	Green electricity price sensitivity coefficient
γ1	Rewards for green power enterprises when they exceed the RPS quota
ʄ1	The fine imposed on the power grid company when the RPS quota is not fulfilled
Pr	Unit excess consumption volume price
θ	Benchmark quota ratio
Ci,i=1,2	Unit power generation cost of thermal power and green power
em	Initial unit carbon emission intensity of thermal power
Cg	Carbon emission quota
Pc	Unit TGC price
PCET	Trading price of carbon emission rights per unit
λi,i=1,2	Carbon emission reduction sensitivity coefficient
hm	Cost coefficient of carbon emission reduction technologies for thermal power enterprises
ʄ2	Fines imposed on green power enterprises when the RPS quota is not fulfilled
π ij, i=ECT,ENT,ECN,ENN,NCT,NNT,NCN,NNN; j=mt,mr,d	Profit of the subject j in Mode i

II. C. 2) Setting the payment function of the electric utility in case of overconsumption by the grid company

1) Grid companies overconsumption, thermal power companies carbon emission reduction, green power companies trading green power (ECT)

Under the strategy combination ECT, the grid company sells renewable electricity that exceeds the limit set by the RPS, so there is $q_R \geq \theta(q_T + q_R)$. Thermal power companies decide the optimal thermal power wholesale price ω_T and carbon emission reduction level E_1, and green power companies set the optimal green power wholesale price ω_R; the grid company, as a follower, sets the thermal power price P_T and the green power price P_R in accordance with the decision of the power generating companies. This study assumes the following electricity demand function:

$$\begin{cases} q_T = a - \beta P_T + \gamma P_R + \lambda_2 E_1 \\ q_R = a - \beta P_R + \gamma P_T - \lambda_1 E_1 \end{cases} \tag{5}$$

where q_T represents the demand for thermal power and q_R represents the demand for green power, and the demand of power generation companies is related to the price of the product and the degree of carbon emission reduction; and $\beta > \gamma > 0$, which indicates that the price self-sensitivity is greater than the cross-price sensitivity; the proportion of renewable power consumption quota for grid companies under the RPS mechanism is specified as $\theta(q_T + q_R)$ where $0 < \theta \leq 1$.

The game tripartite subjects to maximize their own profits as the goal of the game. At this time, the profit of the grid company is:

$$\pi_d^{ECT} = (P_T - \omega_T)q_T + (P_R - \omega_R)q_R + P_r\left[q_R - \theta(q_T + q_R)\right] \tag{6}$$

The profits of thermal power companies are:

$$\pi_{mt}^{ECT} = (\omega_T - c_1)q_T - \frac{1}{2}h_m(E_1)^2 - P_{CET}\left[e_m(1-E_1)q_T - C_g\right] \tag{7}$$

Green power companies make a profit of:

$$\pi_{mr}^{ECT} = (\omega_R - c_2)q_R + P_c q_R + \gamma_1\left[q_R - \theta(q_T + q_R)\right] \tag{8}$$

where, $P_r[q_R - \theta(q_T + q_R)]$ on behalf of when the grid company exceeded the quota requirements, sold the corresponding part of the excess consumption to obtain additional revenue; thermal power enterprises carbon emission reduction technology investment cost is about $E_1\left(0 \leq E_1 \leq 1\right)$ incremental function, with the enhancement of the degree of carbon emission reduction, the emission reduction investment is also increased accordingly, so this paper assumes that The carbon abatement cost of thermal power enterprises is $h_m(E_1)^2/2$, the marginal abatement cost of thermal power enterprises is increasing, when carbon abatement investment is made, the carbon emissions per unit of thermal power products is $e_m\left(1-E_1\right)$, and if the carbon emissions are more than C_g, the carbon emission rights need to be purchased; $\gamma_1\left[q_R - \theta(q_T + q_R)\right]$ represents the amount of incentives given by the government to the green power companies when the grid company overshoots the quota requirement.

