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Review

Key Issues and Technical Applications in the Study of Power Markets as the System Adapts to the New Power System in China

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Abstract: To reach the "30·60" decarbonization target (where carbon emissions start declining in 2030 and reach net zero in 2060), China is restructuring its power system to a new energy-based one. Given this new situation, this paper reviews previous studies on the power market and highlights key issues for future research as we seek to adapt to the new power system (NPS). Based on a systematic literature review, papers on the operational efficiency of the power market, participants' bidding strategies and market supervision were identified. In a further step, papers with high relevance were analyzed in more detail. Then, key studies that focused on market trading under China's new power system were picked out for further discussion. New studies were searched for that pertained to new energy mechanisms and bidding, the transition from coal-fired power, flexible resources and the technical applications of simulations. The quantitative analysis supports the construction of a basic paradigm for the study of power markets that is suitable for the new power system. Finally, the theoretical basis and application suggestions for power market simulations are introduced. This study summarized the existing research on the power market and further explored the key issues relating to the power market as it adapts to the NPS, hoping to inspire better research into China's power sector, and promote safe, low-carbon, and sustainable development in China's power industry.

Keywords: new power system (NPS); power market; new energy; flexible resources; experimental economics; agent-based computational economics

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1. Introduction

The reform of a power system is a major measure and an important part of China's energy restructuring. Since the second round of the electricity reform that was launched in 2015, China's power market has been further liberalized [1]. Meanwhile, the Chinese government has pledged to halt further CO_2 emissions by 2030 and become carbon neutral by 2060 [2]. This requires higher levels of sustainable development in the power system. In recent years, China has been accelerating the replacement of fossil fuels. The proportion of new energy in primary energy consumption continues to rise. Renewable energy power output reached 2.2 trillion kilowatt-hours in 2020, accounting for 29.5% of national electricity consumption. China has fulfilled its commitment that non-fossil energy consumption must account for at least 15% of the primary energy consumption by 2020 as scheduled [3]. In March 2021, China's Central Financial and Economic Affairs Commission called for the building of a new power system (NPS) with new energy as the main source. This government directive is vital to the power industry's direction of development. Against this background, it is particularly important to study the new power system and the power market trading systems that feature a high proportion of renewable energy.

The new power system, compared with traditional power systems, functions in new industrial models. Every part of the power system, including power generation, grid operation, and power load control and energy storage, is changing. On the power supply side, renewable energy will gradually become the main source of electricity generation. On the consumption side, many prosumers are emerging. With regard to grid operation, large-sized grids still dominate, while multiple forms of grids will coexist. From the perspective of the whole system, the operating mechanism and balancing mode will undergo profound changes. The new power system is a clean and low-carbon, safe and controllable, flexible and efficient, intelligent and friendly, open and interactive system. The change of the power market will follow these trends.

At present, China's power market is based on the provincial power market, and power trading is based on medium- and long-term contracts. A spot trading pilot for power is being promoted in the provincial market. New energy power generation enterprises have priority clearance rights in some provinces. That means that they are allowed to sell electricity directly at the volume that they bid, or that they can even sell power without applying for trading volume and prices before the transaction. Their power output will be bought at market prices without any quoting before the trade. Meanwhile, researchers are accelerating the search for strategies to promote regional power markets, which can prompt new energy companies to participate further in the market.

In terms of thermal power, the utilization hours of traditional coal power units are declining as the proportion of new energy is rising [4]. Government requirements for carbon emission reduction are also squeezing the living space of thermal power, as burning clean coal will surely make it more expensive. At present, China's coal-electric installation accounts for about 50% of the power system. Its survival is not only related to the development of the power system, but also related to the social economy and people's livelihoods. We need to pay enough attention to the survival of thermal power. Problems also exist for new energy and the flexible resources that are participating in the power market. The value of flexible resources has not been clarified, and there is no corresponding market mechanism to ensure that large quantities of electricity generated from renewable energy resources can be consumed at market prices. The market mechanisms of auxiliary services also needs to be improved urgently.

Due to the two-track characteristics of China's power market, with both government planning and active markets, a series of issues concerning market operation and convergence are emerging, including the disposal of imbalanced funds [5,6], power market supervision/market power testing [7–9], demand response [10], renewable energy participating in the electricity market [11], the synergy between the electricity market and the carbon market, and the construction of future financial markets for power and market mechanisms for standby capacity. There is no mature international experience that can be drawn on that would help solve these problems.

The goal of this systematic review is to find solutions to develop the Chinese power market, combining China's actual situation with successful foreign experience in power market construction and operation. Therefore, a basic paradigm for the study of power markets is identified by analyzing primary studies that are related to issues on market entities and operational mechanisms. Then, key issues pertaining to power market construction as it relates to China's new power system (NPS) are discussed. To achieve these objectives, we conducted the research guided by the following questions:

1. What are the hot topics in primary studies regarding the construction and operation of power markets, and how do these topics interconnect with each other?
2. What are the key issues in the study of power markets as the system seeks to adapt to the NPS, which will feature a high proportion of new energy?
3. What is the basic paradigm for the study of power markets that would be suitable for the NPS?
4. Which theoretical basis can help simulate the power market to further research into power market mechanisms under the NPS?

5 From which dimensions should simulation modeling be established and how should researchers set related parameters?

The review is structured as follows. Section 2 describes the methodology. Section 3 introduces the analysis of general issues that concern researchers in the study of power markets according to primary research. Sections 4 and 5 discuss key points related to the NPS power market from both theoretical and practical perspectives. In Section 4, key issues and basic paradigm for studying the power market under the NPS are presented, while specific suggestions for the applications of power market simulations are provided in Section 5. Section 6 gives the conclusions and implications.

2. Methodology

The systematic literature review (SLR) framework [12] is adopted in this work to identify, evaluate, interpret and describe the existing body of knowledge on power markets. We focus especially on the operation and supervision of the power market and the bidding strategies adopted by market participants that have caught the most attention. This study follows PRISMA guidance [13] for articles so that we can formulate robust and reproducible research. Figure 1 illustrates the design and logical framework of the respective literature review. The research questions have been outlined in Section 1.

