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Game theory applications in the electricity market and renewable energy trading: A critical survey

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With the acceleration of China's electricity market construction, it is urgent to establish a unified electricity transaction mechanism to balance the interests of all parties and build a competitive electricity market. Game theory has significant advantages in the study of decision optimization among multiple decision-making bodies that interact and compete with each other. Therefore, the application of game theory in the electricity system has attracted the attention and research of a large number of scholars, among which the research on the electricity market accounts for the highest proportion. In this study, the concept and evolution of cooperative game theory, non-cooperative game theory, and evolutionary game theory in game theory are described in detail. Second, the status quo and scale of the domestic and foreign electricity market are sorted out and summarized. Finally, according to the research results of the application of three kinds of game theory in the electricity market in recent years, this study evaluates and analyzes the three typical aspects of the power generation side, the power sale side, and the power consumption side, and puts forward the prospect of the application of game theory in the electricity market in the future.

KEYWORDS

cooperative game, non-cooperative game, evolutionary game, electricity market, renewable energy trading

Introduction

With the implementation of renewable energy generation projects, renewable energy will occupy a large proportion of the future energy structure (Wang et al., 2021;Ding et al., 2020). Since China proposed the double carbon target, the transformation of China's energy structure has accelerated, which has put forward higher requirements for the resource allocation and optimization of China's electricity market (Peng et al., 2022). The National Development and Reform Commission issued the "Guidance of the National Energy Administration on Accelerating the Construction of a Nationwide Unified Electricity Market System", which pointed out that there are some problems in China's electricity market at present, such as unsound system, imperfect function, non-uniform trading rules, and so on.

The establishment of a unified electricity market system can effectively guide users to cut peaks and fill valleys, improve the cost- and benefit-sharing mechanism, and fully stimulate the flexible adjustment ability of the user side. At present, users with distributed energy will not only be consumers but also be able to become sellers of electricity and sell excess electricity to the grid (Li et al., 2022). Meanwhile, with the popularity of electric vehicles, a large number of electric vehicles can become mobile energy storage devices and participate in the electricity market (Cheng and Yu, 2018; Liu et al., 2020; Uhde, 2022). Therefore, the future electricity market will be a complex electricity trading platform that covers multiple interests and considers energy saving and emission reduction.

Game theory, as an efficient analytical tool, can be used to intervene in trading decisions in the electricity market to effectively study the decisions among multiple stakeholders and promote the construction of a unified system in the electricity market (Liu et al., 2020). Since the game theory was first proposed and applied in the field of economics, it has been widely used in political, biological, engineering, and social fields in the past half-century (Wang et al., 2012; Liu et al., 2018). In electrical engineering, the application of game theory can be mainly divided into planning, scheduling, and the electricity market of the power system (Liu et al., 2017).

This study first compares the evolutionary development of game theory in the past half-century and summarizes the scope of application and advantages of cooperative games, non-cooperative games, and evolutionary games. Then, it makes a comprehensive analysis and review of the scale and development of the domestic and foreign electricity market. Finally, this study compares and analyzes the research results of the game theory of the electricity market, and puts forward some suggestions and prospects from the perspective of the game theory.

Game theory

Game theory has been used to study the problem of optimal decision-making between multiple interacting interested parties. In half a century of development, evolution, and application, the game theory has been applied and developed in the fields of economics, biology, politics, and engineering, and has become one of the important tools for decision analysis in the whole social sciences. A complete game contains three elements: participants, strategies, and benefits. The participants refer to the decision makers involved in the game (individuals who make decisions independently, collectively, or by nature). The strategy refers to the set of decisions available to the participants in the game process, and the range of decisions tends to be different for different participants. Revenue refers to the revenue achieved by the participants in the game process, often to maximize their revenue (Liu et al., 2018).

In general, game theory can be divided into classical game theory and evolutionary game theory according to the degree of rationality of participants. The former can be divided into cooperative and non-cooperative games according to whether the participants cooperate; in addition, according to the time sequence of game decision-making, it can be divided into static and dynamic games. Therefore, according to different characteristics, game theory has various ways of classification, as shown in Figure 1.

Cooperative games

A game with binding agreements between participants is called a cooperative game. The cooperative game emphasizes collectivism and its research focuses on how to reach cooperation among participants and how to distribute the additional benefits of cooperation among participants. Usually, the allocation strategy is often designed using axiomatization. Representative theoretical results of cooperative games include concepts such as Nash bargaining game theory and Shapley value (Luo et al., 2022).