2) Grid company over-consumption, thermal power companies do not reduce carbon emissions, and green power companies trade green power (ENT)

In this case, compared with making carbon emission reduction investments, thermal power enterprises tend to purchase the corresponding amount of carbon emission rights through the carbon trading market to fulfill the carbon quota target, thus reducing the capital and technology investment in carbon emission reduction. At this time, the demand of power generation enterprises is related to the price level of the product. The power demand function is:

$$\begin{cases} q_T = a - \beta P_T + \gamma P_R \\ q_R = a - \beta P_R + \gamma P_T \end{cases} \tag{9}$$

Thermal power firms and green power firms set the optimal wholesale prices for their own products; the grid company sets the thermal power price P_T and the green power price P_R based on the decisions of the generators. The profit of the grid company is:

$$\pi_d^{ENT} = (P_T - \omega_T)q_T + (P_R - \omega_R)q_R + P_r\left[q_R - \theta(q_T + q_R)\right] \tag{10}$$

The profits of thermal power companies are:

$$\pi_{mt}^{ENT} = (\omega_T - c_1)q_T - P_{CET}(e_m q_T - C_g) \tag{11}$$

Green power companies make a profit of:

$$\pi_{mr}^{ENT} = (\omega_R - c_2)q_R + P_c q_R + \gamma_1 \left[q_R - \theta(q_T + q_R) \right] \tag{12}$$

Under this strategy combination, only the profit of the thermal power enterprise changes compared to the ECT strategy combination. Thermal power enterprises choose not to invest in carbon emission reduction, the carbon emission of thermal power products produced by them is $e_m q_T$, and the thermal power enterprises purchase carbon emission rights corresponding to the part of $(e_m q_T - C_g)$ through the carbon trading market.

3) Grid company overconsumption, thermal power enterprises carbon emission reduction, green power enterprises do not trade green power (ECN)

From the previous analysis, when the green power enterprises choose not to trade green certificates, their revenue is 0. Thermal power enterprises produce electricity, and the grid company purchases thermal power through the electricity market, at which time the grid company is unable to fulfill the RPS quota, and needs to pay penalties corresponding to the amount of electricity sold. The electricity demand function is:

$$q_T = a - \beta P_T + \lambda_2 E_1 \tag{13}$$

The grid company's profit was:

$$\pi_d^{ECN} = \left(P_T - \omega_T\right) q_T - f_1 \theta q_T \tag{14}$$

The profits of thermal power companies are:

$$\pi_{mt}^{ECN} N = \left(\omega_T - c_1\right) q_T - \frac{1}{2} h_m \left(E_1\right)^2 - P_{CET} \left[e_m \left(1 - E_1\right) q_T - C_g \right] \tag{15}$$

Green power companies make a profit of:

$$\pi_{mr}^{ECN} = 0 \tag{16}$$

The RPS stipulates a quota of θq_T , and f_1 represents the unit penalty to the grid company in case of failure to fulfill the RPS quota, then the total penalty to be paid by the grid company is $f_1 \theta q_T$. Thermal power companies set the optimal thermal power wholesale price ω_T and carbon emission reduction level E_1 ; the grid company sets the thermal power price P_T based on the decision of the thermal power companies.

4) Grid company over-consumption, thermal power enterprises do not carbon emission reduction, green power enterprises do not trade green power (ENN)

Thermal power enterprises choose not carbon emission reduction strategy, the power demand function is affected by the thermal power price level, at this time the power demand function is:

$$q_T = a - \beta P_T \tag{17}$$

The grid company's profit was:

$$\pi_d^{ENN} = \left(P_T - \omega_T\right) q_T - f_1 \theta q_T \tag{18}$$

The profits of thermal power companies are:

$$\pi_{mt}^{ENN} = \left(\omega_T - c_1\right) q_T - P_{CET} \left(e_m q_T - C_g\right) \tag{19}$$

Green power companies make a profit of:

$$\pi_{mr}^{ENN} = 0 \tag{20}$$

Thermal power firms set optimal wholesale thermal power prices ω_T ; grid companies set thermal power prices P_T based on the decisions of thermal power firms.

II. D.Analysis of Evolutionary Stabilization Strategies

Based on the replicated dynamic equations, the analysis obtains all possible scenarios of the ESS state of the three-party evolutionary game for thermal power enterprises, green power enterprises, and grid companies, and further analyzes the conditional intervals of all the ESS scenarios, and identifies the main factors affecting the stability of the evolution of the behavioral strategies of each electric power enterprise under the carbon trading policy.