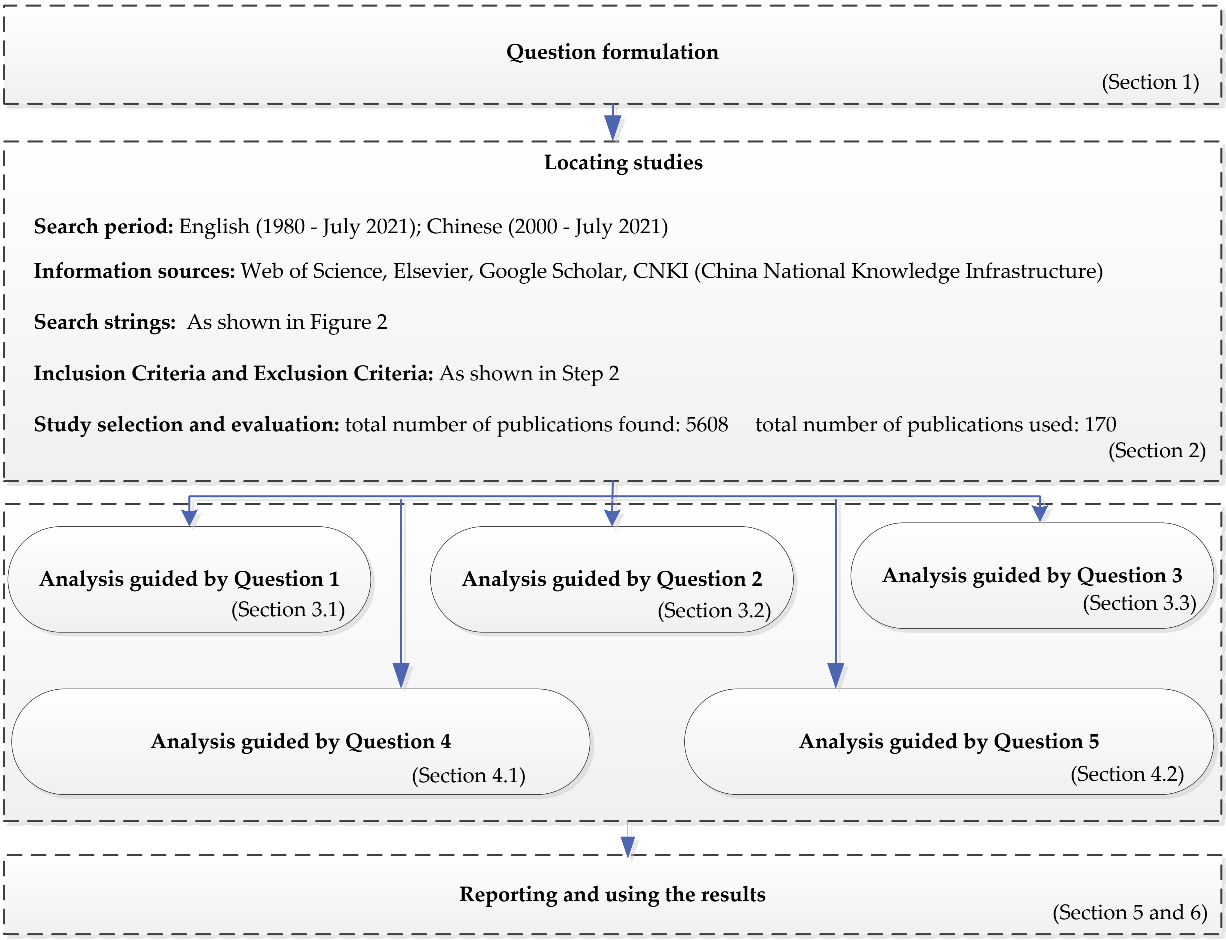


Figure 1. Review Design for the Study of Power Markets as Researchers Adapt to the NPS in China.

We carried out the search process in five steps, including identifying the information sources, defining the eligibility criteria, composing the search strategy and selection processes, which aims to present unbiased, rigorous, and auditable results.

Step 1: Classify the search strings groups and identify the information sources.

This review has searched for both previous studies of the power market and new studies that show how research is adapting to the NPS, focusing on the research objectives and main research questions. Older studies on the power market were searched for with three groups of strings, including "power marker operation", "bidding strategy" and "power market supervision". New studies were searched for with four groups of strings with terms that include "high renewable energy", "coal-fired power units", "flexible resources" and "technical application". The search criteria groups are shown in Figure 2.

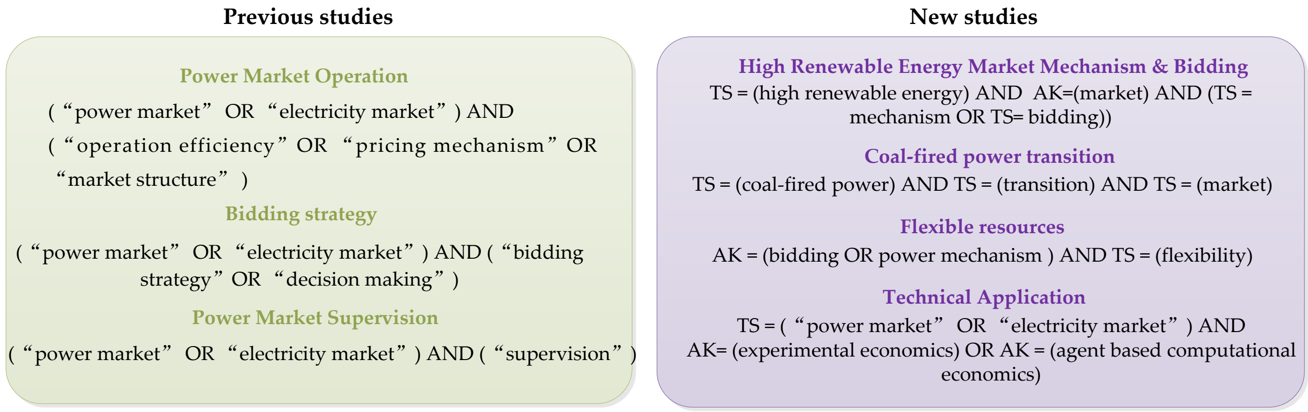


Figure 2. SLR search criteria.

Meanwhile, relevant databases that could be searched were also determined in this stage. We collected literature primarily from Web of Science, Elsevier, Google Scholar and CNKI (China National Knowledge Infrastructure). Other websites of authoritative research institutions that we used included the National Renewable Energy Laboratory and the Lawrence Berkeley National Laboratory. Collectively, these databases covered the main published papers/reports, unpublished manuscripts and conference papers (full-text access) that focused on the power markets of China and foreign countries.

Step 2: Set eligibility criteria for inclusion and exclusion of identified papers.

Eligibility criteria were determined in this phase to exclude ineligible studies from this review. There were several standards for studies to be included or excluded:

- Papers should be in social sciences, business and economics, energy, or relative fields.
- The title or subject must be strictly matched with the search strings. For example, papers that focused on storage efficiency in the power market [14] could be found when we searched for "power market operation efficiency". Alternatively, articles that used experimental methods with neural networks [15] could also be found when we searched for "experimental economics". These kinds of articles should be excluded.
- Papers or reports must be written in English or Chinese. Literature in other languages was excluded in this review.
- English articles must be published between 1980 and 2021 (access in July 2021) and Chinese articles must be published between 2000 and 2021.
- Articles must have at least one keyword in the title or abstract, or cover the topic in the full article.

Step 3: Search and export the studies on power markets.

Based on the search criteria groups in Figure 2, suitable combinations of Boolean variables, such as "AND", "OR", and "NOT", were employed to find the suitable literature. Because there are a range of topics that pertain to the power market, which has been studied extensively, "precise search" was used during the search process. The rankings of the literature were based on their relevance to the strings, which is helpful for further selection. Then, the identified studies were exported for deduplication in Step 4. The detailed search processes are as follows:

Firstly, papers published in refereed journals were searched for using the "Power Market Operation" criteria, which resulted in 1023 primary papers being selected from the business and economics fields from the Web of Science. With the same search strings, 411 papers were found in Elsevier, and 307 papers were found in the CNKI.

Secondly, the term "Bidding strategy", searched for in Web of Science, resulted in 896 papers that were indexed in the fields of business and economics. A further 1460 papers were found in the field of economics and energy in Elsevier, while 177 papers were identified in the CNKI, which was much lower than the number of that in the English databases.

Thirdly, studies on "power market supervision" were searched for using the strings. In this step, 180 papers were found in Web of Science, and, of these, 176 papers satisfied the inclusion criteria. Only three of 72 papers were selected from Elsevier, however. We found 121 articles that were published in the Chinese database.

Then, new studies regarding renewable energy, coal-fired power units, and flexible resources and "technical applications" were searched for using the same method. As a result, 187, 54, 132 and 51 of them were identified in Web of Science, respectively, while 13, 2, 2 and 48 of them were selected in Elsevier, and 18, 5, 5 and 66 of them were identified in CNKI. All eligible papers were exported for further deduplication.

Step 4: Remove duplicates of searched papers.

Because the search process was carried out using different groups of strings, Citespace [16] was used to remove the duplicates in this review. We removed 189 previous studies in this phase according to the names of the exported .txt files of all of the suitable literature.

Step 5: Choosing eligible and relevant studies.

With the assistance of the relevance ranking function in the databases, the last pages with less relevant articles were excluded from further selection. After selecting the most relevant articles, we screened their titles, abstracts, and keywords. The illegible papers were excluded based on the inclusion and exclusion criteria. Then, we further read the conclusion and implications to identify the most important pieces of literature. Finally, through careful reading of the full text, we used the "snowballing" method to find articles that were not identified in the search. This meant that we found a wide range of literature. We removed 194 articles that were duplicates. The screening led to the exclusion of 4256 publications that did not meet the eligibility criteria. There were 893 old studies and 232 new studies that were further analyzed. Finally, a total of 170 studies were included in the review. To express the search process more clearly, the search strategy flow is shown in Figure 3.

After reviewing research hotspots and solutions of power markets around the world, general issues in the study of power markets were summarized. Then key issues in the study of power markets as it pertains NPS were put forward. This involves mechanisms and strategies for renewable energy, the survival and transformation of coal-fired power plants, and the value realization for flexible resources. After theoretical analysis, technical applications of experimental economics and agent-based computational economics in the study of NPS as it relates to the power market are presented. Further, simulation and parameters in terms of power system, power market and market participants are implemented.