In general, the Nash bargaining game theory refers to the equilibrium solution determined by the participants after multiple rounds of bargaining. The solution needs to satisfy the Nash referendum, which includes individual rationality, Pareto optimality, linear transformation independence, etc., and the Nash bargaining solution Si is as follows:

$$S_i = \operatorname{argmax}\prod_{i=1}^{N} \left(U_i(x_i) - U_{i,\min}\right)^{\alpha_i}, \tag{1}$$

where N is the number of participants;U_i is the utility function; and α_i is the bargaining power.

Shapley values are a more straightforward method of cooperation, by which participants form alliances and distribute the total alliance proceeds according to established rules. Typically, the benefits to each participant based on the Shapley value are as follows:

$$U_i(N,v) = \sum_{S\subseteq \frac{N}{\{i\}}} \frac{|S|!\,(n-|S|-1)!}{n!}\left(v(S\cup\{i\}) - v(S)\right), \tag{2}$$

where n is the total number of participants and $|S|$is the base number of the alliance.

Non-cooperative games

Unlike cooperative games, non-cooperative games do not have mandatory binding agreements between participants. It mainly studies the process of optimizing the decision of each participant to maximize their interests. Non-cooperative games can be divided into static and dynamic games. Static games are characterized by the fact that participants make their own decisions without knowing the game behavior of other participants; while the game behavior in dynamic games has a temporal order and participants can adjust their own decisions according to the historical information of the previous period to