The replicated dynamic equation sets of thermal power producers, green power producers and grid companies:

$$\begin{cases} F(x)=x(1-x)[1-z(1-y)]\left[\left(P_f-P_{f1}\right)*Q+P_c\left(E_2-E_1\right)-C_{ec}\right] \\ F(y)=y(1-y)\left\{z\left[P_r-(1-x)P_{f1}-xP_f\right]Q-(1-z)dC_d\right\} \\ F(z)=z(1-z)\left\{(1-y)r+\left[(1-x)P_{f1}+xP_f-P_s\right]Q+C_d\right\} \end{cases} \tag{21}$$

Solving (21) shows that when $F(x)=0$, $F(y)=0$, $F(z)=0$, 9 equilibrium points can be obtained, i.e., (0,0,0), (0,1,0), (0,0,1), (0,1,1), (1,0,0), (1,1,0), (1,0,1), (1,1,1), $\left(x^*,y^*,z^*\right)$. Since $\left(x^*,y^*,z^*\right)$ is a non-asymptotic steady state, only the first 8 equilibria are considered in this study. The Jacobi matrix is further constructed as in equation (22).

$$\omega=\begin{bmatrix} \begin{array}{l}(1-2x)[1-z(1-y)]\\ \left[\left(P_f-P_{f1}\right)Q\right.\\ \left.+P_c\left(E_2-E_1\right)-C_{ac}\right]\end{array} & \begin{array}{l}x(1-x)z\left[\left(P_f-P_f\right)Q\right.\\ \left.+P_c\left(E_2-E_1\right)-C_{ec}\right]\end{array} & \begin{array}{l}x(1-x)(1-y)\left[\left(P_f-P_f\right)Q\right.\\ \left.+P_c\left(E_2-E_1\right)-C_{ac}\right]\end{array} \\ y(1-y)z\left(P_{f_1}-P_f\right)Q & \begin{array}{l}(1-2y)\\ \left\{z\left[P_r-(1-x)P_f-xP_f\right]Q\right.\\ \left.-(1-z)dC_d\right\}\end{array} & \begin{array}{l}y(1-y)\\ \left\{\left[P_r-(1-x)P_f-xP_f\right]Q\right.\\ \left.+dC_d\right\}\end{array} \\ z(1-z)\left(P_f-P_f\right)Q & z(1-z)(-r) & \begin{array}{l}(1-2z)\{(1-y)r+\\ \left.\left[(1-x)P_f+xP_f-P_s\right]Q+C_d\right\}\end{array} \end{bmatrix} \tag{22}$$

According to the Liapunov stability condition, the sufficient condition for the system equilibrium points to reach stability is that the eigenvalues of the Jacobi matrix are all negative. The above eight equilibrium points are brought into Eq. (22) to solve for the ESS point.

Case 1: The ESS is (0, 0, 0), i.e. {the thermal power enterprises do not reduce emissions, the green power enterprises do not trade green power, and the grid company overconsumes}. In this case, thermal power companies profit more through tariff fluctuation, and the total cost of over-consumption by the grid company through the electricity market is less than the cost of purchasing electricity from green power companies (including the environmental value of green power).

Case 2: The ESS is (0, 1, 1), i.e. {the thermal power enterprises do not reduce emissions, the green power enterprises trade green power, and the grid company purchases power from the green power enterprises}. In this case, thermal power enterprises profit more through tariff fluctuation, thermal power feed-in tariffs are lower than green power feed-in tariffs, and the grid company purchases lower sales tariffs from green power enterprises or participates in power trading directly at a higher cost.

Case 3: The ESS is (1, 0, 0), i.e. {the thermal power enterprises reduce emissions, the green power enterprises do not trade green power, and the grid company overconsumes}. In this case thermal power companies profit more from carbon trading, and the total cost of over-consumption by the grid company through the electricity market is less than the cost of purchasing electricity from green power companies.

Case 4: The ESS is (1, 1, 1), i.e. {the thermal power enterprises reduce emissions, the green power enterprises trade green power, and the grid company purchases power from the green power enterprises}. In this case thermal power enterprises profit more from carbon trading, thermal power feed-in tariffs are lower than green power feed-in tariffs, and the grid company purchases lower sales tariffs from green power enterprises, or the cost of directly participating in power trading is higher.

III. Simulation experiments of market transactions based on evolutionary games

This chapter establishes an evolutionary game model related to maximizing the interests of multiple participants in electricity market transactions through simulation experiments. And the evolutionary effect of the model is tested through the validation of parameter sensitivity.