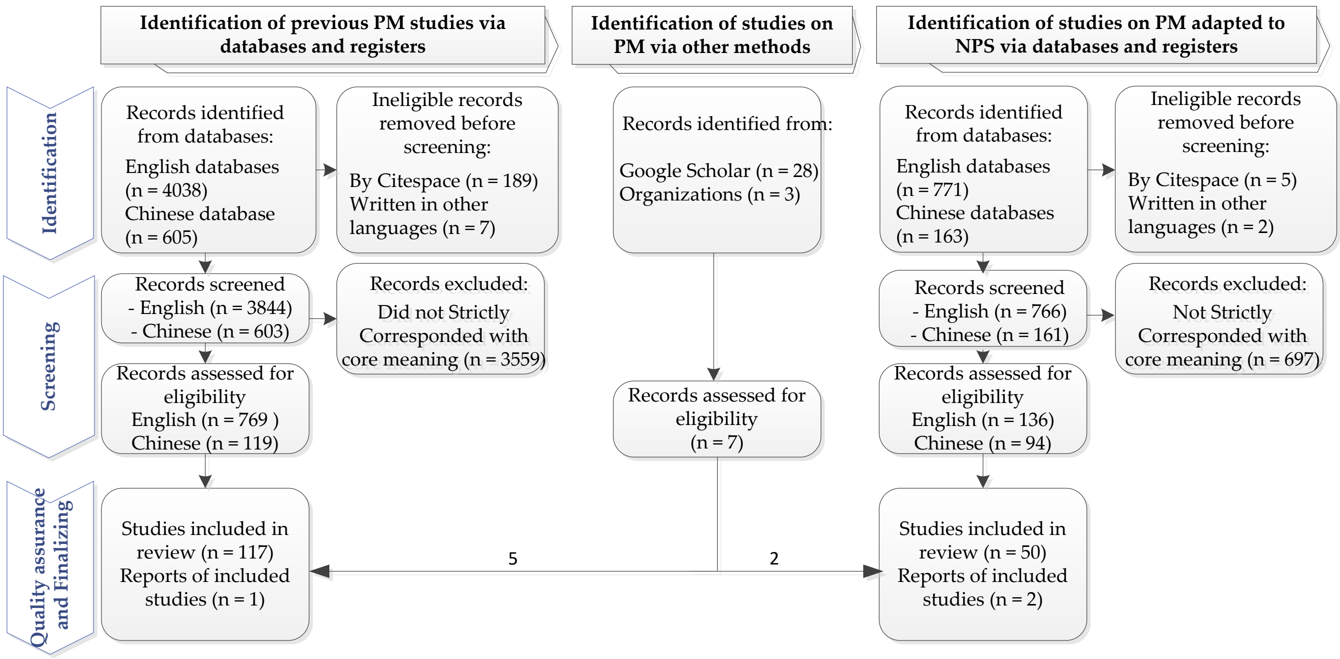


Figure 3. Search process.

3. Key Issues and the Basic Paradigm of Research into New Power Systems in the Power Market

After merging and splitting the spot sales and future trading markets [17], the Nordic power market finally grew into a situation where financial markets for power and spot trading complemented each other. Following the NETA [18] (New Electricity Trading Arrangements) and the BETTA [18] (British Electricity Trading and Transmission Arrangements), the UK has gradually liberalized the market for large and small industrial users and achieved efficient cross-border trading of electricity. With a high proportion of nuclear power and relatively low standard electricity prices, France has relevant experience in regulating the market pricing mechanisms that are adapted to a high proportion of nuclear power. In addition, issues related to electricity markets in Australia [19], California [20], Brazil [21], New Zealand [22] and Germany [23], have also been hotly debated in academia. It can be seen that the construction of electric power markets varies from country to country, due to the unique characteristics of power systems that results from different national conditions.

At present, China's power market is constructed around the provincial electricity energy market, with power transactions relying on medium- and long-term contracts. Research on China's power market is focused on the spot trading of electricity, and mainly revolves around the design of spot market price mechanisms, the bidding games of market subjects, and the interface mechanism between spot trading, medium- and long-term contracts, and auxiliary services. The further development of the power selling side, with energy storage equipment operators and other emerging entities participating in the electric sector and auxiliary services market, is also attracting the attention of scholars. Some other emerging hot research issues include demand response prices or incentives, power financial markets, electricity retail market prices and package design, as well as market risk and market assessment.

3.1. General Issues in the Study of Power Markets

A healthy power market depends on sound market mechanisms, competitive market subjects and strong market supervision. A large amount of research and practice has therefore been carried out on the operational efficiency of the power market, market subject strategies and market supervision and evaluation. Detailed research issues are shown in Figure 4.

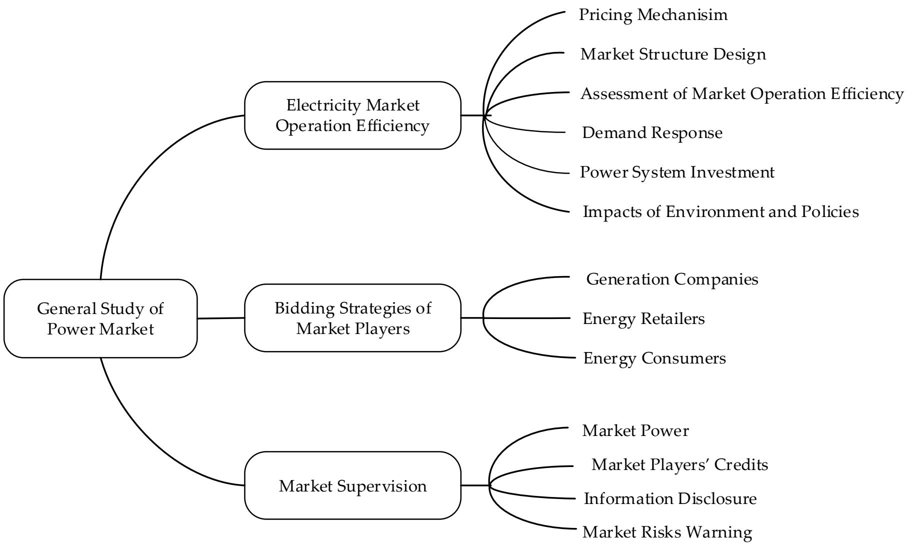


Figure 4. General Issues in the Worldwide Study of Power Markets.

3.1.1. Operational Efficiency of the Power Market

This part reviewed literature which studied market mechanisms or operational efficiency. Therefore, such papers that studied energy efficiency [24] or the operational efficiency of power plants [25] in a market were excluded. After the selection and evaluation of search results with "power market operation efficiency" strings, only 70 papers in the databases corresponded tightly with this topic. In addition, five reports were added into the pool for further analysis.

Around the time of the first power system reform in China, the operational efficiency of the power market was mainly analyzed theoretically and empirically from the perspective of market power [26]. Some scholars also studied the key problems facing the operational efficiency of the power market from a market structure perspective [27]. Other scholars put forward systemic theories and evaluation methods for the operational efficiency of the power market [28].

Apart from evaluating market efficiency [19] based on actual market operation data, foreign scholars have also studied the factors affecting the efficiency of market operations, such as price mechanism design, market structure design, market power, demand response, power system investment and environmental policies, as shown in Table 1. These studies provide a powerful reference for designing new market systems or behaviors.

Table 1. The Study of Power Markets: General Issues and References.

Research on the Operation of the Power Market		References
Price mechanism design	Regional marginal pricing	[29]
	Locational marginal pricing	[30]
	Capacity pricing mechanism	[31–34]
	Ancillary service pricing mechanism	[35]
	Combined clearing of power energy and ancillary service	[36]
	Distributed trading mechanism	[37]
Market structure design		[38]
Market power	Evaluating metrics	[19,39–46]
	Evaluating methods	[47–50]
Demand response		[51–54]
Market efficiency assessment		[19]
Investment in power systems		[55,56]
Environmental policy		[57–59]

Pricing mechanisms are the core of market operation design. A lot of practice and research on the applicability and effect of pricing mechanisms has been carried out by the industrial sector and in academia. For example, the original pricing mechanism of the Texas power market in the US was based on regional marginal pricing in the early stage of market construction, but it changed to a node marginal pricing mechanism [30] in 2010 as the market operating efficiency decreased with the deepening of power system congestion in the region. Focusing on the redispatching market in Europe, some scholars have quantitatively assessed the impact of regional pricing and node tariff mechanisms on the operational efficiency of the power system in a market environment where there is incomplete competition [60]. Such studies provide useful references for the design of electricity pricing mechanisms. According to other investigations, pricing mechanisms in China vary from province to province. Gansu and Jiangsu implement the regional marginal price [29], and the clearing price in the province is the same. Shanxi, Zhejiang and Guangdong, on the other hand, implement the locational marginal price, meaning that the clearing prices in different nodes fluctuate. Based on a full development of the electric energy market, PJM, California and other power markets in the Americas began to explore the key role [31–34] that capacity pricing mechanisms play in balancing between strengthening the reliability of power systems and increasing income for power producers. In addition, because distributed power supply has developed rapidly, reaching a large scale in recent years, its trading mechanisms [37] have also aroused wide concern.