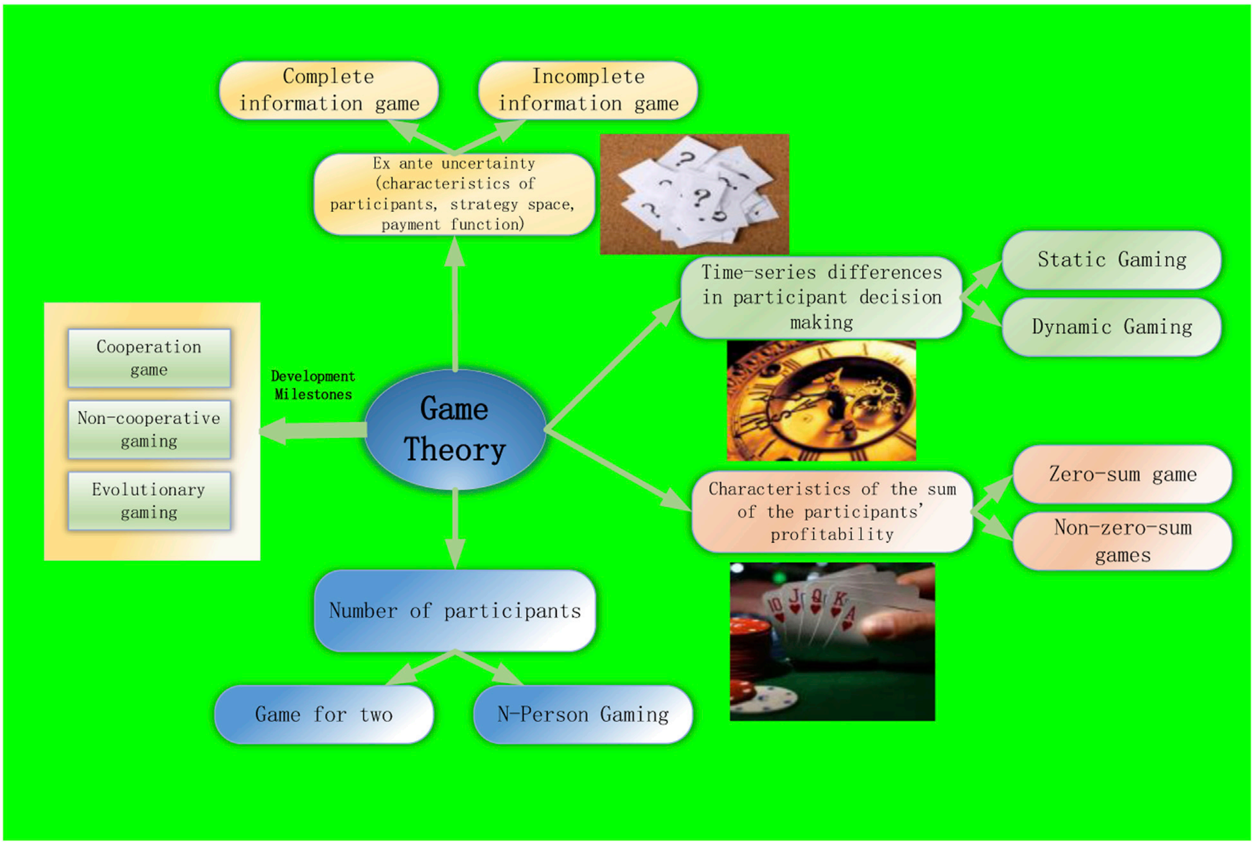

FIGURE 1
Classification of game theory under different characteristics.

achieve the optimization of their own decisions as much as possible.

The non-cooperative game process is widely solved using Nash equilibrium, which means that each participant will make decisions to maximize their interests if the decisions of other participants are determined so that the set of all people's decisions is a Nash equilibrium.

Evolutionary game

The classical game theory usually assumes that players are fully rational, while evolutionary game theory assumes that players are bounded rational, constantly adjusting their decisions based on the experience to maximize their benefits (Zhang et al., 2022; Coninx et al., 2018).

The main elements of an evolutionary game are the selection of an appropriate fitness function and the setting of a reasonable and effective selection and variation mechanism. The fitness function determines whether the evolutionary game has a stable evolutionary strategy, and selection and variation are the driving forces that ensure that evolution takes place. The selection mechanism determines the replicated dynamic equation and finds the solution, and the variation mechanism verifies that the resulting solution is a stable decision solution. The basic form of the replication dynamic equation is as follows:

$$\frac{dx(t)}{dt} = [f(S_i, x) - f(x, x)]x_i, \tag{3}$$

where S_i is the set of decisions of the participants in the evolutionary game; x_i is the proportion of the number of participants who have chosen a decision at moment i; $f(S_i, x)$ is the individual expected payment; and $f(x, x)$ is the average expected payment of the whole group.

Electricity market

Generally, electricity trading refers to the trading of electricity as a commodity between power generators, power sales companies, and electricity consumers. Unlike the daily commodity market, the power system is a unified whole

TABLE 1 China's electricity trading volume in recent years.

Years	Intra-provincial transaction volume	Inter-provincial volume	National trading amount
2016	—	—	8000
2017	13,400	2924	16,324
2018	16,885	3471	20,654
2019	20,268	1,485	21,771
2020	—	-	31,663
2021	30,760	1890	37,787

composed of various participants, and the behavior of any participant will have an impact on the whole power system; therefore, the power generation companies, power sales companies, and the power consumers in the electricity market must be coordinated with each other.

China's electricity market

Power trading centers can be divided into regional power trading centers and regional power trading centers, and up to now, 32 regional power trading centers and two regional power trading centers have been built in China. Since the new round of power industry reform, China's electricity market electric energy trading has shown a year-by-year rising situation, as shown in Table 1. According to the 2021 national electricity market trading brief released by the China Electricity Council, in 2021, China's regions and regional power trading centers together completed 3778.74 billion kWh of traded electricity, an increase of 19.3% year-on-year, accounting for 45.5% of the total social electricity consumption. Among them, the direct trading of medium- and long-term electricity in the electricity market reached 3,040.46 billion kWh, an increase of 22.8% year on year. Thus, in terms of national electricity trading, the development of China's electricity market has progressed rapidly and market-based electricity trading has climbed year by year.

According to the 'Implementation Opinions on Promoting Electricity Sales Side Reform', the goal is to gradually open the electricity sales side market and build a competitive electricity market, thus promoting the optimal allocation of energy resources, and enhancing the capacity of renewable energy consumption and reliability of power supply. The opinion liberalizes the distributed energy market and encourages enterprises or individuals with the conditions to develop distributed energy sources such as distributed photovoltaic and wind energy according to local conditions and to participate directly in the electricity market so that users are no longer just consumers but become producers and consumers who can produce and consume their electricity or sell it to electricity sales companies. In addition, the rise of energy storage, load, and electric vehicles makes the electricity trading mechanism very complex, thus affecting the development of the electricity market to a certain extent.