III. A. Initial setup of simulation experiment

III. A. 1) Base state simulation analysis

Assuming that at the initial state, the strategies of thermal power enterprises choosing to reduce emissions, green power enterprises choosing to trade green power, and grid companies choosing to overconsume are all 0.5, the overall change trend of the emission reduction probability x of thermal power enterprises, the probability y of green power enterprises trading green power, and the probability z of overconsumption of grid companies can be obtained.

Figure 2 shows the three-party game strategy selection in the baseline state. Under the RPS policy, the grid company initially tends to participate in the electricity market without overconsumption, and later gradually changes its strategy, tends to purchase electricity from green power enterprises and evolves to the equilibrium state at the earliest in the fourth month; green power enterprises are more inclined to choose to trade green power and evolve to the equilibrium state gradually in the first 12 months; and thermal power enterprises are more inclined to choose emission reduction, with the probability of about 0.966. Therefore, under the current situation, the grid company initially enters into a three-party game with the probability x, and the probability y of trading green power. situation, the grid company initially enters the power trading market, has no trading experience yet, and is more inclined to the more stable non-excessive consumption; the green power enterprises are affected by the carbon trading and green power trading and other policies, and the probability of trading green power will be gradually reduced; at the same time, the thermal power enterprises in the market can not reach a complete unity in the strategic decision of whether to reduce emissions and are still hesitant and exploratory, which basically corresponds to the actual situation.

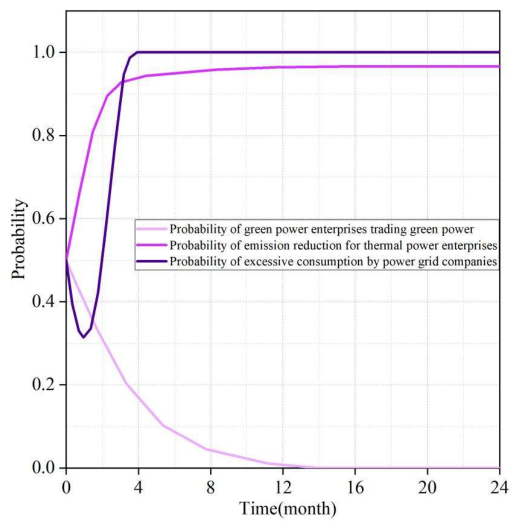


Figure 2: The selection of three-party game strategies under the benchmark state

III. A. 2) Impact of change in main strategy on thermal power companies

When the initial state of thermal power enterprises, green power enterprises, and grid companies are all a certain pure strategy, all three subjects have two strategy choices, which can be selected by thermal power enterprises (emission reduction 0, no emission reduction 1), green power enterprises (trading green power 0, no trading green power 1), and grid companies (overconsumption 0, no overconsumption 1), which can form eight strategy combinations, i.e., (0, 0, 0), (0, 1, 0), (0, 1, 1), (0, 0, 1), (1, 0, 0), (1, 1, 0), (1, 0, 1), (1, 1, 1). The software simulation reveals that when the initial choices of the three market participants are all pure strategy choices, none of them is willing to actively change the strategy to break the equilibrium. However, this equilibrium is not an evolutionary stable state, and it will be destroyed when the strategy choice of one of the subjects is changed by a very small amount. In order to further study the impact of the strategic choices of the two subjects of the green power enterprises and the grid company on the thermal power enterprises, so that each subject makes a tiny mutation of 0.02, take the strategy (0, 0, 0) as an example, so that its initial simulation value is (0.02, 0.02, 0.02), to explore the impact of a subject's strategic choice change on the thermal power enterprises.

This paper analyzes the impact of green power enterprise strategy choice on thermal power enterprises. The initial probability of thermal power enterprises choosing "emission reduction" and power grid companies choosing "excess consumption" is set to be 0.02, and the probability of green power enterprises choosing "trading green electricity" is gradually increased to 0.02, 0.32, 0.52, 0.62, and 0.98. Figure 3 shows the impact of green power companies' strategic choices on thermal power companies. As can be seen from Figure 3, the willingness of green power companies to trade green power will significantly affect the willingness of thermal power companies to reduce emissions. As the probability of green power enterprises choosing to "trade green power" increases from 0.02 to 0.98, the probability of thermal power enterprises choosing "emission reduction" is also increasing, gradually shifting from "no emission reduction" to "emission reduction". In addition, when the probability of green power enterprises choosing to "trade green power" is 0.52, the probability of thermal power enterprises choosing to reduce emissions is about 0.55, and when the probability of green power enterprises choosing "trading green electricity" rises to 0.62, the probability of thermal power enterprises choosing to reduce emissions is as high as 0.94. This is because green power companies trade green power under the premise of controlling the transaction cost of green certificates, and under the RPS policy, power grid companies will be more inclined to over-consume to obtain incentives, thereby reducing the amount of thermal power purchases that do not reduce emissions. In order to facilitate transactions with power grid companies, thermal power companies will gradually choose to reduce emissions and obtain more profits by selling carbon allowances in the carbon trading market.