Demand response is the process whereby end users adjust their own electricity consumption behavior in response to time-based rates. End users are provided with compensation [61] for reducing power usage when wholesale market prices are high or the reliability of power systems is threatened. At present, foreign research on demand response is focused on resident demand response strategies [62,63], business user demand response models and optimization methods [54], as well as on microgrids. Some other emerging flexible resources are also seen as key elements [64] of demand response, including flexible loads [65–67], as well as resource aggregators (RA) [54] that combine distributed power supplies, energy storage systems, and controlled loads.

The optimization of investment planning in power systems is the subject of power trading research at the macro level. Investment is also an important means of building a new power system in stages. However, most research on investment planning in power systems is focused on the physical characteristics of the electricity system, while influences from market factors are ignored by most studies. Typical simulation software for investment planning for power systems include Energy Plan [68], SWITCH [69–71], NEPLAN [72] and PLEXOS [73]. Only PLEXOS takes into account market factors (including recent and real-time market price movements, changes in demand, market risks, etc.), ancillary services and system flexibility. It can also simulate carbon trading management, showing the near-real re-emergence of multi-market coupling and system-to-market coupling. However, other investment planning simulation software are based on the technical and economic characteristics of the power system. They take into account environmental or policy impact, rather than the impact of inner-market factors on system investment planning. Such software specializes in long-term planning and optimization of the energy structure of the system.

3.1.2. Bidding Strategy of Market Participants

The quotation strategy is where the feedback from market participants corresponds to the power market mechanism, and it is also an effective test of the market mechanism. In early research, most scholars focused on power producers. They judged their winning probability by predicting the market clearance price [74], or their competitor's strategy [75], and drew their own bidding strategy based on the probability theory method. The game theory revenue matrix and incomplete competition game models were also the tools that they used to form their own bidding strategies.

During the first round of power system reform in China, a power generation side competition model was formed because the state-owned power grid company is the only buyer. Around 2002, many scholars studied the bidding strategies of power generation enterprises that were based on coal and other fossil fuels, and obtained rich research results. The quotation strategies that were used in those studies were mainly based on cost analysis [76], electricity price forecasts [77], optimal methods [78] and game theory [79]. After that, some scholars used power market simulation experiments to study the bidding strategies and bidding trading systems of power producers based on EWA algorithms [80], Repast algorithms [81], Agents [82,83], and MAS [84]. However, those strategies only served traditional thermal power plants, and the target market was limited to provincial electricity energy markets. The market is changing as China pushes ahead with a new round of power system reform. The power selling side of the market is opening. The types of market participant are increasing, and trading variety is growing. The focus of current research has moved to the portfolio strategies of market participants (represented by power producers, electricity sellers and large users) to cope with medium- and long-term contracts (physical and financial), spot trading, ancillary services and carbon markets. With the progress of technology, research on new market subjects has gradually increased. The bidding strategies of virtual power plants or hybrid power plants [85], microgrids, load aggregators [86], prosumers, energy storage and electric vehicles are becoming hot issues. Some studies have identified trading strategies for a certain type of market, and some researchers have proposed joint optimization strategies for multiple types of markets. Common research methods include two-stage robust optimization, which takes into account risks, and the Markov decision process [87]. Typical references are as shown in Table 2.

Table 2. Typical Literature on Market Players' Bidding Strategies.

Market Players	Strategy Target	References
Traditional power producers	Medium- and long-term market	[88]
	Day-ahead market	[89]
	Real-time market	[90]
	Day-ahead market and real-time market combined	[91]
Electricity retailer	Day-ahead market	[92,93]
Virtual power plant	Day-ahead market and ancillary services	[94,95]
Microgrids	Day-ahead market	[96]
	Day-ahead market and real-time market combined	[91]
	Electric energy market and ancillary services	[97,98]
Prosumer	Day-ahead market	[86]
	Day-ahead market and ancillary services	[99]
Energy storage	Day-ahead market	[100]
	Real-time market and ancillary services	[101]
Electric vehicles	Day-ahead market	[102]
	Day-ahead market and ancillary services	[103]

As can be seen from the table above, most of this research is focused on the electric energy market. The joint strategy for real-time markets and ancillary services is an especially hot research issue. There is little research that focuses on a single secondary service and capacity market strategy. It is worth noting that the market participation strategy for new thermal power units with flexible regulation capabilities has not yet been studied. However, the right strategy is crucial for thermal power units to survive during market reforms. Under new situations, when developing trading strategies, thermal power units should consider not only the income from selling electricity, but also potential benefits from providing ancillary services or spare capacity through flexible resources. Risk aversion through financial contracts [104–106], arbitrage and linkage strategies with the carbon market should also be taken into account. For instance, Bjorgan analyzed the impacts of resources constraints when utilizing a portfolio of contracts to manage adverse markets risks [104]. Furthermore, T. S. Chung introduced a new electricity forward contract that included a bilateral financial contract that allows both the seller and buyer to cope with market price fluctuations [105]. Focusing on the forward risk premia, Spodniak studied the differences between the trading price of electricity in forward contracts and the spot prices to hedge transmission risks [106]. In addition, the feasibility of trading strategies that combine new energy, thermal power, gas and energy storage and other sources is also worth exploring.

3.1.3. Power Market Regulation

A sound electricity market requires regulation. Power market regulators around the world perform nearly the same functions, including detecting potential risks to the healthy operation of the market (usually to detect whether market participants behave in accordance with market rules, standards and processes), judging whether market participants use market power appropriately, looking for defects in market rules and detecting how regional transmission organizations (RTO) influence market operations [107]. Market regulators usually exist in four major forms: (1) a single regulation department that is embedded in the system scheduling operational structure, (2) a single regulatory body that is independent of the system scheduling agency, (3) a single regulatory body that is controlled by the government, and (4) a dual regulatory body, one that belongs to the system scheduling agency, and the other which is independent. Typical regulators include the Office of Gas and Electricity Markets (Ofgem) in the UK, the European Securities and Markets Authority (ESMA), the Australian Energy Market Commission (AEMC) and the Australian Energy Regulator (AER), as well as the Federal Energy Regulatory Commission (FERC) in the US.

A variety of operational risks within the power market have been studied by academics, including supply-side market structure risks, mechanism design risks, the credit risks of market participants, power system security risks and external environmental risks. As an important index of market supervision, market power has attracted much attention from researchers.

In research outside of China, S. Prabhakar Karthikeyan [108] and his team comprehensively expounded a range of market power assessment indicators, common simulation tools, as well as common theories and algorithms. After analyzing typical cases in different countries, they proposed measures to control market power. Common indicators of market power assessment include the Herfindahl–Hirschman index (HHI) [39], the Lerner index (LI) [40,41], the must-run ratio (MRR) [42] and the residual supply index [43]. In addition, the system interchange capacity (SIC) [44], the location privilege (LP) surplus deviation index [45], the contribution congestion factor matrix [46] and other indicators have been put forward and applied by some scholars. Some other scholars claim that HHI evaluation has shortcomings, and have thus put forward a method to evaluate market power in the electricity sector based on oil market simulation [109]. In terms of regions, electricity markets in California of US [110,111], Wales (UK) [112], Germany [113], India [114], and Iran [114] has been surveyed to evaluate their market power.

The research on market power by Chinese scholars can be divided into three major types. For the first type, researchers presented a review of market power regulation and mitigation measures in foreign electricity markets, such as North America and northern Europe. For the second type, which is based on market power indicators, researchers carried out market efficiency assessments and proposed risk warnings for power producers. This research was conducted before the second round of power reform. Some were based on principal component analysis [47], and some were based on game theory [48,49]. Only Zhang Fuqiang [50] and his team considered the strategic behavior of power producers and used intelligent simulations to evaluate market power in different settlement modes. A third type of research has emerged since China deregulated its retail power market in the second round of power reform. This type focuses on the market power of various participants [115], including electricity producers [116], retailers and users. Some of the recent studies help electricity producers discover spot markets using support vector machines (SVM). Some other research has been conducted on the breakdown of medium- and long-term contracts, taking into account the market power of the parties to the contracts [117].

In order to help market participants avoid risks, market designers provide financial instruments based on the operating boundaries of power systems when designing price mechanisms, such as contracts for differences (CFD), transmission congestion contracts (TCCs), and financial transmission rights (FTRs). In addition, some scholars have proposed the concept of an operational health degree for power markets [118], which can be used to measure the electricity market so as to help government departments, system operators (e.g., independent system operators, ISOs) and market management committees monitor market conditions in a timely manner and take appropriate measures if necessary.