With the increasing proportion of grid-connected, renewable energy will accelerate to become the main force of power market transactions. So far, the country has more than 20 provinces (regions and municipalities) of renewable energy to participate in the electricity market-based transactions. For example, Ningxia, Shaanxi, Inner Mongolia, and other places have successively issued policies to clarify the participation of renewable energy in electricity market-oriented transactions. Qinghai, Yunnan, and other places have all renewable energy generation markets. The market-oriented proportions of Xinjiang, Gansu, Ningxia, and other places have also exceeded 50%. As a new type of clean energy, renewable energy's future participation in the market-based power trading is very competitive and renewable energy power is also playing an irreplaceable role.

Renewable energy power generation will be fully involved in the market-based electricity trading and will also become the main power to promote the perfection of the new power system, as well as the optimal allocation of power resources. The country will establish a unified power market, and renewable energy enterprises should be prepared to enter the trading market from the following aspects: the combination of trading and energy storage, trading information, digital and intelligent management methods, scientific participation in market-based trading, etc. Meanwhile, with the accelerated construction of the electricity market and green electricity trading, the carbon trading market is gradually mature, renewable energy to participate in the transaction in addition to the value of electricity, but also has environmental value, the renewable energy power market-oriented trading more need to combine green power trading mechanism, green certificate system, and other supporting policies, the overall consideration of the economic benefits of renewable energy enterprises.

At present, China's power trading mainly includes medium- and long-term power trading and power spot trading, while moderate liberalization of frequency regulation, peak regulation, and other auxiliary services trading including renewable energy power green certificate trading and other related trading content.

International electricity market

The International Energy Agency released its Electricity Market Report in January 2022, which reported that strong economic growth led to a 6% increase in the global electricity demand and that the growth in energy demand led to tight supplies of natural gas and coal, causing electricity prices to rise in several countries, while, at the same time, the global electricity sector's CO_2 emissions reached a record high (International Energy Agency, 2022). Despite the surge in fossil fuels, renewable energy generation has been growing at a faster rate as it reached another higher record in 2021.

Several countries around the world have been reforming their electricity markets over the past decades. Europe and the United States are more mature in building electricity marketization, although they also face many challenges due to the large number of renewable energy sources connected to the grid. In recent years, the integration of the UK's electricity system with various types of renewable energy sources and the setting of demanding emission targets by the UK government has driven the reform of the UK's electricity market to accommodate the requirements of the new electricity system. Historically, electricity marketization in the United Kingdom has undergone three changes: first, the electricity pool in England and Wales; second, the electricity trading arrangement; and third, the electricity market reform implemented in 2013 to address energy supply and demand constraints (Liu et al., 2022). The Russian electricity sector has undergone two important changes: first, the conversion of the electricity sector into a state-owned monopoly; and second, the integration of generation, transmission, and distribution was restructured for market liberalization (Lstova et al., 2018).

To sum up, the future global electricity demand will grow steadily while the proportion of renewable energy generation will keep increasing. In addition, with the rapid development of the energy Internet, the increasing number of electric vehicles, distributed energy sources, and energy storage, the future power system will be more complex. To meet the needs of social progress and economic development, it is urgent to build a fair and just power trading mechanism and create a unified electricity market system with reliability and competition.

Application of game theory in the electricity market

Cooperative game in the electricity market

While the electricity demand has been growing steadily in recent years, renewable energy is taking up a larger and larger proportion of the power structure. Meanwhile, with the progress and development of science and technology, renewable energy sources have developed from relying on government subsidies at the beginning to becoming independent competitive electricity market players, just like thermal power. However, the uncertainty of the renewable energy output and the uncertainty of the electricity price in the spot market led to the risk of loss when the power generation enterprises do not complete their power generation targets and cannot maximize their interests. Therefore, on the generation side, renewable energy sources can form alliances with traditional power generation companies based on the cooperative game theory to maximize their profits. In reference to Lu et al. (2020), the low cost of wind power and the better regulation ability of thermal power are combined to maximize the benefits of the wind-fire joint bidding strategy and reduce the abandonment of wind power, and the cooperative game theory is used to allocate the alliance benefits. Zhang et al. (2021) constructed a cooperative scheduling model of scenery storage clusters based on a cooperative game to improve the cluster revenue and the stability of power plants.