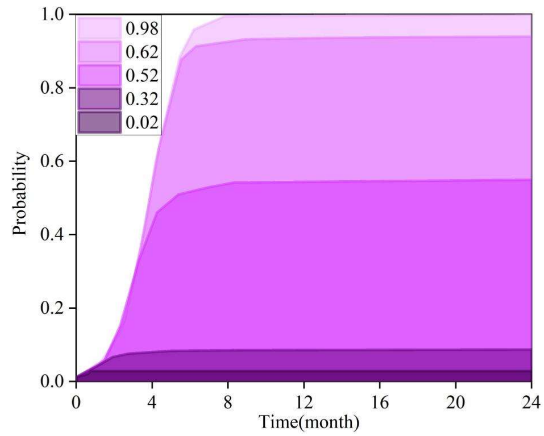


Figure 3: Impact of green-enterprise strategies on thermal power enterprises

III. B. Multi-participant evolutionary game modeling

Based on the decision variables and parameters involved, the multi-participant evolutionary game model constructed in this paper is solved using replicated dynamic equations and so on, and the change of the profit function of each subject of the market transaction with the number of iterations t of the market dynamics is calculated.

Figure 4 shows the change of profit in the iterative process of the multi-participant game in the electricity market. Based on the iterative process and solved values in Fig. 4, the grid company's return no longer changes after the 140th time, and the equilibrium return is 8.758*105 yuan; the green power enterprise's return is stable after the 68th time of the game, and the equilibrium return is 3.39*105 yuan; and the thermal power enterprise reaches stability after the 49th time of the game, and the equilibrium return is 4.44*105 yuan. This shows that the constructed evolutionary game model can better simulate the adaptive learning process of each participant's game in the market, and realize the spontaneous competition process of market players within a certain range to reach the Nash equilibrium.

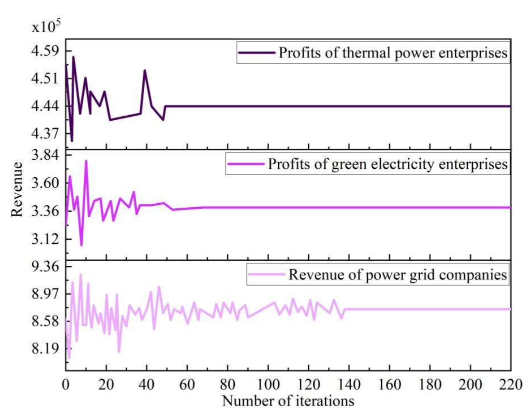


Figure 4: Changes in revenue during the iterative process of multi-agent games

III. C. Evolutionary sensitivity analysis

III. C. 1) Impact of carbon price on the price of electricity market clearing

Under the RPS mechanism in this paper, the ratio of carbon trading price to carbon cost transmission is the core factor affecting the game equilibrium solution, grid company's overconsumption, thermal power enterprises' carbon emission reduction decision, and green power enterprises' behavior of trading green power. In order to explore the impact of carbon trading price πcar. On the clearing price of the electricity market, we increase πcar from 50 yuan/t to 90 yuan/t in steps of 10 yuan/t, and respectively count as carbon price 1-carbon price 5, and other parameters remain unchanged, to analyze its impact on the clearing price of the electricity market.

Figure 5 shows the impact of carbon price on the electricity market clearing price. Analyzing the impact, it is found that the power market clearing price is positively correlated with the trend of carbon trading price. This is due to the thermal power company's carbon emission cost increases, green power companies clean cost also increases, its submitted power offer continues to increase, the market clearing price of electricity from 0.12 yuan / degree correspondingly increased to a maximum of 0.91 yuan / degree, the grid company's purchase price is also synchronized with the increase. The range of market clearing price changes can be seen from the carbon price for the power market clearing price is very influential, and by different power hours. Among them, time period 3 (8:30-12:30), 4 (12:30-16:30) for the load peak, thermal power enterprises of coal-fired generating units power is larger, the market clearing price of electricity by the impact of carbon trading price is also the most sensitive, showing a significant increase in the trend.