3.2. Key Issues in the Study of Power Markets as the System Adapts to the New Power System

As a major measure for reaching China's carbon reduction targets, constructing a new power system based on renewable energy is a complex systematic project that involves various sides in the electricity sector, including electricity producers, grids and load control sources. There will be new requirements for every part of the power system. Electricity generation units should be more flexible and capable of coordinating with the grid. The grid should be optimized for the configuration of clean energy. End users are expected to interact flexibly with the grid to help ensure power security. The market mechanism is the basic guarantee when constructing a new power system. Furthermore, the operation of new energy sources and thermal power units with regulatory capabilities and flexible loads [119], needs to be reinterpreted under the new situation. Therefore, research on how the power market needs to adapt to the new power system should be focused on building market mechanisms to promote the participation of new energy in the market, helping thermal power units survive during periods of market reform and discovering flexible resources.

3.2.1. Mechanisms and Strategies for Renewable Energy Producers Participating in the Power Market

Governments in different countries have introduced price mechanisms [120–122] and incentive policies [123] to encourage renewable energy producers to produce more. The fixed electricity prices and tradable green certification mechanisms [124] that were introduced by the EU have been successful at stimulating renewable power generation. Germany has introduced a fixed feed-in tariff mechanism, a market premium mechanism and a bidding system for the different stages of renewable energy development. The German government can adjust its fiscal incentives flexibly considering the downward trend of renewable energy costs. With these policies, Germany is seeing a rapid growth in renewable energy production. The United States and Australia promote new energy through renewable energy quota systems and renewable energy certification mechanisms. They guarantee the trading volume of wind and photovoltaic power through power purchase agreements (PPAs), and encourage renewable energy companies to directly participate in the wholesale electricity market based on contracts for difference (CFDs).

Problems appear when renewable energy producers participate in the electricity market. Firstly, the wholesale price in the power market has fallen as the scale of new energy generation has rapidly expanded. Falling prices have suppressed investment from conventional power suppliers, and this may harm the safety and stability of the whole power system. Secondly, the unstable output from new energy generation makes the markets' clearing prices more volatile. The gap between clearing prices in day-ahead markets and real-time markets widens, adding to the uncertainty regarding the returns gained by conventional thermal power plants. Thirdly, the climbing market share of renewable energy poses challenges to the design of market mechanisms.

Research into the power market is currently focusing on how to innovate the spot market price mechanism, auxiliary service price mechanism and capacity price mechanism to adapt to the new market, which now features a high proportion of new energy. Many scholars are proposing new market mechanisms for auxiliary services that are adapted to the new situation [125]. Godoy and his team are among these researchers. They designed a cost-based ancillary services market mechanism and verified its technical and economic feasibility through a simulation of the Chilean [126] electricity market. Some scholars studied the joint clearance of the electricity spot market and the auxiliary services market [127–129], while some others have proposed mechanisms to prompt flexible resource providers, including energy storage [130] and distributed power supply [131], to participate in the secondary services market.

The optimization of the power system and microgrid structure in the green power market [132] is also attracting the attention of researchers. S. Arango Aramburo [133] has studied the impact of the access to new energy on the investment cycle of power system capacity. A. Hasankhani [134] compared the differences between the scale of renewable energy in smart microgrids before and after participating in the power market, and optimized the energy management of microgrids. The issue of how demand response contributes to promoting new energy electricity connections to the grid [135] has also been explored, and researchers weighed the relationship between the scale of demand response and social welfare.

3.2.2. The Survival and Transformation of Coal-Fired Power Units

The rapid expansion of new energy power generation is squeezing out traditional coal-fired power plants. Firstly, coal-fired power generators have to keep their overall utilization hours at low levels because large quantities of electricity generated from renewable energy sources must be consumed before thermal power. Meanwhile, coal power plants have to adjust their own output to make up for new energy generation and maintain the stable operation of the grid. When electricity generated by renewable resources is sufficient, thermal power units need to reduce their output. When renewable power plants are unable to support power consumption at peak times, thermal electric plants need to increase their generation. Thus, the operational cost of coal-fired power plants is rising. Secondly, the wholesale price of electricity is falling as a result of the rapid expansion of renewable power generation. Coal-fired power plants are losing competitiveness due to falling electricity prices. Some thermal power plants even report severe losses in regions with high prices of coal. Thirdly, the environmental cost of coal-fired power plants is also rising because China is promoting green and low-carbon development through the carbon trading market, which further cuts the competitiveness of thermal power plants. Fourthly, the complexity and cost of decision making is surging as coal-fired power plants adapt to the power and carbon market linkage system. It is a new challenge for traditional power suppliers which have just become accustomed to the market environment in the past few years.

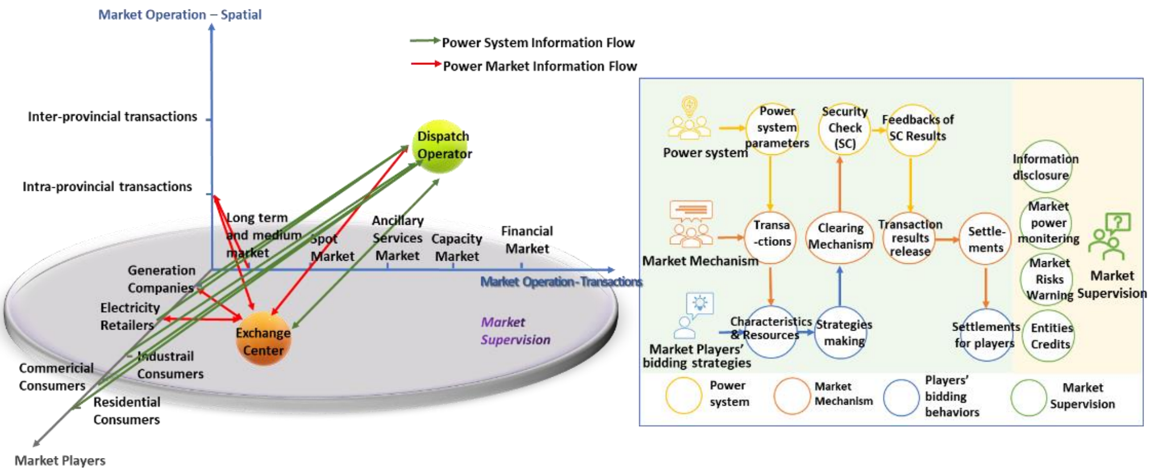
However, thermal power accounts for more than 60% [136] of China's total installed power capacity, with nearly 50% generated by coal-fired power plants. Therefore, the thermal power sector plays an important role in China's power security. Meanwhile, China is limited to just relying on energy storage and demand-side resources to provide auxiliary services for the new power system. Flexible thermal power units' capacity for adjusting electricity consuming load and frequency is worth exploring, especially with the target of transforming 200 million KW of coal-fired power units into flexible resources during China's 14th five-year plan period [137]. In addition, the survival and development of coal-fired power units is also worth an in-depth discussion from the perspective of people's livelihood. Therefore, whether coal-fired power plants can be successfully transformed through technological improvements and reasonable market mechanisms is a key issue for the construction of the new power system.

3.2.3. Value Realization and Supporting Mechanism for Flexible Resources

The value of flexible resources in the new power system is expected to be realized using market mechanisms. More and more attention is being paid to the value of flexible resources, including energy storage, electric vehicles, demand-side resources and thermal power plants with flexible regulation capabilities. However, current research on flexible resources is generally limited to optimization planning or resource allocation within power systems, discussing, for example, the system optimization of flexible resources for power supply, grid operation and load management. Another limited research issue is studying how to optimize the configuration of flexible resources for adequate demand response [138]. Only a few studies have explored the value [139,140] of flexible resources in the electricity market, which lack systematic quantitative analysis. Significantly, there are no studies on value modeling, market system design, and simulation deduction and decision analysis when it comes to flexible resources that will operate under market conditions within the new power system. To fill in this gap, we need to recognize the value of flexible resources and design a market mechanism that can clearly reflect price signals, so as to help renewable energy resources participate in the electricity market.