On the power generation side, based on the cooperative game theory, renewable energy enterprises and traditional power generation enterprises jointly participate in the electricity market, which improves the operation of traditional power generation enterprises while maximizing economic and environmental benefits and helps the power structure to transition smoothly toward renewable energy.

On the user side, the rapid development of the national economy and the growing electricity demand has led to the rapid development of microgrids to meet the requirements of power users for power quality and reliability. In reference to Fan et al. (2022), an alliance between multiple microgrids is established through communication and control systems to achieve effective energy interoperability among microgrids and improve the overall revenue of the alliance. In reference to Li et al. (2020), a two-stage robust optimization model of the microgrid cluster is established with the objectives of renewable energy consumption and benefit maximization, to achieve the optimal operation of the campus microgrid. Chong et al. (2021) applied the Shapley value in the cooperative game theory to end-to-end power trading to improve the efficiency of grid management.

In summary, with the construction of smart grids and the increasingly large variety and a number of market participants, as shown in Figure 2, the healthy operation of the electricity market will face a huge challenge and the cooperative game theory allows multiple participants to ally to form a complementary situation of strengths to improve the overall revenue of participants.

Non-cooperative games in the electricity market

Electricity market reforms have promoted multi-way choices among electricity market participants in an attempt to maximize their returns, thus enhancing the intense competition among electricity market participants. In recent years, non-cooperative

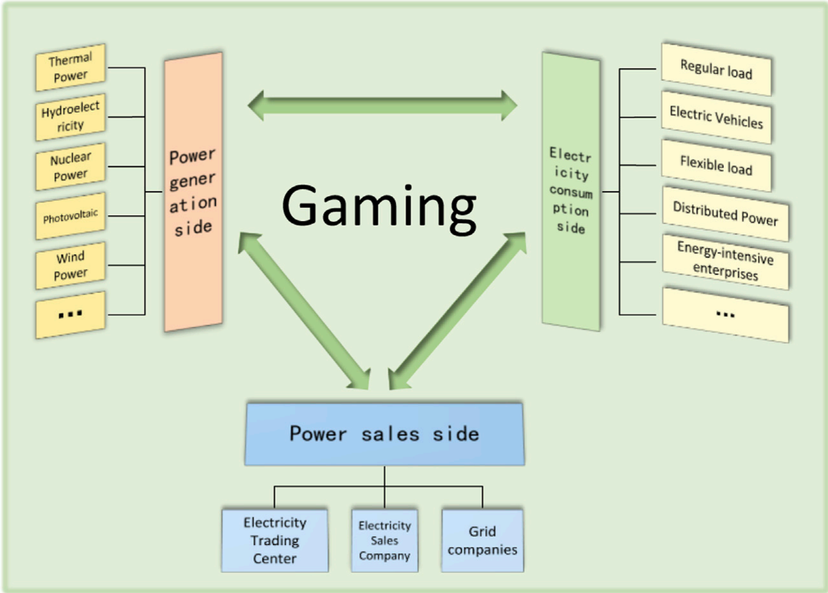

FIGURE 2
Game subject of electricity market.

games have achieved many results in the study of games with multiple players in the electricity market. Ma et al. (2019) constructed a decision model including power generation enterprises, power selling enterprises, and large users, and constructed a game competition process based on the Berge–NS equilibrium model.

On the electricity sales side, to address the planning and operation of new electricity sales entities in the context of electricity marketization, Lin et al. (2020) constructed a non-cooperative game model with the revenue of each electricity sales enterprise as the goal. Meanwhile, with the continuous improvement of the smart grid, the demand-side response will become an important means to cut peaks and fill valleys.

On the customer side, direct power purchase transactions for large customers have been an important part of China's electricity marketization. Based on the non-cooperative game theory, the scheduling optimization of micro-grid clusters can maximize economic benefits while improving the capacity of renewable energy consumption. Xiwang et al. (2022) considered the participation of the hydrogen-production storage generation system in the microgrid game and constructed the capacity optimization allocation model for the wind-light-hydrogen microgrid based on the non-cooperative game theory.

In summary, the goal of the electricity market reform is to establish a highly reliable and dynamic competitive market. Therefore, there is a fiercely competitive relationship among various market participants, and the non-cooperative game theory improves the ideas for each market participant to maximize their interests.