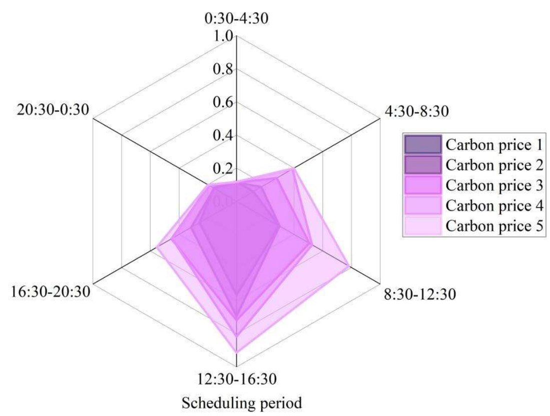


Figure 5: Impact of carbon prices on the clearing price of the electricity market

III. C. 2) Evolution of Grid Company Choice Probabilities under Clearing Price Fluctuations

Fluctuations in the price of electricity will affect the decisions made by green power companies and thermal power companies. For example, thermal power enterprises will choose to invest in carbon emission reduction technology to reduce the unit price of electricity, or purchase emission credits through the carbon market, etc.; green power enterprises will choose to increase the amount of green power trading to seek greater benefits. The decisions made by the two types of enterprises under the fluctuation of power clearing price will directly affect the purchase choice of green power or thermal power by the power grid company.

The constructed evolutionary game model is utilized to evolve the choice probability of the grid company. Figure 6 shows the evolution process of the choice probability of the grid company. Under the fluctuation of electricity clearing price, if the green power companies increase the green power trading volume, then the probability that the grid company chooses to buy more electricity from the green power companies reaches the highest 0.667; at the same time, if the thermal power companies choose to invest in the carbon emission reduction technology to reduce the unit price of thermal power, the probability that the grid company chooses to buy electricity from the thermal power companies is also 0.621. On the contrary, if the green power companies and the thermal power companies choose the opposite strategy, then the probability that the grid company chooses will be reduced to 0.436 and 0.484, respectively.From the evolution situation, the evolutionary game model in this paper has a very good evolutionary effect.

III. D. Evolutionary stability analysis

III. D. 1) Sensitivity analysis for parametric thermal power price sensitivity coefficient (β)

To study whether the parameter adjustment in the evolutionary game model has an influential effect on the decision-making behavior of multi-participant subjects. The parameter β is adjusted to 25%, 50%, 75% and 100% respectively, and its influence on the decision-making of different participants is analyzed through evolution.

Figure 7 shows the impact of adjusting the parameter "thermal power price sensitivity coefficient (β)" on the evolution of decision-making of green power enterprises, thermal power enterprises and grid companies. For the adjustment of parameter β, the reduction of the parameter has basically no effect on the final stabilized offer of thermal power enterprises, and the rate of arriving at the stabilized strategy is basically the same under different parameters, with the rate of quoting a high price being more than 99.1% after t = 0.31 s. For the green power enterprises, the parameter remains unchanged, and a high price is quoted. For green power enterprises, the rate of reporting high price is the smallest when the parameter is unchanged, i.e., making the slowest decision, and the rate of reporting high price gradually increases during the process of parameter increasing. At β=100%, the thermal power company reaches 0.99 in t=0.09 s. For the grid company, the evolutionary stabilization strategy shifts from overpricing to underpricing when the parameters are adjusted to 75% and above.