3.3. Basic Paradigm for the Study of Power Markets under the New Situation

A power market is a complex economic system, with branches forming where the system couples with others. To simplify this study, we built a framework with three dimensions, including market operations, market player strategies and market supervision, to outline a basic paradigm for power market research under the new situation. As shown in Figure 5a, the power market operates through the interaction of different sub-markets. Depending on its different functions, transaction times and spaces, the power market can also be divided into different submarkets. Market players make strategic decisions in different scenarios based on the market mechanisms, which leads to diverse market results. The interaction between market participants and the market operation mechanisms affects the health of the power market. Connecting all kinds of market players, the power trading center is responsible for publishing market information, organizing transactions of different types, managing the credit of market participants and assessing market risk. The dispatch center checks the safety of the power system according to the clearing information of the trading center, and forms the final clearing and dispatch orders. The market supervision department supervises the credit of market players, information disclosure, market force detection and risk warning. As shown in Figure 5b, the power system, market mechanisms and strategies of market participants are key factors that help us understand market systems. These three aspects will be further discussed in the following part of this paper.



(**a**) (**b**)

Figure 5. Basic paradigm for the study of power markets: (**a**) research dimensions of power market; (**b**) general process of power transactions.

Typical types of power markets include the electric energy market, the auxiliary services market, the capacity market, the power financial market and the transmission rights market. The electric energy market can be further divided into the wholesale market and the retail market according to the trading volume. In the wholesale market, participants can trade through the trading center, or they are allowed to make direct transactions through bilateral negotiations.

From the perspective of the time dimension, the electric energy market can be divided into the medium- and long-term market, and the spot trading market. The medium- and long-term power market is designed to avoid market risks and maintain the safety of power systems. Transactions in the medium- and long-term market can be made either physically or in a financial manner. From the perspective of the spatial dimension, power markets can be classified as provincial markets, regional markets, national markets and transnational markets, according to the different structures of the power grids. Different countries choose different trading modes according to the unique structures of their grids.

Auxiliary services are helpful for maintaining the reliable operations of the grid and ensuring the quality of electricity transmission. The ancillary services market is an important complement to the spot market. As China advances the reform of the power market, a key issue is how it can determine the supply boundaries [141] and supply costs of auxiliary services within the auxiliary services market. Another hot issues is how the supply costs would change [142] with different operational strategies.

One study [141] is a review of the international research results from studies of auxiliary service standby mechanisms that are based on the actual operations of regional power markets, covering the types of auxiliary service standby mechanisms, the coordination and optimization mechanisms of the standby power market, and methods for assessing backup demand. If the auxiliary services market is regarded as the safety mechanism to ensure the stability of power system in real time, then the capacity market is the mechanism that ensures the stable supply of electricity over the medium and long term. The key issue when studying the capacity market is how to encourage market participants to build effective power generation units, improve investment efficiency and ensure the stable supply of electricity [143] under the premise of reducing investment costs. Financial derivatives are important tools for risk management in the power market. In the power markets of typical countries, market participants use contracts for difference (CFDs), power futures and power options products and other financial derivatives [144,145] to suppress the risks from fluctuating spot prices.

With the urgent need to build a new power system and market trading system, it is especially necessary to explore the market mechanisms, capacity mechanisms or capacity markets [146], and market interface mechanisms that can be adapted to China's own conditions. Under China's new power system, based as it is on renewable energy, the important value of flexible resources, an emerging market resource, needs not only to be quantified, but also to be realized under the market mechanisms. Therefore, whether to design a new market mechanism for renewable energy and flexible resources, how to design and connect the mechanisms, what effect the new mechanism could bring, and other questions are issues worth exploring. Further, the research on the portfolio and bidding strategies of market participants, including traditional thermal power capacities and emerging renewable energy and flexible resources, is of great significance to help market players integrate into the new market conditions and to promote the healthy development of the market.

4. The Theoretical Basis and Technical Applications of Power Market Simulations to Help Markets Adapt to the New Power System

The effects of designing market mechanisms and conducting research into market participants' strategies need to be verified under specific market circumstances. Power market simulation technology is an effective means of avoiding the loss of benefits that the strategy's design may cause to the actual system. The power market is an open and dynamic, complex and adaptive system with parallel interactions and nonlinear dynamics. Each market participant is independent but can interact with any other. Traditional simulation tools that are based on unified decision making are not suitable for complex power systems with decentralized decision making as the basic feature [147]. The simulation of power markets based on experimental economics and computational economics not only considers the rational and irrational behavior that may occur in the real environment, but can also simulate people's limited rational decision making and realize complex computations using intelligent agent technology. Therefore, it is an effective tool for studying market mechanisms and the strategies of market participants.

4.1. The Theoretical Basis of Power Market Simulation

4.1.1. Principles and Applications of Experimental Economics

Experimental economics (EE) is a branch of economics that uses data from experiments to address economic questions. Experimental economics was developed in the second half of the 20th century and matured during the 1960s and 1980s. Drawing on the experimental methods that are used in the natural sciences, EE simulates the actual decision making that goes into market transactions according to the strategy of selected subjects. Experimental economics is used to prove the theoretical hypotheses of economics and test the effects of specific rules in the economic system through controlled experiments. The research issues of experimental economics have developed from simple theoretical tests to summarizing regularities and forming new theories using systematic experiments. The design process of economic experiments has also changed from simply copying the scenes in classic models to designing "tailor-made" experiments [148] for new research issues.

With the development of computer technology, experimental methods have become diversified, which makes large-scale experiments and remote interactive experiments feasible. The scope of research has been extended from microscopic and purely theoretical topics to macro [149], financial [150–153] and social networks [154]. Many government agencies use the results from experimental economics research to guide practice [155] in auctions and central bank policy making. Through systematic reviewing-related research, some scholars divide experimental economics into seven branches [148]: individual preference and decision making, game theory, industrial organization, labor economics, public economics, finance, and macroeconomics. Power market simulations that are based on experimental economics can help verify the theoretical value of the above theories when studying multi-subject interactions in markets and market dynamics, providing a key basis for understanding the competitive behavior and theoretical modeling of market participants. Through power market simulation, we can also research the influence of different trading mechanisms that consider the rational and irrational behavior of real market participants on the efficiency of resource allocation.

4.1.2. Principles and Applications of Agent-Based Computational Economics

Only a limited number of market players can be considered to be the 'rational economic men' of classical economics. Market participants' behavior is not universal, and it is therefore difficult to interpret using traditional mathematical models. With the convergence of technologies in multiple fields and the progress of research and development technologies, agent-based computational economics (ACE) has become an effective tool for overcoming the shortcoming of traditional economics.

Through artificial intelligence and computer modeling and simulation technology, ACE can be used to study complex phenomena in economic systems. Based on the system evolution model, which constitutes a large number of independent market players, the decision-making methods and intelligence levels of different market participants can be calculated using a series of calculations. The simulation system based on agent-based computational economics (ACE) can not only verify some existing economic theories, but also address problems that cannot be well explained through other branches of economics. For example, in the real market environment, even if there is no top-down government/management influence, why do some market participants still follow behavior patterns that are beneficial to the overall development of the market system? Such a problem can be explained using agent-based computational economics (ACE).

In addition, the ACE model can help researchers understand the impact of different systems on the social efficiency and individual welfare of economic systems, and solve the problems of long-term games and individual psychological behavior, which are weak points in existing economic research. In power market simulations, each agent is given different capabilities in their initial state. During the trial cycle, individual agents predict potential changes in the market and give feedback based on their own characteristics. All agents in the system compete with each other and influence each other, together constituting a complex, dynamic, evolutionary system.

Major application scenarios of the existing research based on ACE are as follows. The first type of research is the simulation of individual learning mechanisms, of which the complex network evolution game, based on individual learning abilities, is a cutting-edge problem [156]. This simulation method is mainly based on genetic algorithm and neural network technology.

The second type is to depict behavior patterns. Typical research in earlier periods concentrated on the impact of cultural communication on economic globalization. After introducing the concept of open innovation, Chinese scholars combined computational economics with open innovation problems, and gave market players different equity preference attributes, so as to build a multi-intelligence simulation model. Then, market subjects' preferred strategies, based on their different preference types in different innovation modes, are deduced. Such research provides a useful point of reference [157] for studying open innovation alliances and enterprise innovation development from the micro perspective.

Thirdly, the ACE model is also applied in the study of trading networks in economic systems, focusing mainly on the formation and evolution of networks, as well as the optimization of network organization. Social problems, such as the seasonal migration of shepherds, are typical issues at the heart of this research.

The fourth is to study the market model based on ACE. The evolutionary process and institutional influences on various kinds of markets attract the most researchers. The simulation of the securities market conducted by SFI(Santa Fe Institute) [158] is a typical scenario where ACE is applied.