Evolutionary game in the electricity market

In the process of constructing game models, it is perfectly rational that assumes the game participants, which is too idealistic for the highly complex and multi-party coupling electricity market. In the process of evolutionary game modeling, participants only need limited rationality and limited information communication, which makes it close to the actual electricity market operation state and reflects the dynamic decision-making process of multiple interest groups more realistically.

In the research for power generation enterprises, Dou et al. (2020) introduced an evolutionary game to study the demand-side response behavior of customers based on the establishment of a regional electricity-gas interconnection integrated energy system dispatch optimization model. Peng et al. (2019) proposed a differential evolutionary game algorithm to achieve the dynamic evolution of bidding decisions for power generation enterprises. Zhao et al. (2020) applied improved genetic algorithms and the evolutionary game to thermal power offer decisions to provide a decision reference for electricity market transactions of thermal power companies. Cheng and Yu (2018) discussed the equilibrium stability of a multi-group evolutionary game containing traditional power generations, renewable energy companies, and grid companies.

In the study of application on the electricity sales side, Sun et al. (2018) considered the influence of user characteristics and distributed energy and constructed a decision-making mode for users to choose electricity sales enterprise based on the evolutionary game theory to provide a decision reference for electricity sales enterprises.

In the electricity market, the customer side has the largest variety and number of participants, which makes it difficult to balance the interests of all parties on the customer side. Usually, the customer side often participates in the electricity market transactions in the unit of the microgrid. Huang et al. (2020) used an evolutionary game to balance the conflicting interests of various investors in the microgrid source-storage planning scenarios. Most of the aforementioned studies on the application of game theory on the customer side have ignored the role of flexible loads (electric vehicles, air conditioners, etc.) in energy dispatch. Flexible loads on the customers have the feature of flexible dispatch, which can alleviate the pressure of supply and demand in energy dispatch and also reduce the customer's electricity bill in the electricity market.

In summary, compared with the classical game theory, the evolutionary game theory does not require participants to have complete rationality, which can reflect the actual operation of the electricity market more realistically and is more adaptable to the complex and diverse electricity market. However, the evolutionary process of the evolutionary game is a continuous revision and improvement process, which takes a longer time.

Prospect discussion

With the construction of a smart grid and the all-around liberalization of the electricity market, the application of game theory in the electricity system will be of great value. Compared with the application of electricity system dispatching and planning, the exploration and practice of game theory in the electricity market present a more positive and upward trend.

There are a large number of participants in the electricity market and the parties are highly correlated. Subtle changes in any party may cause fluctuations in the whole market. Therefore, the data on the electricity market are complex and huge. Temporally, it includes real-time data and data from more than 10 years, and spatially, containing data from regions, areas, and even individuals. Therefore, how to effectively mine, process, and transmit data are crucial to the gaming behavior in the electricity market. Currently, with the booming development of computer technology, based on the concept of energy Internet, data collection, processing, and analysis in the electricity market can be satisfied by Internet technologies such as cloud computing, big data, and blockchain. Thus, it can provide comprehensive and reliable data support for the game between participants in the electricity market. In addition, to alleviate the pressure of grid dispatch, domestic and foreign scholars put forward the concept of flexible load, which can alleviate the demand pressure of the power grid and improve energy utilization.

Conclusion

At present, the electricity market presents a situation of distributed renewable energy and flexible load increase, social capital entering the electricity sales market, and the goals of market participants are complex and diverse. As an advanced analytical tool to study the problem of multiple decision-making subjects, the game theory has shown great potential in the establishment of trading mechanisms in the electricity market. In this study, through the summary and prospect of research on the electricity market based on game theory, the following conclusions are drawn.

1) The theoretical research of game theory in the electricity market, taking into account the operational characteristics of renewable energy power generation enterprises and traditional power generation enterprises, realizes the strong alliances through the cooperative game, which is conducive to enhancing the output of renewable energy and the smooth transition of the electricity structure to a low-carbon model.
2) Electricity marketization is based on national conditions, building a competitive electricity market adapted to social progress and economic development needs. Non-cooperative games provide ideas for market participants to pursue the maximization of interest and help to thoroughly stimulate market vitality.
3) The evolutionary game with finite rationality of participants can better adapt to the complex and diverse characteristics of electricity market participants and build a game model that is more in line with the actual electricity market operation, which is conducive to the decision-making optimization of participants in the game process.

Author contributions

WH: conceptualization, writing—reviewing and editing, and supervision; HL: writing—original draft preparation, investigation, and resources.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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