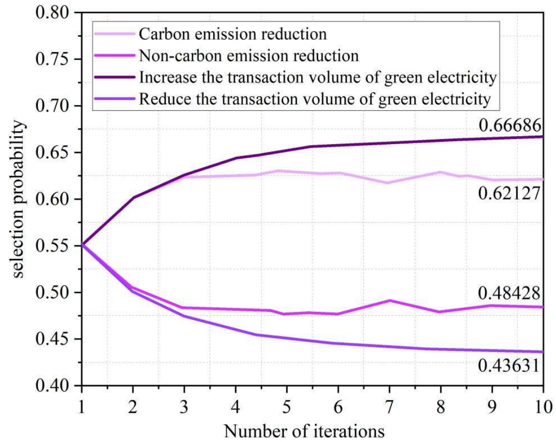


Figure 6: The power grid company selects the probability evolution process

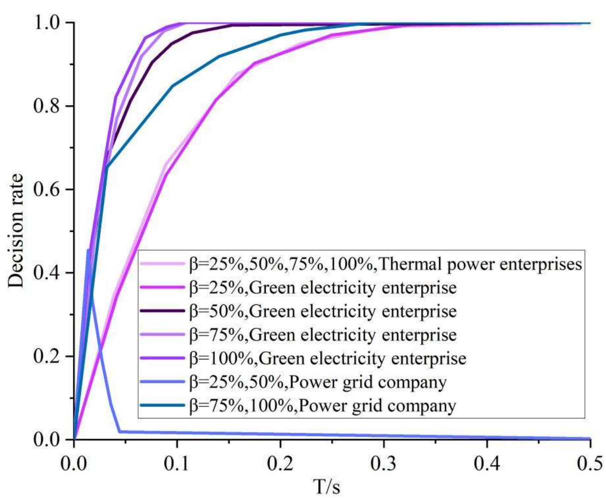


Figure 7: Influence of β adjusted on the decision-making of 3 participants

III. D. 2) Sensitivity analysis for parametric green power price sensitivity coefficient (γ)

The parameter γ is adjusted to 25%, 50%, 75%, and 100%, respectively, and its influence on the decision-making of different participants is analyzed by evolution. Figure 8 shows the simulation results of the three types of evolutionary games with adjusted parameter γ. For parameter γ, it can be seen from Fig. 8 that the final stabilized offer of green power enterprises does not change with the parameter changes, and the rate of arriving at the stabilized strategy is basically the same under different parameters, for example, the probability of quoting a high price is around 0.931 with t=0.2s. For thermal power companies, when the parameter is adjusted to 100%, the group quotes high price with the largest rate that is to make the fastest decision, with t=0.10 for example, the parameter is reduced from 100% to 25%, the probability of quoting high price is 0.984, 0.981, 0.962, 0.659 respectively. for grid companies, the parameter is basically converged to stabilize the strategy of quoting high price when it is at 100%, and as the parameter is lowered, the grid companies start to report high price after the inflection point at a similar time, and eventually tend to report low price stabilization strategy, the smaller the parameter, the later to reach the stabilization strategy.

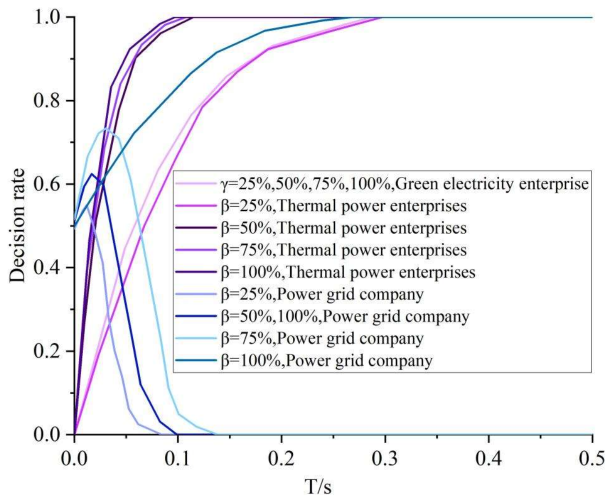


Figure 8: Influence of γ adjusted on the decision-making of 3 participants

IV. Conclusion

This paper constructs an evolutionary game model to maximize the evolution of the interests of multiple participants in the market transaction and to provide support for the decision-making of all parties.Under five different carbon prices, the market clearing price of electricity shows an upward trend of 0.12 yuan/kWh to a maximum of 0.91 yuan/kWh. The fluctuation of electricity price makes the probability of the grid company's choice of green power companies and thermal power companies under different decisions also change. The probability of choosing the green power enterprise that increases the green power trading volume reaches up to 0.667. Making adjustments of 25%, 50%, 75%, and 100% for the 2 parameters, respectively, it is found that the rate of making stabilization strategies varies among the 3 participants. Using the constructed evolutionary game model, it is possible to judge the decision-making direction of multiple participants in market transactions and the resulting benefits, so as to find the benefit maximization path. In the future, a dynamic evolutionary mechanism can be introduced to improve the corresponding speed of the model.

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