4.2. Simulation Applications and Parameter Settings for the Power Market as It Adapts to the NPS

The power market simulation system is a comprehensive system that uses specific rules and design processes to simulate the real power market based on the characteristics of real power systems and real markets. The core modules of power market simulation cover power system modeling, power market rules and the characteristics of market participants. Based on the core modules, new scenarios can be designed by adding, deleting and changing parameters, so as to study key issues and test hypotheses pertaining to market constructions under the new power system.

4.2.1. Parameter Settings for the Modeling and Simulation of Power Systems

The modeling and simulation of power systems is based on the physical properties [159–161] of power systems, such as the structure of regional power supply, load, grid nodes and the limit of power transmission lines. As China expects to embrace a new power system with a large amount of renewable energy, the value of all kinds of electricity generation units (especially flexible resources) needs to be verified for the new market situation [162]. In order to simulate the market to study specific issues, a variable scenario for modeling power systems can be constructed by adding the types and proportions of electricity generation units. The types of units covered by the simulation include new energy sources, energy storage (usually in form of electrochemical, hydrogen storage, and flywheel), distributed power supplies and thermal power units with flexible regulation capabilities. Common parameters of power system simulation that are based on electric power system theory and prediction theory are shown in Table 3. In addition, under the construction of the new power system, the market share occupied by new energy, the rate of new energy penetration, and other indicators can be added. By adding such indicators, other issues [163], such as testing paths towards the dual carbon emission target, discovering the value of diverse resources and improving the strategies of market participants, can be researched under the simulation with extended parameters.

Table 3. Power System Simulation Parameters.

Parameters	Description
Structure of the power supply	Type, location, installed capacity and other properties.
Forecast of electricity output (accuracy) generated from renewable energy of the system	The reliability of the system can be verified by setting a proper coefficient of power generation using renewable energy units. Based on weather forecast data, the dispatch center estimates potential output from renewable resources and provides the power generation coefficient of new energy to market participants for reference.
Standby rate	The standby rate is the ratio of the gap between the system's total available capacity and the peak load. It is an important index to measure the reliability of the power system [164].
Number of nodes	The complexity of the power system can also be reflected by the number of nodes. The closer the location and number of nodes is set to the actual grid topology, the more effective the power system simulation will be.
Power generation schedule of units	Factors influencing the power generation schedule of the units include system operation factors and non-system operation factors.
Power flow	Excited by the potential of the power supply, electric current flows from the power supply to every load in the power system through distribution components, and thus power is distributed throughout the whole grid.
The constraint of power flow in N-1 transmission section	When grid topology operates normally according to the given constraint, if disconnecting any line in the section, power flow in the rest of the lines is not overloaded. The constraint of power flow in a section is the maximum allowable power current when the section is running normally [165]. If the power flow surpasses the limitation, a nodal price would be formed.
Constraint of active power balance	Active power balance means that active power on the generation side and the consumption side is equal. The frequency of the power system is directly related to the balance of active power, and the auxiliary services of frequency regulation can be referenced.
Constraint of reactive power balance	Reactive power balance is the condition that reactive power on the generation side and the consumption side is equal. When the reactive power is insufficient, the reactive compensation is required.
Plans for maintenance of power generation, transmission and transformation equipment	Plans for maintenance covers two types of equipment, including power generation equipment, as well as power transmission and transformation equipment. The maintenance plans for power distribution and transformation equipment affect the structure of power transmission for a short time.
System load forecasting (accuracy)	The dispatch center predicts the total load of the power system for several days based on data obtained about the system. The accuracy of system load forecasting directly affects the analysis of market supply and the demand of market participants, and then affects market quotation behavior.

4.2.2. Parameter Settings to Simulate the Rules and Conditions of the Power Market

The simulation of market rules and conditions is focused on market mechanisms and related policies. Through setting different parameters, diverse market scenarios can be simulated. Market rules are reflected by a range of parameters, such as the entry and exit of market players, symbols of trade, and rules of clearance and settlement. Market conditions are simulated by the ratio of supply and demand, market forces and policy-related indicators. Common parameter settings that are based on power market trading, theory and industrial economics theory are shown in Table 4.

Table 4. Power Market Rules and Environment Simulation Parameters.

Parameters	Description
Trading methods	Major trading methods include bilateral consultations, centralized bidding and listing transactions. The spot trading market is divided into the day-ahead market, the intra-day marker and the real-time market. A variety of trading methods can be combined according to the transaction cycle, thus new symbols can be built in to increase the diversity of market symbols.
Trading transactions	Depending on different types of markets, typical symbols include medium- and long-term (yearly, monthly, weekly) transactions, contract power transfer, power generation rights trading, spot trading and ancillary services trading. New trading instruments for renewable energy and flexible resources will be added in order to meet the needs of further construction in the power market.
Limitations on the declared price	Based on the relationship between demand and supply, in order to avoid market manipulation and vicious competition, minimum and maximum declared prices must be set for the direct trading of electricity in different transaction modes. Different ranges for price limitations can be set through power market simulation to verify the market's capacity.
Rules for clearance	Major rules of clearance include high–low matching and unified clearance. High–low matching is the priority match between the highest spread on the demand side and the lowest spread on the supply side. Whether the spread pair matches can be judged by the following formula: $L_n - S_m \geq 0$, match $L_n - S_m < 0$, not match where L_n is the spread pair on the demand side, while S_m represents the spread pair on the supply side. Unified clearance refers to the selection of the last pair of spread pairs that match successfully according to the principles of high–low matching. The arithmetic average of the selected pair will be designated as the closing spread of all participants. When studying the development degree and diversification of the power market, different rules of clearance and trading methods can be combined to conduct diversified trading. Thus, the market affordability can be tested.
Settlement mechanisms	Settlement is reached either at the marginal electricity price or at the actual declared price by power generations units: $\min F_m,\ F_m = \sum_{i=1}^{I} C_{om} \cdot P_i$ where F_m represents the cost of power purchases paid by the grid, P_i represents the power generation volume bid by the power producer (or electricity generation unit) i, and i refers to power producer. I is the total number of power producers, and C_{om} represents the marginal electricity price of the system.

Table 4. *Cont.*

Parameters	Description
Changing rate of the balancing funds account	As the price fluctuations of electricity bought from the power market by the grid cannot be transmitted to power retail prices in time, a balancing funds account is built to link power sales prices to power purchase prices: $V_i = \frac{F_i - F_{i-1}}{F_{i-1}}$ where V_i is the changing rate of the funds in the balancing account, F_i represents the amount of balancing funds this year, while F_{i-1} refers to the amount of balancing funds last year.
Market turnover rate	Market turnover rate is the ratio representing the number of market participants declaring during the statistical period (which can also be a transaction for one time) divided by the number of market subjects that finally complete the transaction. The turnover rate is used to analyze whether market competition is insufficient or judge collusion by market participants: $V_i = \frac{F_i}{G_i}$ where Vi is the turnover rate, Fi refers to the number of market subjects which finally complete the transaction, and G_i is number of market participants declaring during the statistical period.
HHI	The Herfindahl–Hirschman index (HHI) is a composite index that measures industrial concentration. It reflects the changes in market share, i.e., the dispersion of the size of manufacturers in the market: $I_{HHI} = \sum_{i=1}^{N} (100S_i)^2$ where S_i is the market share occupied by market supplier i per trade sequence during the evaluation cycle, while N represents the number of suppliers in the market during the evaluation cycle.
Renewable energy subsidies	According to the effectiveness of the market mechanism and the development of new energy, the amount of renewable energy subsidy can be changed to verify the risks brought about by the marketization of renewable energy resources.
Deviation parameters	The parameters reflecting the deviation of power generation (more or less) on the generation side include the exemption range and the appraisal price. The parameters measuring the deviation of electricity consumption (more or less) also include the exemption range and the appraisal price.

To study the key issues relating to the market trading system under the new power system, the access of emerging market participants can be modified through the module of participant characteristics. When designing market mechanisms to stimulate flexible resources, it is necessary to make explicit the value and price conduction mechanism of the flexible resources. Simultaneously, some parameters, including the price declaration mode, the upper and lower limits of the price, the clearing method and the settlement method, can be modified so as to check market feedback.

In addition, whether the symbols are sufficient to meet market demand can be verified through combining multiple symbols and trading methods, with the actual situation in the simulation area taken into consideration. To verify the settlement rules, the model, content and the method of settlement that is used by different users can be combined and simulated through power market simulation. Thus, the settlement rules, with their regional characteristics, such as deviation assessment and double rule assessment, can be included in the study.

4.2.3. Market Participant Characteristic Parameters

As the most basic units of the power market, market participants affect the construction of the trading mechanism to a certain extent. The market subject module is focused on the characteristics of transaction behaviors and the strategies of market participants. In the simulation system, the subject that is making decisions can be intelligent or real people. Therefore, parameters are designed to simulate the characteristics of human-machine decision making, including the type, quantity, distribution, feedback behavior and learning ability of market participants. The parameters that are commonly used to simulate market participants characteristic, which are based on power market theory, behavioral economics theory and forecasting techniques, are shown in Table 5.

Table 5. Market Participants Characteristic Parameters.

Parameters	Description
Power producer, asset type and status constraints	This parameter covers the type of units and operating parameters of the power producer. When the user of the simulation system is the power producer, the power generation enterprise can develop its own strategies by simulating the trading strategy of its competitors based on market conditions.
Cost composition	Cost is an important basis for making transaction decisions. Power generation costs primarily cover start-up costs, empty operating costs, fuel costs, environmental costs, and other economic costs. Under China's dual carbon reduction goal, environmental costs have become an important constraint on the development of thermal power enterprises. Power sales companies need to consider retail contract prices, wholesale prices and other related parameters.
Marginal revenue of the power generation unit	This parameter refers to the income earned through increasing or decreasing the power generation of the unit, and its relationship with the power generation and market price is: $MR_i = \frac{d(PG_i)}{dG_i} - P$ where MR_i is the marginal revenue of the power generation unit i, G_i refers to the output of unit i, and P is the electricity price in the power market.
Forecasts for market prices and power generation	A power plant forecasts its own power generation output based on its installed capacity. Combining this with market price forecasts, the power plant declares reasonable prices and a power generation plan. At the same time, the market price and power generation coefficient can also be set to verify the anti-jamming of the quoting strategy.
Power generation plans	Power generation enterprises make production plans based on existing contracts. Power market simulation provides users with a chance to choose the optimal solution from different generation plans so as to avoid market shocks.
Intelligent agent simulation	Through simulating the trading behaviors of competitors, intelligent agent simulation technology helps power producers to formulate their own trading strategies. By simulating the transactions of multiple participants, it can also help verify market results. Intelligent agents can be divided into rational and irrational, or radical and conservative. Commonly used parameters include the number of intelligent agents, learning mechanisms and feedback mechanisms.

To better study the key issues relating to the market trading system under the new power system, on the one hand, we should expand the research to cover a diversity of market subjects. A range of participants, such as different renewable energy resources, energy storage, distributed power supplies, flexible thermal power units, and flexible loads that can respond to power consumption peaks, should be included. On the other hand, stronger decision-making abilities should be developed for market subjects. Training the learning, prediction, portfolio and risk management abilities of the intelligent agents is helpful. By enriching the parameters for the simulation of market transaction behaviors, the effect of different trading mechanisms can be tested, providing beneficial points of reference for market participants for better decision making.

5. Discussion

This paper provided a rigorous systematic review of the study of power markets with clear framework conditions using pertinent literature databases and full-text access for query articles. The disregard of non-English and non-Chinese language publications in the databases and the disregard of conference articles without full-text access could be regarded as limitations of this review. Moreover, the exclusion of the last pages papers in the relevance rankings could also be a limitation.

This review covered existing research on the study of power markets, including market operational efficiency, the bidding strategies of market participants and power market supervision. Based on the search results, it can be concluded that English papers focused more on bidding strategies than on the operational efficiency of markets. However, Chinese papers paid more attention to the operational efficiency of markets and supervision than to bidding strategy.

Previous studies on the operational efficiency of power markets mainly focused on the structure design or evaluation. As illustrated in Section 3.1.1, such studies have three major flaws. Firstly, such empirical analyses were limited to the unilateral bidding market scenario that was formed during the first electric power reforms in China. Secondly, previous researchers ignored the constraints and influences of environmental factors. Thirdly, those studies have not considered the systematic impact of a high proportion of new energy connecting to the power system and power market. Given the different roles of market players, studies on bidding strategies can be sorted according to three aspects, namely, generation companies' strategies, energy retailers' strategies, and energy consumers' strategies. With regard to the development of the power market, studies on the strategies of prosumers [86], virtual power plants [94,95], microgrids [91] and energy storage [91] were given more attention. Furthermore, most of them focused on the spot market, especially the day-ahead market. Moreover, previous studies in the bidding strategy field were implemented using cost analysis, electricity price forecasts, optimization algorithms or game theory. Little research was conducted using a power market trading simulation system, which is based on experimental economics and agent-based computational economics. To some extent, these can provide points of reference for bidding strategy studies that focus on the adaptation to the NPS. However, most of them studied participants as price takers, and only a few publications [166] studied the market strategies of flexible resources in joint energy and flexible product markets. This work emphasized the significance of power market simulation systems for the study of power markets, and proposed parameter setting suggestions for power system simulations, power market rules simulation and market participants characteristics.

This literature review introduced several key issues in Section 3.2 that relate to the adaptation to the NPS. In Section 3.2.1, relatively new studies were discussed, with 42 papers found that were published in Web of Science and 121 papers in Elsevier. However, only two of these papers were published after the NPS was proposed. Only one of them focused on the financial implications for investors in renewable energy [167]. The other one introduced a day-ahead clearing model for the simultaneous energy and ancillary services market with a high penetration of renewable energy sources [127]. Although some papers also talked about market issues with renewable energy resources, most of them focused more on power system operations [168,169] than the power market operations. In conclusion, few studies discussed the mechanisms and strategies for an investor in a market with a high amount of renewable energy.

Only five papers were identified as highly relevant publications based on in the "Coal-fired power transition" search term. Some studies discussed phase-out issues [170,171], rather than the transition strategy for coal-fired plants to adapt to the energy transition. Although one paper [172] proposed that coal-fired power plant could be retired in Australia in the future, it did not discuss the policy implications for coal-fired power plants during this transition. Under the construction of the NPS, one should consider not only the income from selling electricity, but also the potential benefits from providing flexibility using coal-fired units.

As for the study of flexible resources in power markets, Muñoz [173] discussed the current limitations of Chile's electricity market going forward, which aimed to provide incentives for the efficient resources to give the system more flexibility. Moreover, Das, P. [174] argued that technology, policy and new modeling strategies are needed to expand large-scale renewable energy, which supports the standpoint of this review.

6. Conclusions and Implications

Research on electric power markets are now discussing how the markets can adapt to the new power system, which will be based on renewable energy. Market mechanisms, market participants' strategies, and market supervision are three key elements for the healthy operation of the power market. This paper provided a rigorous systematic review of the study of power markets given this new situation. The article also provided a comprehensive overview of the key issues in the new studies on power markets and its applications and techniques. After the analysis, a basic paradigm for the study of power markets that is suitable for the new situation was put forward to provide a clear review of the study of power markets and inspire better research on market trading mechanisms under the new power system. The main contributions of our research are as follows:

1. The general issues of power market research were summarized in terms of market operation, bidding strategies of market players, and market supervision. The quantitative analysis shows that China's previous power market studies paid more attention to the market mechanism design and operation supervision. However, bidding strategies were discussed more than power market supervision in other countries.
2. Key issues related to research on the power market were picked out for further study as the market adapts to the new power system, which features a high proportion of new energy. These issues include market mechanisms to promote the participation of new energy, flexible resource value discovery and supporting mechanisms, as well as the survival of thermal power units. The systematic review indicates that the mechanism and strategies for a new energy-dominated power market were not fully considered in previous studies. Moreover, for the survival of coal-fired power plants in this new environment, most studies focused on the phase out issues rather than the market mechanisms and strategies relating to their transformation. In addition, research on flexible market products is still rare, although more attention is being paid to this issue [174].
3. A basic paradigm for the study of power markets that is suitable for the new power system was established, which provides the basic direction for power market research under the new situation.
4. The theoretical basis of power market simulation was presented in our paper. Meanwhile, the applications of experimental economics and agent-based computational economics in the study of power markets were reviewed. The quantitative analysis shows that although the current studies can provide a point of reference for the study of power markets, there are few pieces of literature on the new power market with the application of EE and ACE. More research is needed in the future to adapt to the construction of the NPS.
5. Specific parameter settings were recommended for simulating power market transactions, which can serve as a theoretical basis and practical guidance for other researchers to better study the power market.

The power market is a complex economic system. To better construct a new power market that is dominated by new energies, more studies on the key issues are needed. Studies on the new power market can be developed using EE and ACE techniques., which can help to reduce the costs of power market construction, promote the low-carbon transformation of the electricity sector, and improve the market trading mechanisms of the new power system.

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